



Experimental study on holdup and pseudo-slug flow pattern in horizontal and slightly inclined dense-gas/liquid flow

Carlos Mauricio Ruiz-Diaz¹ · Cristhian E. A. Pacheco¹ · Gustavo Bochio¹ · Alberto T. Postal² · Oscar M. H. Rodriguez¹

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Abstract

The formation of dense gases is driven by high pressures, critical temperatures, and high content of CO₂, conditions characteristic of ultra-deepwater production environments such as the Brazilian pre-salt. This study presents an experimental investigation of horizontal and slightly upward inclined dense-gas and liquid two-phase flow under hydrodynamic conditions representative of these scenarios. Due to the lack of experimental data in such regimes, the accuracy of existing predictive models remains limited, potentially leading to economic losses and environmental or safety risks. Experiments were conducted using a high-pressure inclinable loop equipped with a 30 m pipeline, employing pressurized sulfur hexafluoride (SF₆) as the gas phase and mineral oil as the liquid phase. The test section was configured at 0°, 5°, and 10°, and 125 experimental points were collected, including pressure, temperature, flow, holdup, and flow pattern data. Two-phase flow visualization was carried out using a high-speed camera, while liquid holdup and phase fraction distribution were determined with a collimated gamma-ray densitometer. The observed flow patterns included stratified smooth, stratified wavy, stratified wavy with mixing at the interface, slug, pseudo-slug, dispersed, and the rarely reported dual-continuous pattern. Notably, the dual-continuous flow pattern was identified for the first time under upward inclined conditions (5° and 10°). The experimental results demonstrate that pipe inclination and dense gas velocity are key factors in the transition between slug and pseudo-slug flow patterns. Additionally, interfacial instabilities and liquid splashing were observed at high dense-gas velocities. These findings address important knowledge gaps and support the development of more accurate predictive models for multiphase flow in complex production scenarios.

Keywords Gas-liquid flow · Dense gas · Flow patterns · Holdup · Gamma ray · Drift-flux

List of symbols

A	Annular
A	Cross-sectional area
C_0	Distribution parameter
$C_1, C_{0,1}, C_3, C_4$	Coefficient
d	Pipe diameter
dA	Beam cross-sectional area variation

D_h	Hydraulic diameter
D	Dispersed
DC	Dual-continuous
f	Franning friction factor
Fr	Froude number
g	Gravitational acceleration
GRD	Gamma-ray densitometer
h	Heigh inside the cross-section
H	Holdup
i	Discrete denotation
I	Intensity measured
L	Length
la	Laplace variable
LEMI	Industrial multiphase flow laboratory
$\dot{m}$	Mass flow rate
MAE	Mean absolute error
MARE	Mean absolute relative error
ME	Mean error

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✉ Carlos Mauricio Ruiz-Diaz
 carlosruiz978@usp.br

¹ Industrial Multiphase Flow Laboratory (LEMI), Mechanical Engineering Department, São Carlos School of Engineering (EESC), University of São Paulo (USP), São Carlos, SP, Brazil

² Research, Development and Innovation Center (CENPES), Petrobras, Rio de Janeiro, RJ, Brazil

MRE	Mean relative error
RMSRE	Root mean square relative error
PDF	Probability density function
PSL	Pseudo-slug
QCV	Quick close valve
R	Radio
Re	Reynolds number
SF_6	Sulfur hexafluoride
SL	Slug
ST	Stratified smooth
SW	Stratified wavy
SW/MI	Stratified wavy with mixing at the interface
U	Velocity
U_{gm}	Drift flux velocity
x	Two phase quality

Subscripts

g	Gas phase
l	Liquid phase
m	Mixture
s	Superficial
t	Dimensional time
tp	Two-phase

Greek symbols

α	Void fraction
β	Gas volumetric fraction
Δ	Variation
$\mathcal{E}$	Error metric
ε	Roughness
θ	Inclination angle of the pipe measured from the horizontal plane
μ	Dynamic viscosity
ρ	Density
σ	Surface tension

1 Introduction

Multiphase pipe flow is fundamental in various engineering disciplines and represents the most common type of flow in industrial systems, often resulting from phase changes or fluid immiscibility. This phenomenon is particularly relevant in ultra-deep offshore oil and gas production, where high pressures, critical temperatures, and elevated CO_2 concentrations lead to the formation of dense gases. Liquid-liquid flow [1] predominantly occurs in wells, while gas-liquid flow [2] is typical in subsea flowlines and risers, often involving mixtures of hydrocarbons, water, and gas. In the Brazilian offshore production scenario, the combination of very high pressures and high CO_2 content promotes the

formation of a particular type of gas-liquid flow, in which the gas phase exhibits a density comparable to that of the liquid phase. Therefore, this research focuses on two-phase flow involving pressurized sulfur hexafluoride (SF_6) and oil to mimic the observed low liquid-gas density ratio of real production. The modeling of dense-gas/liquid flow presents significant challenges, especially due to the scarcity of experimental data, which is even worse varying inclinations from horizontal [3].

The phenomenological modeling of dense-gas/liquid flow continues to be an underexplored area, as existing models for gas-liquid and liquid-liquid flows in horizontal [4], vertical [5], and inclined [1, 6] lines do not account for dense gases in their formulations. This limitation suggests that computational tools may provide inadequate predictions, given that the data utilized to calibrate those models do not correspond to the specific production conditions of ultradeep water production. This data gap compromises the accuracy of predictions, potentially leading to economic losses and risks concerning safety and environmental impact.

Flow patterns and holdup are some of the most relevant parameters in the study of gas-liquid two-phase pipe flow. Consequently, non-intrusive techniques such as gamma-ray and X-ray tomography systems have been widely employed. Those methods allow for the analysis of phase-fraction distribution across different flow patterns through cross-sectional scanning of the pipe. Several studies have demonstrated the application of those techniques. For instance [7, 8], employed X-ray tomography to obtain phase fraction distribution profiles for stratified, slug, and annular flow patterns using dense gas (SF_6), with maximum gas density achieved of 54 kg/m^3 [9]. used a collimated densitometer with a cesium-137 ($Cs-137$) source to determine wave amplitude in wavy stratified flows of sulfur hexafluoride (SF_6) and oil, based on phase fraction distribution curves. In addition [10], analyzed CO_2 bubbles entrained in the liquid phase of stratified flow, also using X-ray tomography to map the phase fraction distribution. Finally [11], applied X-ray imaging to identify, with high temporal and spatial resolution, the interfaces between gas and liquid and oil and water in three-phase flows, with the measurements validated through a gamma-ray system.

Two-phase models such as homogeneous and separated flow are commonly employed; however, their accuracy in holdup predictions for slug flow patterns is limited, underscoring the need for developing novel correlations to determine the holdup in this flow pattern [12–14]. Drift-flux correlations [15, 16], as proposed by [17], are usually applied for slug flow and offer another alternative for predicting holdup and pressure gradient [18]. A variant of slug flow that is observed in dense-gas/liquid flow is the

pseudo-slug flow pattern, for which there is limited data on holdup and even signal characteristics. Existing literature has provided preliminary insights, and simplified models have been proposed to estimate holdup in pseudo-slug flow [19–21]. Experimental studies [22] have further refined closure correlations, enhancing our understanding of this new kind of flow pattern.

Recent studies document regime transitions and holdup in air-water flow and relatively large pipe (0.1016 m i.d.), where empirical slug/pseudo-slug and slug/churn transition criteria are proposed based on modified Froude numbers and inclination [23]. Measurements with wire-mesh sensor (WMS) in the same transitions over 2° to 90° of inclination are presented [24]. In horizontal flow, plug and slug flow transition boundary has been obtained from liquid-holdup models suited for slug flow, with prediction sensitivity to pipe diameter and liquid viscosity [25]. Under wet-gas conditions, studies using natural gas-condensate (CFD benchmarked to experiments) in 6 to 10 inch lines reported a marked dependence of holdup and liquid entrainment on inclination [26].

This study establishes an objective approach to differ pseudo-slug from slug flow in dense-gas/liquid flow in horizontal and slightly upward-inclined pipes, and quantifies the influence of inclination on specific flow patterns, including pseudo-slug and dual-continuous flow pattern. Experiments were conducted in a pressurized closed-loop facility using sulfur hexafluoride (SF₆) and mineral oil at low liquid-gas density ratio ($\rho_l/\rho_g < 10$). The low-density ratio assures that the experiments are closer to the real application, i.e., in the Brazilian pre-salt subsea lines, a density ratio lower than 10 is observed. Therefore, it is a dimensionless number necessary to achieve a better hydrodynamic similitude with real practice. The limitations are that thermodynamic similitude is not achieved, and heat transfer is not considered. Nevertheless, we believe that obtaining viscosity ratios closer to those real ones is a significant step forward. Phase fraction is measured by gamma-ray densitometry, over controlled ranges of pipe inclination and superficial velocities, and analyzed via statistical, numerical, and visual methods based on phase-fraction distribution profiles. This operating window, and working fluids, provide a meaningful contribution given the scarcity of studies that examine those gas-liquid flow patterns under high pressure.

