



Experimental investigation on air-water-high viscosity oil three-phase flow in 15° inclined downward pipe

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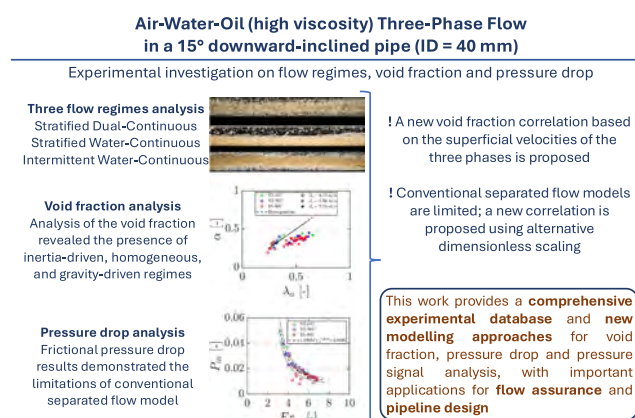
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HIGHLIGHTS

- Experimental investigation of air–water–high-viscosity oil three-phase flow in a 15° downward-inclined pipe.
- Three distinct flow regimes identified based on gas–liquid and liquid–liquid interfacial dynamics.
- New void fraction correlation proposed for inclined three-phase flow systems.
- A new dimensionless scaling approach proposed for frictional pressure drop prediction.
- New experimental database and predictive tools provided for flow assurance and well/pipeline design applications.

GRAPHICAL ABSTRACT



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ABSTRACT

This study presents an experimental investigation of air–water–high-viscosity oil three-phase flow in a 15° downward-inclined pipe with an internal diameter of 40 mm, addressing key gaps in three-phase flow, downward-inclined configurations, and high-viscosity oil systems. Flow visualization revealed three distinct regimes, namely: ST–DC (stratified dual-continuous), ST–WC (stratified water-continuous), and IN–WC (intermittent water-continuous), which are based on gas–liquid and liquid–liquid interfacial dynamics. Analysis of the void fraction revealed the presence of inertia-driven, homogeneous, and gravity-driven regimes, with the gas superficial velocity governing the onset of gravity effects. A new void fraction correlation based on the superficial velocities of the three phases is proposed. Frictional pressure drop results demonstrated the limitations of conventional separated flow model, motivating the development of a new correlation based on alternative dimensionless scaling. Furthermore, analysis of pressure signal fluctuations showed that classical dimensionless parameters developed for gas–liquid two-phase flow fail to predict characteristic frequency behavior. Overall, this work provides a comprehensive experimental database and discusses new approaches for modeling the main hydrodynamic parameters of three-phase flow in inclined pipelines, with important implications for flow assurance and well/piping design.

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Nomenclature		ρ	Density, [kgm^{-3}]
		Φ	Two-phase multiplier, [-]
		<i>Subscripts</i>	
C	Chisholm parameter, [-]	a	Air
C_o	Distribution coefficient, [-]	$cond$	Conduit
D	Pipe diameter, [m]	$cont$	Continuous
DFE	Degrees of Freedom for Error, [-]	d	Drift
dp/dz	pressure drop gradient, [Pam^{-1}]	dis	Dispersed
f	Friction factor, [-]	eff	Effective
f_c	Characteristic frequency, [-]	f	Frictional
Fr	Froude number, [-]	g	Gravitational
g	Gravitational acceleration, [ms^{-2}]	l	Liquid
J	Superficial velocity, [ms^{-1}]	m	Mixture
N_a	Dimensionless number, [-]	max	Maximum
OC	Oil cut, [-]	min	Minimum
p	Pressure, [Pa]	o	Oil
P_m	Dimensionless number based on the frictional pressure drop, [-]	ref	Reference
Q	Volumetric flow rate, [m^3s^{-1}]	t	Total
R^2	Coefficient of determination, [-]	w	Water
Re	Reynolds number, [-]	$2P$	Two-phase
$RMSE$	Root Mean Squared Error, [-]	$3P$	Three-phase
SSE	Sum of Squares due to Error, [-]	<i>Abbreviation</i>	
X	Lockhart-Martinelli parameter, [-]	CFD	Computational fluid dynamics
X'	Modified Lockhart-Martinelli parameter, [-]	DC	Dual Continuous
x	Axial position, [-]	FIV	Flow induced vibration
V	Velocity, [ms^{-1}]	IN	Intermittent
WC	Water cut, [-]	PMMA	Polymethyl methacrylate
<i>Greek letters</i>		PSD	Power Spectral density
α	Void fraction, [-]	SFM	Separated Flow Model
θ	Pipe inclination, [$^\circ$]	ST	Stratified
λ	Input phase fraction, [-]	WC	Water continuous
μ	Viscosity, [Pas]		