Table 1 Experimental apparatus capabilities

Parameter	Measurement	Units
Internal diameter	0.0526	m
Inclination	−90 to 90	deg
Length-to-diameter ratio (L/d)	186–500	–
Max. Oil flow rate	40	m ³ /h
Max. SF ₆ mass flow rate	3062	kg/h
Max. absolute pressure	1.5	MPa

2 Methods

The experimental data were collected using the inclinable test platform of the Industrial Multiphase Flow Laboratory (LEMI). This large-scale facility is designed to operate with SF₆ and mineral oil (Turbina X-22) in a closed-loop configuration and is fully equipped with instrumentation and safety systems to replicate a wide range of two-phase flow patterns under various hydrodynamic conditions. The setup accommodates test section, and it is specifically engineered to handle dense-gas/liquid flows across various pressure and temperature ranges. An overview of the system's capabilities is provided in Table 1, where L denotes the distance measured from the mixer outlet to the visualization window.

Experiments were conducted at ambient temperature under controlled pressurization, ensuring a liquid to gas density ratio below 10. Gas and liquid temperatures and pressures were separately measured, and flow rates were measured and controlled, upstream of the mixing section, ensuring precise control of the inlet conditions. The two-phase flow pressure and temperature were also measured at the test section for the correction of the gas flow rate.

In this study, tests were conducted at three inclination angles: 0° (horizontal), 5° (upward), and 10° (upward). On the inclinable steel platform there is a 30-meter pipeline, divided into two 15-meter straight sections. It allows continuous inclination from −90° to 90°, enabling the study of two-phase flow under any upward and downward angles.

In Fig. 1, gas injection was controlled by a pressurized booster system and measured using a Coriolis flowmeter, enabling precise regulation of superficial velocities between 0.05 m/s and 4.2 m/s. Liquid flow was delivered by a positive displacement helical pump and monitored with three volumetric flow meters, covering a range of superficial velocities from 0.008 to 5.5 m/s. During the experiments, oil volumetric flow rates ranged from 1.67×10^{-5} to 1.11×10^{-2} m³/s and gas mass flow rates varied between 1.17×10^{-2} to 0.851 kg/s. The tests were conducted at temperatures from 17 °C to 31 °C and absolute pressures ranged from 1.35 to 1.45 MPa. Flow visualization was performed using a high-speed camera positioned in front of a 350 mm acrylic visualization section, enabling detailed dynamic recording of flow patterns. Holdup measurements were performed using a 45-degree-oriented gamma-ray densitometer. To obtain the phase-fraction distribution profiles with the gamma-ray densitometer, a specially designed vertical displacement system and a collimator were employed.

For the holdup measurements, the equipment consisted of a cesium-137 (Cs-137) gamma radiation source with a maximum particle energy of 660 keV, and a sodium iodide detector doped with thallium (NaI (Tl)). The Lambert-Beer attenuation law was applied [23], and from that it is possible

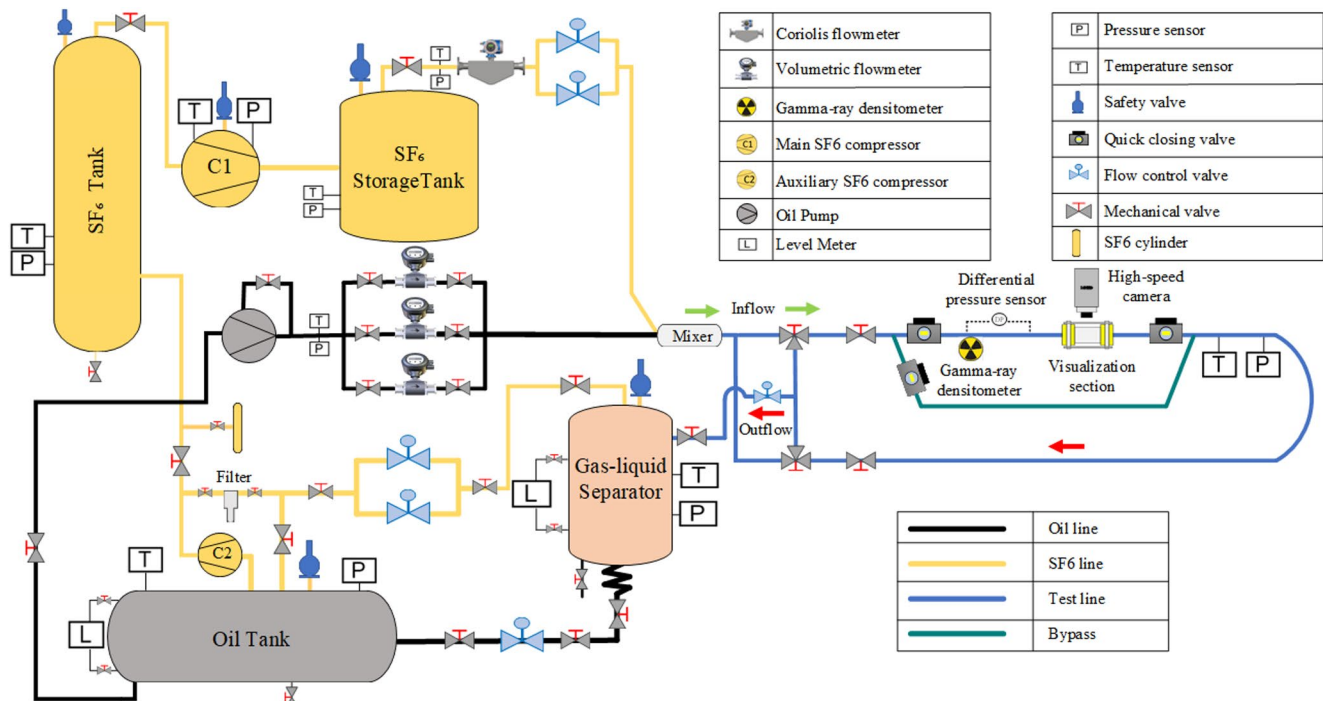


Fig. 1 Experimental high-pressure two-phase flow loop and instrumentation layout at the Industrial Multiphase Flow Laboratory

to derive an expression to determine the void fraction (α), Eq. (1).

$$\alpha = \frac{\ln\left(\frac{I}{I_l}\right)}{\ln\left(\frac{I_g}{I_l}\right)} \quad (1)$$

were the variable I represents the mixture measured intensity, I_g corresponds to the intensity measured when the pipe was filled only with dense gas, and I_l refers to the intensity measured when the pipe was filled with oil. The liquid holdup is given by Eq. (2).

$$H_l = 1 - \alpha \quad (2)$$

The validation of the gamma ray measurements is made using the quick close valves (QCVs) installed in the test line. Those are used to encapsulate the substances under the desired experimental conditions in a pipe section of 8 m. Once gravitational segregation is complete, the liquid holdup is computed from geometric relations using the model described in [1]. This holdup measurement is compared with the readings obtained from the gamma-ray densitometer.

2.1 Collimated gamma-ray densitometer vertical displacement system

To obtain the phase-fraction distribution profiles, a collimator was developed and installed in front of the detector, which has a 5.0×10^{-4} m slit, with a width of 6.7×10^{-2} m. A displacement system designed to facilitate vertical movement so that chordal measurements could be made along the pipe's cross-section (Y-axis). This displacement system was used to obtain the phase fraction distribution profiles for different flow patterns observed horizontally.

Phase fraction measurements are spatially and temporally averaged at discrete points denoted by subscript i (Fig. 2). At each discrete point, i , the phase fraction is measured over a certain area, A , for a certain period, T , as described by

Eq. (3), resulting in the local phase fraction, $\overline{H_{li}}$.

$$H_l = \overline{H_{li}} = \frac{1}{T} \frac{1}{A} \iint H_{li} dAdT \quad (3)$$

A geometrical expression is proposed to estimate the liquid holdup, H_l , from the phase fraction distribution profiles. The phase fraction distribution profile is approximated by polynomial regression of the local phase fraction data, i.e., $\overline{H_{li}} \cong H_{l,h}$, according to Eq. (4).

$$H_l \cong H_{l,h} = \frac{1}{A_T} \int H_l(h) x dh \quad (4)$$

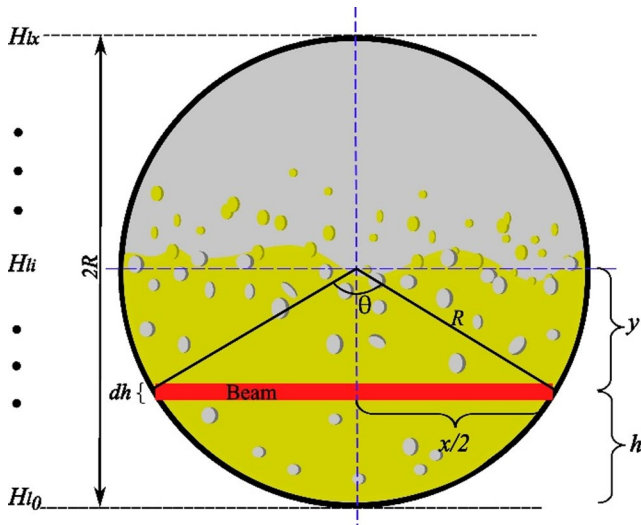


Fig. 2 Graphical representation of the cross section for geometric determination of volumetric fraction

where x and dh represent the length and height of the local gamma-ray beam that crosses the pipe's section at a position h . A_T is the pipe's cross-sectional area, and $xdh = dA$. The geometrical expression for H_l is given in Eq. (5), which allows the in-situ holdup to be calculated from the integral solution of the phase fraction distribution curves (as shown in Fig. 9a and b). When the variable x is expressed in terms of h (liquid height) and the pipe radius (R), $H_l(h)$ represents the function that describes the phase distribution curve. The geometric configuration used for its derivation is shown in Fig. 5.

$$H_l \cong \frac{2}{\pi R} \int_0^{2R} H_l(h) \sin \left[\cos^{-1} \left(\frac{R-h}{R} \right) \right] dh \quad (5)$$

Since a single polynomial was not sufficient to describe the phase fraction distribution curve, it was necessary to segment the curves into regions where suitable polynomial fits could be obtained, with determination coefficient (R^2) close to 1. Based on this approach, Appendix A presents the adjusted polynomial regressions for each flow pattern, which enable the determination of the in-situ liquid holdup (H_l).

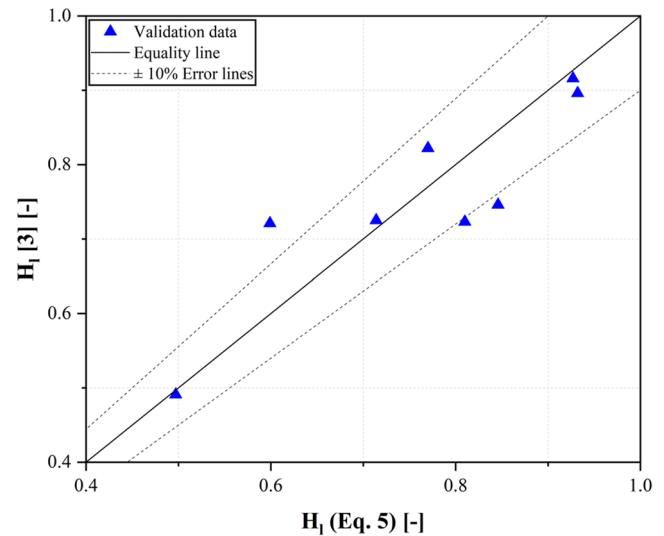


Fig. 3 Comparison between holdup obtained via Eq. 5 and reported by [3]

The geometric expression presented in Eq. (5) was validated using experimental data reported by [3], obtained for horizontal dense-gas/liquid flow under superficial velocity conditions similar to those tested in the present study. In [3], the gamma-ray densitometer was installed at 45° relative to the pipeline for the measurement of in-situ holdup data. Table 2 presents the superficial velocity and holdup (H_l) values obtained in this work and those reported by [3]. A difference in holdup values was already expected, because of slight variations in superficial velocities between the two datasets.

Comparing the H_l values using the chordal measurements and calculated through the integration of the phase distribution curve (Eq. (5)) with the H_l values measured by [3], a point spreading of about $\pm 10\%$ was observed, as presented in Fig. 3. The quantitative agreement and trend are satisfactory, and, therefore, the methodology of geometrical obtaining of H_l is considered validated.

2.2 Drift flux model

Drift-flux Models have been widely employed to predict holdup and describe gas-liquid two-phase flows, with particular focus on the slug and pseudo-slug flow patterns observed during the experiments. The drift velocity and

Table 2 Experimental data obtained in the present study and data reported by [3]

Experimental results of this study				Experimental results obtained by [3]			
U_{sg} [m/s]	U_{so} [m/s]	H_l [-]	Flow pattern	U_{sg} [m/s]	U_{so} [m/s]	H_l [-]	Flow pattern
0.456	0.100	0.599	SW	0.301	0.106	0.721	SW
0.947	0.100	0.497	SW	0.859	0.137	0.491	SW
0.124	0.496	0.927	SL	0.201	0.508	0.916	SL
0.940	1.970	0.770	DC	0.908	2.076	0.822	DC
0.440	0.490	0.810	SW/MI	0.546	0.393	0.723	SW

distribution parameter applied to the slug and pseudo-slug flow patterns are summarized in Table 3.

The general concept of the drift-flux model was first proposed by [27] to calculate holdup, as shown in Eq. (6), where U_{sg} denotes the superficial gas velocity (Eq. (7)), U_m is the mixture velocity (Eq. (8)), d the pipe diameter, and A is the cross-sectional area.

$$H_l = 1 - \frac{U_{sg}}{C_o U_m + U_{gm}} \quad (6)$$

$$U_{sg} = \frac{\dot{m}_g}{\rho_g A} \quad (7)$$

$$U_m = U_{sg} + U_{sl} \quad (8)$$

The two-phase Fanning friction factor (f_{tp}) is computed from Eqs. (9–10) [28] as a function of (Re_{tp}), the relative roughness (ϵ/D_h), and the hydraulic diameter (D_h). For turbulent flow ($Re_{tp} > 1000$), Eq. (9) is a Colebrook-type implicit relation accounting for wall roughness (ϵ) and viscous effects; f_{tp} is computed iteratively. For laminar flow ($Re_{tp} < 1000$), Eq. (10) yields the analytical result $f_{tp} = 16/Re_{tp}$.

$$\frac{1}{f_{tp}} = -4.9 \log_{10} \left(\frac{\epsilon/D_h}{3.7} + \frac{1.256}{Re_{tp} \sqrt{f_{tp}}} \right) \quad (9)$$

for Turbulent regime : $Re_{tp} \geq 1000$

$$f_{tp} = \frac{16}{Re_{tp}} \quad \text{for Laminar regime : } Re_{tp} < 1000 \quad (10)$$

The mixture Reynolds number and the gas injection fraction are presented respectively in Eqs. (11, 12).

$$Re_{tp} = \frac{\rho_l U_m D_h}{\mu_l} \quad (11)$$

$$\beta = \frac{U_{sg}}{U_{sg} + U_{sl}} \quad (12)$$

where μ_l is the dynamic viscosity of the liquid.

The flow map given by [3] served as the starting point to generate the test matrix for each inclination, providing a preliminary prediction of what could be experimentally obtained. A total of 8 flow patterns were identified by [1]. For our case study, the flow pattern maps were drawn considering the specific experimental conditions of our laboratory, considering the properties of our fluids under defined pressure and temperature. A HAAKE MARS 3 rheometer was employed to obtain the oil viscosity curve as a function of temperature. Considering the inclination of the platform,

three flow maps were generated, corresponding to inclinations 0° , 5° , and 10° . The properties of the working fluids are presented in Table 4.

2.3 Error metrics

Five error metrics were used to assess the performance of the proposed models in comparison to the measured data ($\epsilon_1, \epsilon_2, \epsilon_3, \epsilon_4, \epsilon_5$). Specifically, the Mean Relative Error (MRE) (ϵ_1), Mean Absolute Relative Error (MARE) (ϵ_2), Root Mean Square Relative Error (RMSRE) (ϵ_3), Mean Error (ME) (ϵ_4) and Mean Absolute Error (MAE) (ϵ_5). The equations for calculating these error metrics are defined in Eqs. (13–17).

$$\epsilon_1 = \frac{1}{N} \sum_{i=1}^N \frac{q_{calculated,i} - q_{measured,i}}{q_{measured,i}} \times 100\% \quad (13)$$

$$\epsilon_2 = \frac{1}{N} \left| \sum_{i=1}^N \frac{q_{calculated,i} - q_{measured,i}}{q_{measured,i}} \right| \times 100\% \quad (14)$$

$$\epsilon_3 = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\frac{q_{calculated,i} - q_{measured,i}}{q_{measured,i}} \right)^2} \quad (15)$$

$$\epsilon_4 = \frac{1}{N} \sum_{i=1}^N (q_{calculated,i} - q_{measured,i}) \quad (16)$$

$$\epsilon_5 = \frac{1}{N} \sum_{i=1}^N |q_{calculated,i} - q_{measured,i}| \quad (17)$$

3 Results and discussion

During the horizontal flow tests, 18 points were collected. Six flow patterns were observed in this inclination: 7 points of stratified smooth (ST), 3 points of stratified wavy (SW), 3 points of slug (SL), 3 points of stratified wavy with mixing at the interface (SW/MI), 1 point of dispersed (D), and 1 point of dual-continuous (DC), as shown in Fig. 4.