1. Introduction

In the petroleum and gas industry, the production and transportation of oil and gas, both onshore and offshore, often occur in the presence of water, either due to naturally water-bearing formations or as a result of water injection used to maintain reservoir pressure (Açikgöz et al., 1992; Hewitt, 2005; Zhang and Sarica, 2006; Kjolaas et al., 2022). In multiphase flow systems, accurate estimation of void fraction and pressure drop is of primary importance for reliable design and operation (Pan, 1996; Zhang and Sarica, 2006; Kjolaas et al., 2022; Höhn et al., 2025). In addition, correct prediction of the flow regime is essential, as it describes the spatial and temporal arrangement of the phase interfaces. This arrangement directly influences key flow parameters, heat transfer coefficients, and flow-assurance issues such as corrosion and wax deposition (Pan, 1996; Matzain et al., 2002; Paolinelli, 2018). These flow-assurance issues, together with Flow-Induced Vibration (FIV) phenomena, are strongly affected by the characteristic frequency of slug flow, as highlighted in the recent review by Arabi et al. (2025a). Experimental measurements of void fraction, pressure drop, and slug frequency are also frequently used to validate numerical simulations performed using Computational Fluid Dynamics (CFD) (Arabi et al., 2025a; Passoni et al., 2023; Ranjbari et al., 2023; Ferroudji et al., 2026).

Compared with gas-liquid and liquid-liquid two-phase flows, gas-liquid-liquid three-phase flow exhibits an additional level of complexity (Kjolaas et al., 2025), owing to the simultaneous presence of strongly coupled gas-liquid and liquid-liquid interfacial dynamics (Descamps et al., 2006, 2007; Zhai et al., 2025). For instance, Piela et al. (2009) reported that the presence of liquid drops affects bubble coalescence, which in turn influences the transition from dispersed bubble

flow to intermittent flow. It has also been reported that bubble dynamics is influenced by the nature of the emulsion (oil-in-water or water-in-oil) and by the phase-inversion process. These complex interactions explain the presence of multiple and complex flow regimes in three-phase flow (Açikgöz et al., 1992; Hewitt, 2005; Keskin et al., 2007; Yaqub et al., 2020a, 2020b).

The classification of three-phase flow regimes is commonly performed in two steps, by identifying the nature of the gas-liquid and liquid-liquid interfaces. This approach has been widely adopted in the literature for horizontal (Açikgöz et al., 1992; Pan, 1996; Keskin et al., 2007), vertical (Woods et al., 1998; Spedding et al., 2000), and inclined pipes (Spedding et al., 2000). However, a clear consensus on three-phase flow-regime terminology has not yet been established, as summarized in the reviews presented by Hewitt (2005) and more recently by Yaqub et al. (2020a).

Traditional flow-regime maps are fundamentally limited to two-dimensional representations based on two independent variables, which is appropriate for two-phase flows. However, gas-liquid-liquid three-phase flows depend on three independent flow rates, making their behavior inherently three-dimensional. Consequently, any two-dimensional representation requires fixing the third parameter, which restricts the ability of these maps to fully capture the complexity of such systems. This simplification partly explains the lack of consensus in the literature regarding the most appropriate set of parameters for three-phase flow-regime mapping, as summarized in Table 1, which reports the coordinate systems used and the corresponding fixed parameter. The absence of a universally applicable flow-pattern map may also be attributed to the fact that systematically investigating all flow regimes over a wide range of oil properties, particularly viscosity, is a large-scale

and experimentally demanding task. Consequently, most studies have focused on a limited number of representative oils (Saushin and Goltzman, 2020). This limitation is particularly critical when considering the influence of oil properties, especially oil viscosity, on the hydrodynamics of gas–liquid and liquid–liquid two-phase flows (Al-Wahaibi et al., 2007; Al-Wahaibi and Angeli, 2007; Gokcal et al., 2009, 2010; Moreiras et al., 2014; Naidek et al., 2023; Al-Sarkhi et al., 2024; Zhai et al., 2024; Miranda-Lugo and Rodriguez, 2025).

In Table 1, WC and OC refer to water cut and oil cut, respectively, which are defined as:

$$WC = \frac{J_w}{J_l} = \frac{J_w}{J_w + J_o} \quad (1)$$

$$OC = \frac{J_o}{J_l} = \frac{J_o}{J_w + J_o} \quad (2)$$

In the open literature, gas–liquid–liquid three-phase flow has received considerably less attention than gas–liquid and liquid–liquid two-phase flows. The main experimental investigations are summarized in Table 2, which also reports the working fluids, oil physical properties, pipe diameter, pipe inclination, and the parameters investigated (flow regimes, flow map, void fraction, pressure drop, and characteristic frequency).