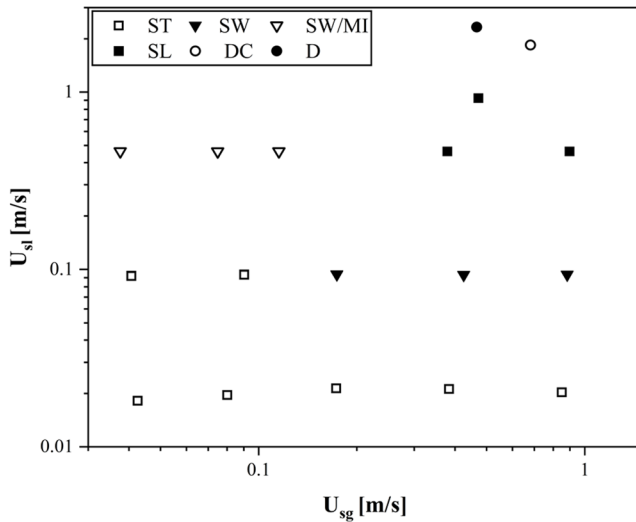
In Fig. 5, representative points are shown that delineate the regions where the identified flow patterns occur at 5° (Fig. 5a) and 10° (Fig. 5b). Those flow pattern maps exhibited similar behavior in comparison with that for horizontal flow, but with some particular characteristics. It is important to note that at these upward inclinations, the region where the stratified smooth flow pattern commonly develops disappears, thus expanding the region of occurrence of slug and pseudo-slug flow patterns. At 5° , 46 experimental data

Table 3 Expressions for the Drift Flux Model applied to slug and pseudo-slug flow patterns

Correlation	Drift velocity	Distribution parameter
[16]	$U_{gm} = 0.0246 \cos \theta$ $+ 1.606 \left(g \sigma \frac{\Delta \rho}{\rho_l^2} \right)^{0.25} \sin \theta$	$C_0 = \frac{2}{1 + \left(\frac{Re_{tp}}{1000} \right)^2}$ $+ \frac{1 - 0.2 \sqrt{\frac{\rho_g}{\rho_l}} (1 - e^{-18\alpha})}{1 + \left(\frac{1000}{Re_{tp}} \right)^2}$ $C_o = \frac{2 - \left(\frac{\rho_g}{\rho_l} \right)^2}{1 + \left(\frac{Re_{tp}}{1000} \right)^2}$ $+ \frac{\left[\left(\sqrt{1 + \left(\frac{\rho_g}{\rho_l} \right)^2} \cos \theta / (1 + \cos \theta) \right)^{(1-\alpha)} \right]^{0.4}}{1 + \left(\frac{1000}{Re_{tp}} \right)^2} + C_{o,1}$ $C_{o,1} = \left(C_1 - C_1 \times \sqrt{\frac{\rho_g}{\rho_l}} \right) \times \left[(2.6 - \beta)^{0.15} - \sqrt{f_{tp}} \right] \times (1 - x)^{1.5}$
[17]	$U_{gm} = (0.35 \sin \theta + 0.45 \cos \theta)$ $\sqrt{\frac{g D_h (\rho_l - \rho_g)}{\rho_l}} (1 - \alpha)^{0.5} C_2 C_3 C_4$ $C_2 = \begin{cases} \left(\frac{0.434}{\log(\mu_l/0.001)} \right)^{0.15} & ; \left(\frac{\mu_l}{0.001} \right) > 10 \\ 1 & ; \left(\frac{\mu_l}{0.001} \right) \leq 10 \end{cases}$ $C_3 = \begin{cases} (la/0.025)^{0.9} & la < 0.025 \\ 1 & la \geq 0.025 \end{cases}$ $C_4 = \begin{cases} -1 & ; \text{for } (0^\circ > \theta \geq -50^\circ \text{ and } Fr_{sg} \leq 0.1) \\ 1 & ; \text{if both } (-1) \text{ conditions are not satisfied} \end{cases}$	$C_o = \frac{2 - \left(\frac{\rho_g}{\rho_l} \right)^2}{1 + \left(\frac{Re_{tp}}{1000} \right)^2}$ $+ \frac{\left[\left(\sqrt{1 + \left(\frac{\rho_g}{\rho_l} \right)^2} \cos \theta / (1 + \cos \theta) \right)^{H_l} \right]^{-1.9}}{1 + \left(\frac{1000}{Re_{tp}} \right)^2} + C_{o,1}$ $C_{o,1} = \left(C_1 - C_1 \times \sqrt{\frac{\rho_g}{\rho_l}} \right) \times \left[(1.0 - \beta)^{0.15} - \sqrt{f_{tp}} \right] \times (1 - x)^{1.15}$
[18]	$U_{gm} = (0.35 \sin \theta + 0.54 \cos \theta)$ $\sqrt{\frac{g d (\rho_l - \rho_g)}{\rho_l}} C_2 C_3$ $C_2 = \begin{cases} \left(\frac{0.434}{\log(1000\mu_l)} \right)^{0.15} & ; 1000\mu_l > 10 \\ 1 & ; 1000\mu_l \leq 10 \end{cases}$ $C_3 = \begin{cases} \left(\frac{1}{0.035} \left(\sqrt{\frac{\sigma}{g(\rho_l - \rho_g)d^2}} \right) \right) & ; \text{for } \sqrt{\frac{\sigma}{g(\rho_l - \rho_g)d^2}} < 0.035 \\ 1 & ; \text{for } \sqrt{\frac{\sigma}{g(\rho_l - \rho_g)d^2}} \geq 0.035 \end{cases}$	$C_o = \frac{2 - \left(\frac{\rho_g}{\rho_l} \right)^2}{1 + \left(\frac{Re_{tp}}{1000} \right)^2}$ $+ \frac{\left[\left(\sqrt{1 + \left(\frac{\rho_g}{\rho_l} \right)^2} \cos \theta / (1 + \cos \theta) \right)^{H_l} \right]^{-1.9}}{1 + \left(\frac{1000}{Re_{tp}} \right)^2} + C_{o,1}$ $C_{o,1} = \left(C_1 - C_1 \times \sqrt{\frac{\rho_g}{\rho_l}} \right) \times \left[(1.0 - \beta)^{0.15} - \sqrt{f_{tp}} \right] \times (1 - x)^{1.15}$
Complementary equations	$la = \sqrt{\sigma / (g \Delta \rho)} / D_h \quad Fr_{sg} = \sqrt{\frac{\rho_g}{\rho_l - \rho_g}} \times \frac{U_{sg}}{g D_h \cos \theta} \quad x = \frac{\hat{m}_g}{\hat{m}_g + \hat{m}_l}$ $C_1 = 0.2 \text{ for circular and annular pipe geometries}$ $C_1 = 0.4 \text{ for rectangular pipe geometries}$	

Table 4 Physical properties of the fluids at 1.5 MPa (absolute) and 25 °C

Phase	Fluid	Density [kg/m ³]	Viscosity [Pa.s]
Oil	Turbine X 22	~867.1	~0.04
Dense-gas	Sulfur hexafluoride -SF ₆	~100.2	~1.70 × 10 ⁻⁵

**Fig. 4** Experimental flow pattern map at 0°

points were obtained, corresponding to slug (SL), pseudo-slug (PSL), dispersed (D), and dual-continuous (DC) flow patterns. For the inclination of 10°, 51 experimental data points were collected, showing the same flow patterns.

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 at 5° and 10° inclinations. This flow pattern had not been observed previously in upward gas-liquid flow, considering that it is commonly observed in liquid-liquid flow [1]. Visual details on how the inclination of the pipeline impacts flow patterns in dense-gas/liquid flow can be observed on Fig. 6.

While stratified smooth, stratified wavy, and stratified wavy with mixing at the interface flow patterns predominate under horizontal conditions (Fig. 6a–c, respectively). Inclinations of 5° and 10° favor the occurrence of the slug flow pattern (Fig. 6d) or dispersed (Fig. 6e). The unexpected appearance of the dual-continuous flow pattern under different experimental conditions, even in inclined pipes, highlights the complex behavior of dense-gas/liquid flow and points out to the presence of additional transition frontiers not usually seen in typical gas-liquid flow (Fig. 6f).

Relative uncertainties for the superficial velocities remain bounded and consistent across the three inclinations. For the gas phase, uncertainty is tightly clustered near ≈ 1.1% at all angles, with ranges of 1.10–1.33% (0°), 1.09–1.33% (5°), and 1.10–1.33% (10°). For the oil phase, uncertainty shows a broader but controlled dispersion, 1.11–5.55% (0°), 1.10–12.94.10.94% (5°), and 1.36–9.15% (10°), indicating stable metrological performance across configurations and no impact on the adopted flow-pattern classification.

3.1 Pseudo-slug flow pattern at 5° and 10°

As documented in the literature, pseudo-slug (PSL) in upward near-horizontal and inclined pipes is a transitional regime between stratified and slug flow. It can be viewed as

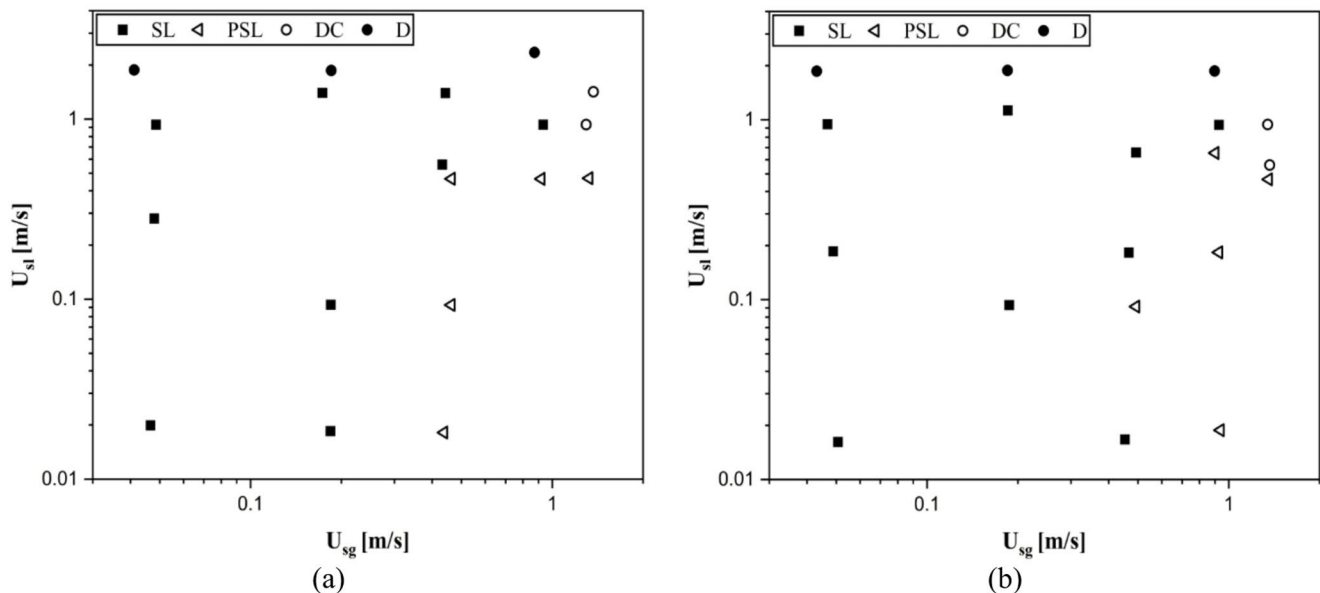
**Fig. 5** Experimental flow pattern map at: **a** 5°, and **b** 10°

Fig. 6 Flow patterns identified experimentally **a** ST, **b** SW, **c** SW/MI, **d** SL, **e** D, and **f** DC

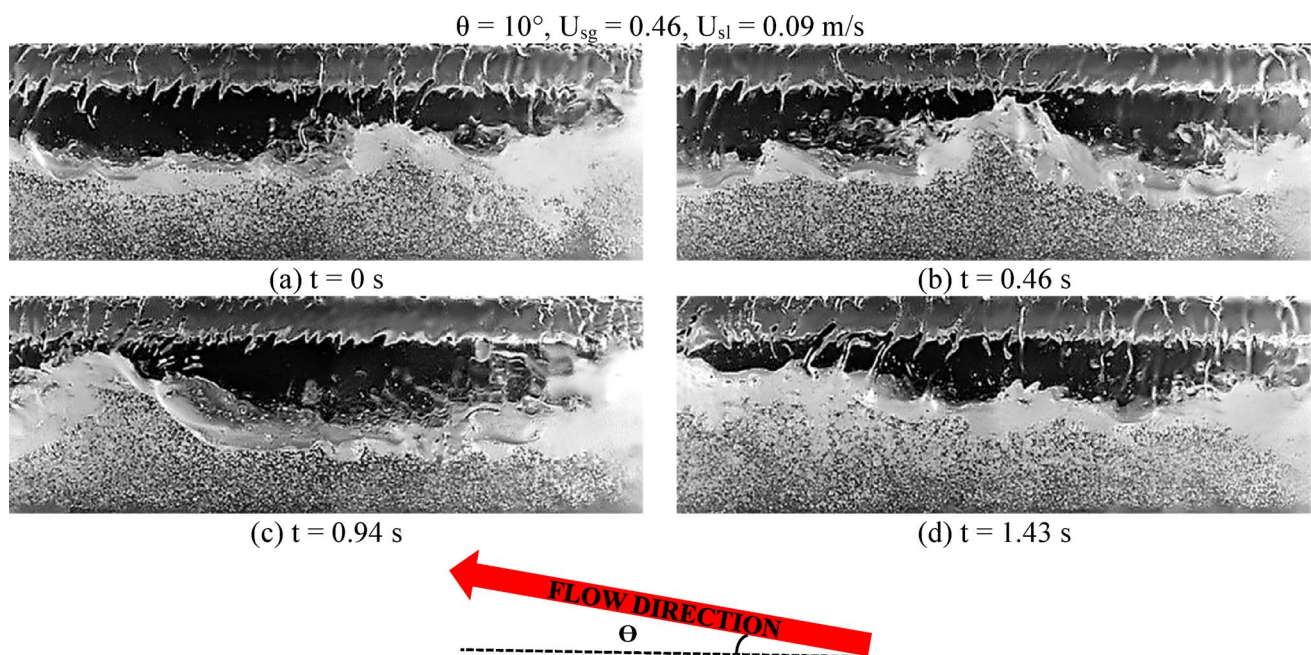
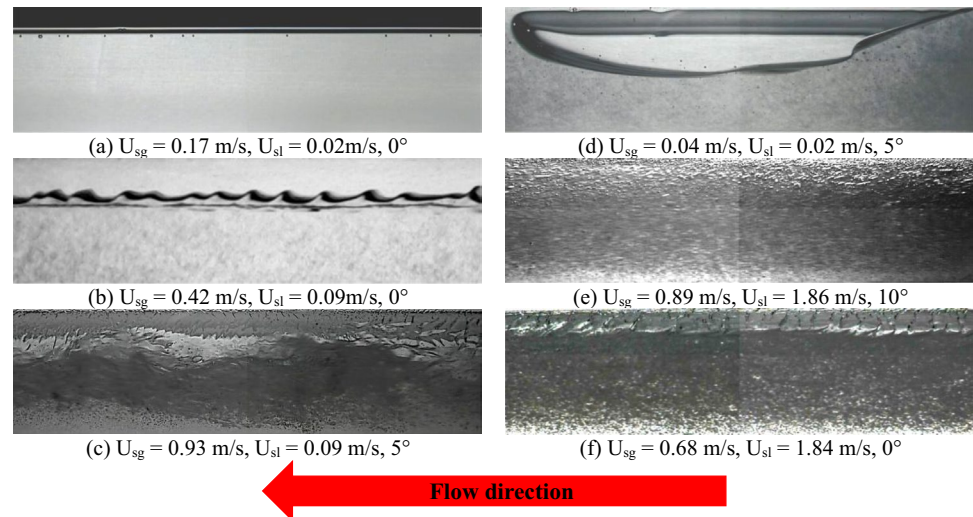


Fig. 7 Stage-I (splash) development in dense-gas/liquid pseudo-slug flow. **a** Generation of interfacial wave driven by liquid back-flow, **b** splash formation as the crest overturns, **c** strong droplet detachment

from the interface and convection downstream, **d** droplet coalescence while the gas region remains continuous. A high level of gas dispersion within the liquid is also evident in all panels

a segregated system with large interfacial waves, continuous gas passage, and localized liquid-film reversal along the lower pipe wall, which makes the conventional slug unit-cell model inapplicable. The ensuing wave-shear interaction produces a distinctive momentum exchange between the gas and liquid phases. In the present study, PSL formation is interpreted as a two-stage process. Stage I (splash) denotes the onset of interfacial-wave growth promoted by intermittent liquid back flow at the pipe's bottom, which locally thickens the film and steepens the interfacial slope. As the crest develops, large liquid droplets detach from the wave crest into the gas core and are convected downstream by the

gas. The splash phenomenon is associated with increased relative phase velocity, leading to interface disturbances and growth in wave amplitude; detached droplets exhibit varied sizes and trajectories, occasionally reaching the pipe's top. Under the present dense-gas/liquid conditions, splash becomes apparent at 5° and 10°, and is frequently observed at gas superficial velocity of 0.5 m/s. Figure 7 shows this Stage-I sequence, wave development, crest overturning, droplet detachment, and subsequent coalescence.

Stage II (abrupt wave amplification/pseudo-slug expression) arises as the instability strengthened by the ongoing liquid back flow evolves, and the interfacial-wave amplitude

increases sharply, such that the liquid front approaches the pipe's top, while the gas core remains continuous. This high-amplitude wavy flow with back flow, often accompanied by sporadic splash, is the visible signature of pseudo-slug, and distinguishes it from fully developed slug flow, which would exhibit core blockage, or stratified wavy flow. Figure 8 presents a representative time series under dense-gas/liquid conditions showing wave amplification and strong gas dispersion within the liquid phase, while a continuous gas flow is preserved despite pronounced interfacial wave amplitude amplification.