Concerning studies focusing on flow regimes, several authors (Wilkins and Jepson, 1996; Al-Hadhrani et al., 2014; Ribeiro et al., 2019; Ren et al., 2021) limited their analysis to identifying flow regimes based solely on the gas–liquid interface, thereby neglecting the water–oil interface. By applying the drift-flux model to void-fraction measurements, Lahey et al. (1992) showed that both the distribution parameter and the drift velocity depend on the nature of the three-phase flow regime. While the majority of the studies listed in Table 2 mainly report experimental databases, several attempts have been made to correlate experimental results. For instance, some authors modeled gas–water–oil three-phase flow parameters by treating the system as a gas–liquid two-phase flow, in which the liquid properties are defined using weighted averages of the water and oil properties. In most cases, this weighting is performed using the water cut. This modeling approach has been widely applied to pressure-drop prediction (Tek, 1961, cited by Açıkgöz et al., 1992; Stapelberg and Mewes, 1994; Chen and Guo, 1999; Poesio et al., 2009; Hussein et al., 2021). Alternatively, Zhang and Sarica (2006), Dehkordi et al. (2019b), Kjølås et al. (2022), and Zhou and Fan (2024), among others, adapted gas–liquid slug-flow mechanistic models to gas–liquid–liquid three-phase flow. Although the physical rigor of this modeling approach may be open to discussion, it provides simple and practical predictive models by leveraging the extensive body of knowledge developed for gas–liquid flows, which have been studied much more thoroughly than gas–liquid–liquid flows. Furthermore, because in most of the flow regimes observed in this work water and oil are

dispersed within each other (see Section 3.1), treating the liquid mixture as a pseudo-homogeneous phase represents a reasonable practical approximation.

Analysis of Table 2 indicates that only a limited number of studies have simultaneously investigated all five key parameters. Moreover, the majority of the identified studies focus on horizontal pipes. In practice, however, transportation pipelines are rarely strictly horizontal and typically exhibit variations in inclination, including both upward and downward sections (Elseth et al., 2005; Ersoy et al., 2017; Ualiyeva et al., 2023, 2025). Elseth et al. (2005) reported significant deviations in gas–liquid–liquid flow patterns, pressure drop, and void fraction with changes in pipe inclination, even though their study was limited to a relatively small inclination range (-6° to 10°). More recently, Ualiyeva et al. (2023, 2025) highlighted the lack of experimental databases for multiphase downward flows at steep inclinations (i.e., downward angles exceeding 10°), reinforcing the need for experimental data in this range of operating conditions.

In addition, as shown in Table 2, most gas–liquid–liquid three-phase flow studies have been conducted using low- and medium-viscosity oils. However, the oil and gas industry is increasingly confronted with the production and transportation of high-viscosity oils (Sanieri et al., 2004; Tao et al., 2026; Arabi and Pallares, 2026). Multiphase flows involving high-viscosity oils exhibit behavior that differs markedly from that observed with conventional oils (Vuong et al., 2009; Zhang et al., 2012; Wang et al., 2013; Soto-Cortés et al., 2021a, 2021b; Al-Safran and Ghassemi, 2025; Arabi and Pallares, 2026), thereby highlighting the need for dedicated studies. It is important to note that no universally accepted criterion currently exists for clearly distinguishing intermediate-viscosity flows from high-viscosity flows. According to Al-Awadi (2011), relative terms such as “low” and “high” viscosity are associated with specific viscosity ranges, where oils with viscosities between 0.001 and 0.05 Pa·s are classified as low-viscosity oils, whereas viscosities exceeding 0.1 Pa·s are considered high-viscosity oils. Recently, Guzmán et al. (2026) suggested that high-viscosity oils correspond to viscosities greater than 0.6 Pa·s. Soto-Cortés et al. (2025) explained that the transition between low and medium/high-viscosity flow regimes depends on the balance between inertial and gravitational forces, and viscous and surface tension forces. They quantified this balance using a newly introduced dimensionless number (N_a) defined as:

$$N_a = \sqrt{\frac{(\rho_l - \rho_g)gD}{\rho_l}} \frac{\mu_l}{\sigma} \quad (3)$$

where ρ_b , ρ_g , g , D , μ_b , and σ are the liquid density, gas density, gravitational acceleration, pipe diameter, liquid viscosity, and surface tension, respectively.

According to Soto-Cortés et al. (2025), $N_a < 1$ corresponds to low-viscosity flows, whereas $N_a > 1$ characterizes medium/high-viscosity flow, which is representative of all the operating conditions considered in this work.

Based on the above literature review, significant knowledge gaps remain regarding gas–liquid–liquid three-phase flow involving high-viscosity oils flowing in downward inclined pipes. Experimental studies under such operating conditions are extremely scarce, despite their direct relevance to petroleum production and transportation systems. Moreover, only a limited number of investigations have simultaneously characterized the flow regimes, pressure drop, void fraction, and characteristic frequency, which are the key parameters required for the development and validation of CFD models.