A phenomenological distinction can be established between pseudo-slug (PSL) and stratified wavy (SW) flow. While both may arise in horizontal pipes, PSL also occurs under upward inclination, consistent with its onset mechanism and it exhibits a large variation in the liquid film thickness, high-amplitude/low-frequency interfacial waves, and a thin layer of oil flows around the upper part of the pipe wall. The PDF of the void-fraction signal resembles that of an intermittent flow. By contrast, SW flow shows small variations of liquid-film thickness, small-amplitude/high-frequency waves that are more regularly spaced. Entrainment of liquid droplets may occur in both patterns, but it tends to be more intense in PSL flow.

3.2 Holdup analysis

3.2.1 Horizontal position: 0°

Figure 9 shows the phase fraction distribution profiles of all flow patterns observed in horizontal flow. Those curves can be divided into three regions: the upper region, where the

liquid holdup tends to zero and corresponds to a predominance of the less dense phase (gas); the lower region, where the liquid holdup tends to 1, and corresponds to a predominance of the denser phase (oil), and the intermediate region, which reflects the transition zone between the two phases, which can contain interfacial waves with or without dispersion of one phase into the other.

The curve for the SL shows that most of the pipe's cross section contains liquid, with approximately 0.55 of liquid fraction at the top ($h/D=1$). This is due to the intermittent nature of this flow pattern and the average predominance of the liquid phase, in which liquid slugs alternate with relatively short gas bubbles positioned at the top side of the pipe. The dual-continuous (DC) flow pattern is characterized by strong dispersion of gas bubbles in the liquid phase and liquid droplets in the gas phase, but there is still the presence of a noticeable interface separating the two parallel dispersed flows. By comparing the phase fraction distribution profiles of stratified flow (ST, SW, and SW/MI) with that of dispersed flow (D), it can be concluded that the profile corresponding to dual-continuous flow (DC) exhibits an intermediate behavior between these two flow patterns. The stratified flow has a profile that changes trend twice, at the transition from the upper region to the intermediate, and at the transition from the latter to the lower region; and the liquid fraction goes from 0 to 1. Dispersed flow has one trend only, asymptotically going from a certain value of liquid fraction ($H_l = 0.32$) to 1. At the top side dispersed flow exhibits a high concentration of gas bubbles dispersed in the liquid phase. Dual-continuous flow has one characteristic of each of those, i.e., it has one asymptotic trend only, like dispersed flow, but the liquid fraction goes from 0 to 1, like

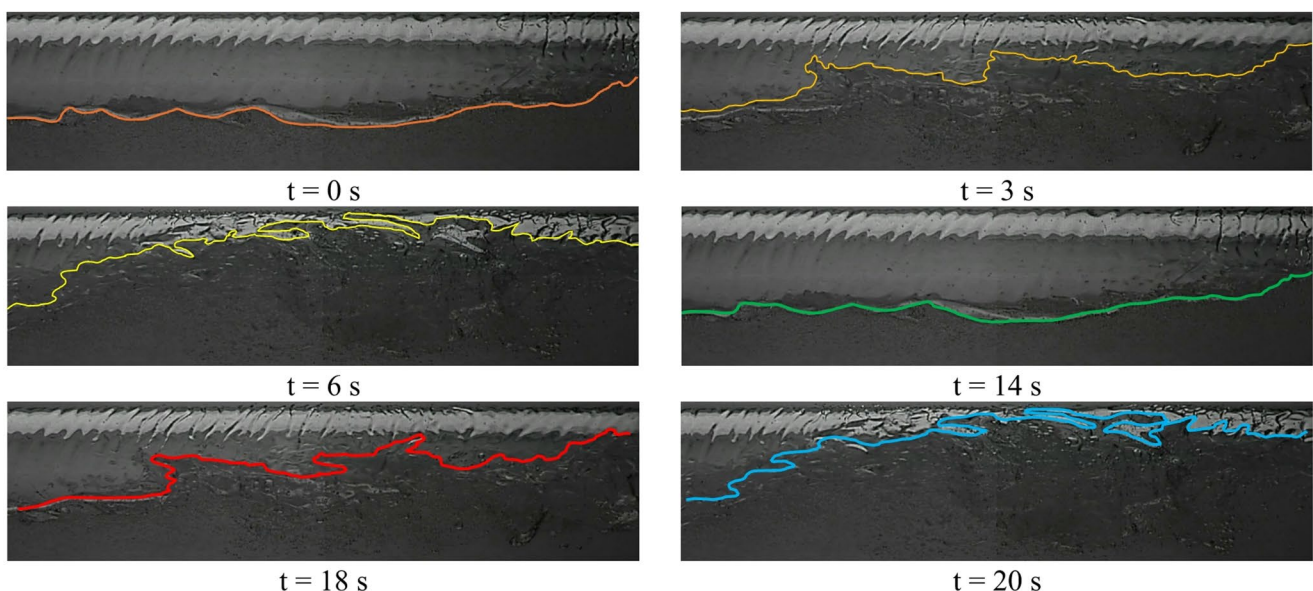


Fig. 8 Time series of images illustrating the behavior of the dense-gas/liquid pseudo-slug flow pattern

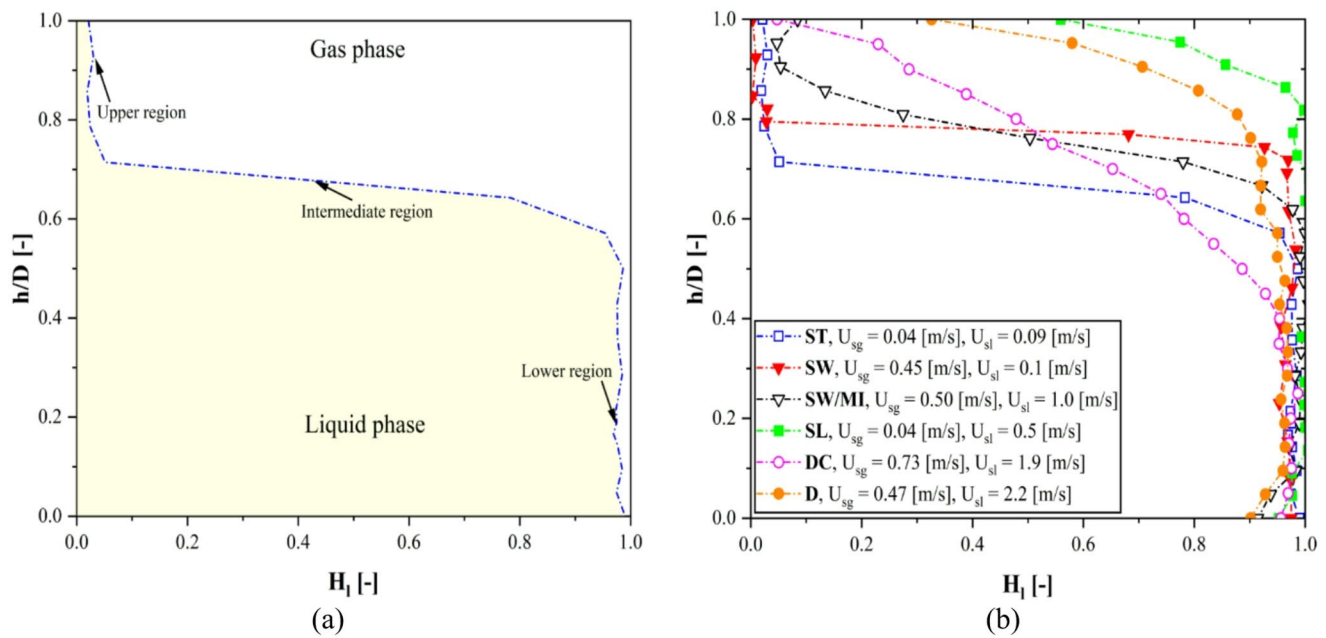


Fig. 9 Phase fraction distribution profiles representative of **a** ST ($U_{sg} = 0.04$ m/s, $U_{sl} = 0.09$ m/s), and **b** ST, SW/MI, SL, DC, and D flow patterns in horizontal flow

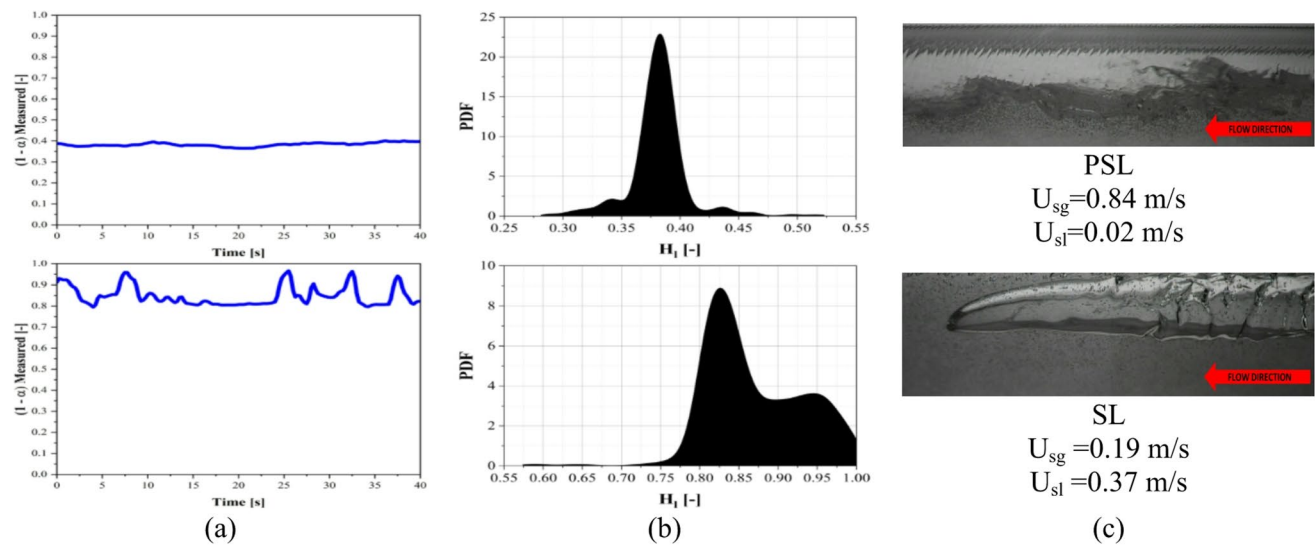


Fig. 10 **a** Gamma-ray densitometer time trace, **b** Probability density function of the liquid holdup, and **c** Representative image of PSL and SL flow patterns at 5° pipe inclination

stratified flow. At 0° , Holdup relative uncertainty is essentially constant around 6%.

3.2.2 Inclined positions: 5° and 10°

3.2.2.1 Qualitative analysis of holdup signals for flow pattern classification The collected data was analyzed statistically and visually to identify critical flow characteristics. A particular focus was on differentiating pseudo-slug from slug flow. The gamma-ray densitometer time trace can be

seen in Fig. 10a, the probability density function (PDF) of liquid holdup in Fig. 10b, and a representative image of the PSL and slug flow pattern at a 5° inclination in Fig. 10c. In the first line of Fig. 10 data one can see data on pseudo-slug flow, and in the second line, data on slug flow. The time trace with multiple prominent peaks is associated with slug flow pattern (Fig. 10a, second line). This behavior reflects the inherent intermittency of slug flow, characterized by alternating regions of liquid slugs and gas pockets. These distinct liquid holdup distributions generate more than one

main peak in the PDF curve, corresponding to holdup values that can be associated with the liquid slug (higher value) and gas bubble (lower value).

The time trace of pseudo-slug flow (PSL) exhibits a curve with much less variation in time (Fig. 10a, first line). The PDF curve exhibits a single pronounced peak (Fig. 10b, first line). The dominant peak reflects a relatively stable flow structure with a more consistent liquid holdup, whereas the smaller adjacent peaks indicate interface oscillations. These oscillations suggest fluctuations in the oil level caused by reverse flow and the passage of large-amplitude interfacial waves, phenomena that are characteristic of this flow pattern. In Fig. 11a, at a 5° inclination, eight data points were classified as PSL, indicating that this flow pattern predominates within the range of superficial gas and liquid velocities investigated. The transition to SL occurs at higher liquid superficial velocities. Therefore, the higher liquid volumetric fraction favors the gas blockage and the formation of the intermittent structures typical of slug flow pattern. At 10° inclination, Fig. 11b, eleven experimental points were classified as PSL, five of which overlapped with those identified at 5°, confirming the presence of this flow pattern under both conditions. The remaining data points at 10° correspond to SL, indicating a slight rightward shift of the PSL region in the flow map relative to 5°. This result suggests that SL becomes dominant at lower gas velocities and at higher upward inclinations. The transition to PSL at 10° generally occurred when the superficial gas velocity reached approximately 0.5 m/s. This indicates that the higher the inclination, the higher the liquid holdup, thus higher gas superficial velocities are required to avoid gas blockage and the formation of intermittent structures.

Furthermore, the holdup analysis based on PDFs reveals distinct statistical signatures for the two flow patterns. PSL displays a unimodal distribution (Fig. 11a), and SL exhibits a bimodal distribution (Fig. 11b), consistent with the alternation between gas bubbles and liquid slugs.

Holdup exhibits a clear inclination dependence in its relative uncertainty. For inclined configurations, relative uncertainty is at 20% and remains within a controlled band that is consistent across both angles. Thus, the uncertainty associated with holdup is higher under inclination yet bounded and compatible with the resolution required for the pattern recognition and holdup trends reported.

3.2.2.2 Quantitative analysis of holdup data prediction To evaluate the performance of the selected holdup prediction models, a graphical comparative analysis was conducted using the experimental holdup data obtained at pipe inclinations of 5° and 10°. The parameters considered to the numerical comparison were defined in Sect. 2.3.

The graphical comparison between the experimental liquid holdup values and those predicted by the models proposed by [16–18] for both 5° and 10° inclinations is presented in Fig. 12a and b, respectively. It can be observed that most of the data points are distributed around the line of equality, with a certain degree of dispersion that varies among the models and the evaluated conditions. Overall, the [18] model exhibited good performance in predicting high holdup values for $H_l \geq 0.8$ for both inclination angles. However, that model showed larger errors at lower holdup values, particularly at the 10° inclination. The [17] model demonstrated the most consistent distribution around the line of equality at both inclination angles. Its predictions

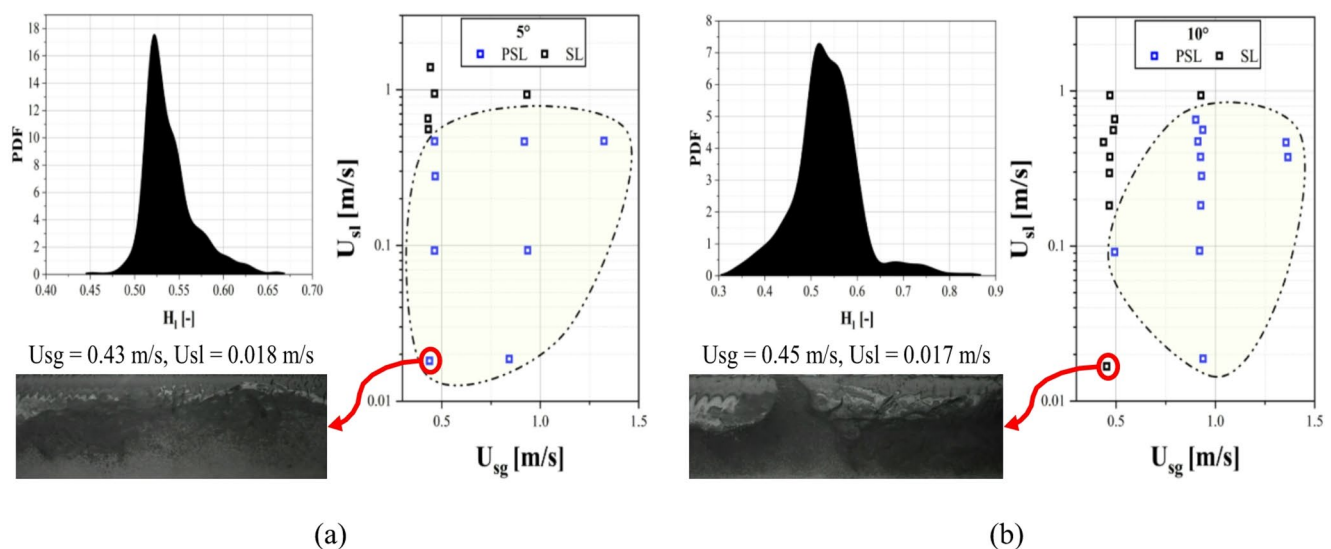


Fig. 11 Flow pattern analysis of slug (SL) and pseudo-slug (PSL) flow patterns in upward dense-gas/liquid flow through an inclined pipe: **a** 5°, and **b** 10°

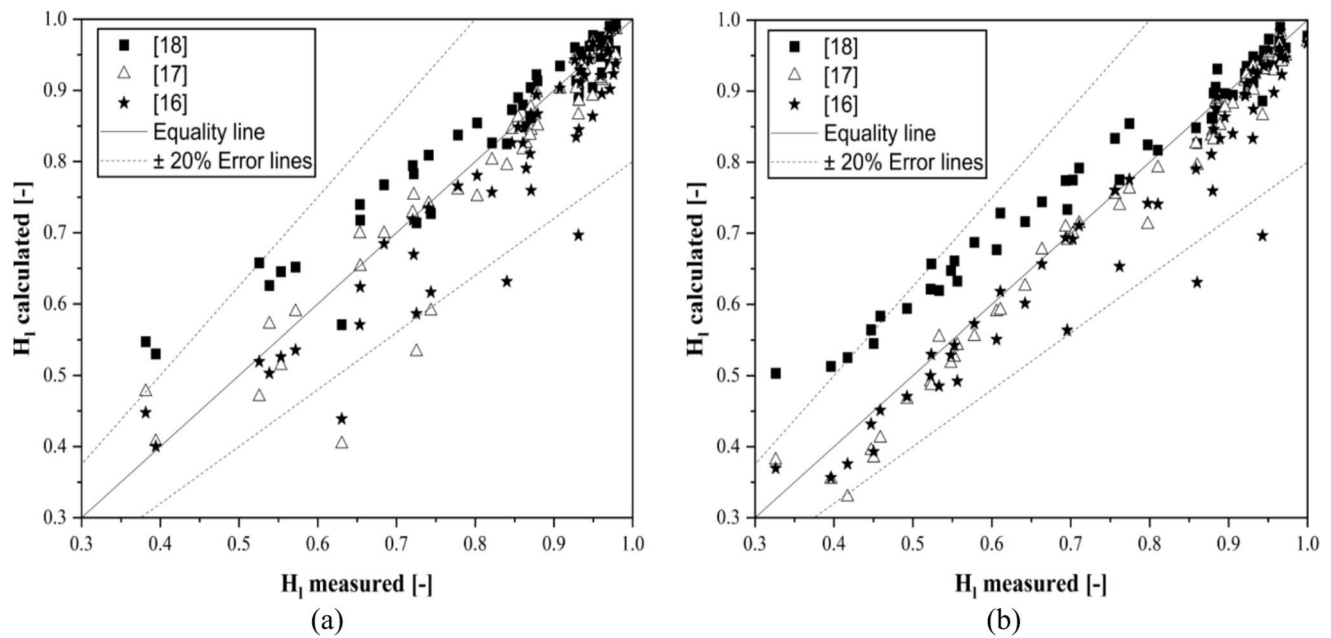


Fig. 12 Comparison between holdup experimental data and the models' predictions at: **a** 5°, and **b** 10°

Table 5 Statistical performance of the models used for liquid holdup prediction in comparison to experimental results at 5°, and 10°

Inclination angle [Degrees]	Models	ε_1 [%]	ε_2 [%]	ε_3 [%]	ε_4 [-]	ε_5 [-]
5°	[16]	-4.91	5.96	9.21	-0.04	0.05
	[17]	-2.43	4.83	8.55	-0.02	0.03
	[18]	4.37	6.24	10.45	0.02	0.04
10°	[16]	-4.85	5.56	8.15	-0.04	0.04
	[17]	-3.04	4.05	5.95	-0.02	0.03
	[18]	8.01	9.05	13.94	0.04	0.05

remained clustered around the equality line with relatively small deviations. The [16] model exhibited a more pronounced point spreading, and a tendency to underestimate the holdup values, particularly in the low holdup range.

In Table 5, one can see a quantitative error comparison between experimental liquid holdup values and those predicted by the three evaluated models for both 5° and 10° inclination angles. This quantitative comparison serves as a basis for identifying the most appropriate model for predicting holdup in slightly-inclined dense-gas/liquid flow.

The comparison between experimental data and three selected models [16–18] revealed significant differences in predictive accuracy depending on the pipe inclination. At 5°, Bhagwat's model [17] consistently outperformed the others, presenting the lowest MARE (4.83%) and RMSRE (8.55%), indicating a higher alignment with experimental observations. Additionally, this model showed minimal average deviation with $\varepsilon_4 = -0.02$ and $\varepsilon_5 = 0.03$, suggesting that its predictions not only exhibited lower bias but also smaller spread in individual errors. Choi's model [16],

while close in performance, exhibited a greater underestimation trend with a negative mean relative error of -4.91% and a slightly higher RMSRE (9.21%). Soedarmo's model [18], on the other hand, showed a tendency to overestimate the liquid holdup, reflected by a positive $\varepsilon_1 = 4.37\%$ and the highest RMSRE among the three models (10.45%).

At an inclination of 10°, the differences became more pronounced. Bhagwat's model [17] maintained its superior accuracy with the lowest MARE (4.05%) and RMSRE (5.95%), along with the smallest absolute and average deviations ($\varepsilon_4 = -0.02$, $\varepsilon_5 = 0.03$). Choi's model again underestimated the measurements, recording a slightly more negative $\varepsilon_1 = -4.85\%$ compared to 5°, while maintaining a competitive RMSRE of 8.15%. In contrast, Soedarmo's model [18] significantly deviated from the experimental values, showing the highest errors across all metrics: a strongly positive bias ($\varepsilon_1 = 8.01\%$), an MARE of 9.05%, and an RMSRE of 13.94%. These results indicate that Soedarmo's formulation [18] may not be suitable for the upward inclination cases evaluated, especially under the

presence of complex flow patterns such as pseudo-slug and dual-continuous flows.

Model proposed by [17] demonstrated the best overall performance at both 5° and 10° inclinations, exhibiting the lowest MARE and RMSRE values, along with minimal deviations across all evaluated metrics. In contrast, the model proposed by [18] consistently overpredicted the liquid holdup values, particularly at 10°, where the highest RMSRE (13.94%) and the largest error bias (8.01%) were recorded.

Additionally, it was observed that increasing the inclination from 5° to 10° negatively affected the predictive accuracy of the models, especially in the case of [18], where a substantial increase in error metrics was noted (MARE increased from 6.24 to 9.05 and RMSRE from 10.54 to 13.94).

The combined analysis of the graphical results and the quantitative error evaluation indicates that the [17] model is the most suitable for predicting liquid holdup under dense-gas/liquid flow conditions in slightly inclined pipelines. Nevertheless, in applications where high holdup values are predominant, the [18] model may represent a viable alternative.

4 Conclusions

Pipe inclination is a determining factor in dense-gas/liquid flows in horizontal and slightly upward-inclined pipes. During the experimental campaign (125 points), we observed that at 5° both slug (SL) and pseudo-slug flow (PSL) occur over a broad range of phase superficial velocities, while at 10° the PSL domain shifts toward higher gas superficial velocities and SL dominates otherwise; reverse flow in mild inclinations appears to facilitate PSL. Phase-fraction distribution profiles enabled objective pattern recognition, documenting stratified smooth (ST), stratified wavy (SW), stratified wavy with mixing at the interface (SW/MI), slug flow (SL), dual continuous (DC), and dispersed flow (D), and supported that in-situ holdup estimation is consistent with the geometric derivation and external data. These findings are consistent with recent reports on inclination-dependent transitions in related fluids and geometries and extend them to a dense-gas/liquid flow window (SF_6 -oil, $\rho_l/\rho_g < 10$), including the observation of dual-continuous flow at slight upward inclinations.

Regarding predictive tools, Bhagwat's correlation provided the most robust performance under the tested inclined conditions, whereas Soedarmo's formulation showed sensitivity to inclination, performing better at high holdup,

but with lower overall consistency, reinforcing the need to match model choice to the operating window. Experimental uncertainties remain bounded by superficial velocities, and are higher, but controlled for holdup under inclination, which does not alter flow pattern classification or holdup trends. The main limitations are that only one diameter was tested, three upward inclinations, a specific pair of fluids. The chordal spatial sampling via gamma-ray densitometry proved to be a good choice, and the holdup data was in good agreement in comparison with data obtained in a more traditional way. The results provide a transparent dataset and evidence-based guidance for flow pattern recognition and holdup assessment in dense-gas/liquid flows.

Appendix A

Accordingly, the curves shown in Fig. 9a, b corresponding to the SW and SW/MI flow patterns were divided into three segments (as described in Sect. 3.2 and Fig. 9a). For the slug (SL), dual-continuous (DC), and dispersed (D) flow patterns, the curves were well represented by a two-segment piecewise function. In this formulation, the upper segment corresponds to the gas-rich region, whereas the lower segment corresponds to the liquid-rich region.

Polynomial regression of $H_l(h)$ based on phase fraction distribution curves.

Flow pattern	Curve segment	Polynomial regression [-]
SW	(1) Upper region	$H_l(h) = 1.062y^2 - 2.023y + 0.966$
	(2) Lower region	$H_l(h) = -1.314y^3 + 1.514y^2 - 0.478y + 1.003$
	(3) Intermediate region	$H_l(h) = \frac{y-0.798}{-0.053}$
SL	(1) Upper region	$H_l(h) = -11.434y^2 + 18.341y - 6.356$
	(2) Lower region	$H_l(h) = -0.142y^2 + 0.128y - 0.981$
SW/MI	(1) Upper region	$H_l(h) = -1.126y^2 + 1.937y - 0.811$
	(2) Lower region	$H_l(h) = -2.002y^3 + 1.729y^2 - 0.376y + 1.006$
	(3) Intermediate region	$H_l(h) = \frac{y-0.862}{-0.207}$
DC	(1) Upper region	$H_l(h) = -1.487y^2 + 0.601y + 0.956$
	(2) Lower region	$H_l(h) = \frac{y-7.384}{-7.408}$

Flow pattern	Curve segment	Polynomial regression [-]
D	(1) Upper region	$H_l(h) = -4.993y^2 + 7.291y - 1.746$
	(2) Lower region	$H_l(h) = -0.176y^2 + 0.063y + 0.962$

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Data availability The data supporting this study's findings are available from the corresponding author upon reasonable request.

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