To address these gaps, the present study experimentally investigates air–water–high-viscosity oil three-phase flow in a 15° downward inclined pipe. Particular emphasis is placed on the identification of flow regimes together with the measurement of pressure drop, void fraction, and characteristic frequency over a wide range of operating conditions. The resulting experimental database provides new insights into the

Table 1

Coordinate systems used for gas–liquid–liquid three-phase flow regime mapping, indicating the two plotted coordinates and the third parameter held constant.

Coordinates	Fixed parameter	References
J_w vs J_g	J_o	Açıkgöz et al. (1992), Pan (1996), Woods et al. (1998), Odozi (2000)
J_w vs J_l	-	Stapelberg and Mewes (1994)
J_l vs J_g	OC or WC	Wilkins and Jepson (1996), Keskin et al. (2007), Shmuel et al. (2015), Ribeiro et al. (2019), Dehkordi et al. (2019a), Yaqub et al. (2020c)
J_o vs J_w	J_a	Wegmann et al. (2007)
J_o vs J_g	J_w	Bannwart et al. (2009)
J_g vs J_w	OC	Hanafizadeh et al. (2017)
OC vs J_g or WC vs J_g	J_l	Spedding et al. (2000), Boeije et al. (2026)

Table 2

Summary of the main experimental investigations carried out on gas–liquid–liquid three-phase flow.

Authors and year	Fluids	Pipe diameter [mm]	Pipe inclination [°]	Oil properties		Parameters investigated				
				Density [kg/m ³]	Viscosity [Pa.s]	Flow regime	Flow pattern map	Void fraction	Pressure drop	Characteristic frequency
Açikgöz et al. (1992)	Air-water-oil	19	0	864	0.1164	X	X			
Lahey et al. (1992)	Air-water-oil	19	0	864	0.1164			X		
Stapelberg and Mewes (1994)	Air-water-oil	23.8 and 59.0	0	858	0.031	X*	X*		X	X
Nädler and Mewes (1995)	Air-water-oil	59	0	841	No details				X	
Pan (1996)	Air-water-oil	77.92	0 and +1	865	0.048	X	X	X	X	
Wilkens and Jepson (1996)	CO2-water-oil	97	0 and +5	800	0.002	X*	X*		X	X
Woods et al. (1998)	Air-water-oil	26	+90	~829	~0.012	X	X	X	X	
Odozi (2000)	Air-water-oil	77.92	−1.5, 0	~861.7	~0.041	X	X	X	X	X
Spedding et al. (2000)	Air-water-oil	26	+86.5 and +90	~829	~0.011	X	X	X	X	
Spedding et al. (2005)	Air-water-oil	25.9	0	828.5	0.0122	X	X			
Elseth et al. (2005)	Hydrocarbon gas-salt water-crude oil	78	−6, −1, 0, +1, +5, and +10	854.2	0.0395	X*	X*	X	X	
Spedding et al. (2007)	Air-water-oil	25.9	0	740	0.0007			X		
Keskin et al. (2007)	Air-water-oil	50.8	0	828.5	0.0122					
Hale et al. (2007)	Air-water-oil	77.9	0	858.8	0.0135	X	X			
Wegmann et al. (2007)	Air-oil-oil	5.6 and 7.0	0	No details	No details			X		X
Poesio et al. (2009)	Air-water-oil	21	0	~818.5	~0.0045	X	X			
Bannwart et al. (2009)	Air-water-crude oil	28.4	0	886	1.2				X	
Wang et al. (2013)	Natural gas-water-oil	52.5	0 and +90	No details	0.9					
Mukherjee et al. (2014)	Air-water-kerosene	25.4	+90	970	3.4	X	X		X	
Al-Hadhrani et al. (2014)	Air-water-oil	22.5	0	884.4	0.15, 0.28, and 0.57	X	X	X	X	
Shmuel et al. (2015)	SF6-water-oil	69	0	787	0.0012	X	X			
Kee et al. (2015)	CO2-water-oil	100	0 and +90	800	0.0018	X*	X*		X	
Karami et al. (2016)	Air-water-oil	152.4	0	847.9	0.102	X	X	X	X	
Hanafizadeh et al. (2017)	Air-oil-water	20	−45, −30, −15, −5, 0, +5, +15, +30, and +45	823	0.0027	X*	X*			
Paolinelli (2018)	Air-water-oil	100	0	760	0.0013			X	X	
Ribeiro et al. (2019)	Air-water-oil	75	0	810	0.01	X*	X*			
Alsaadi (2019)	Air-water-oil	151.5	+2	820	0.0113	X*	X*	X	X	X
Dehkordi et al. (2019a)	Air-water-oil	40	0	760	0.0017	X	X		X	X
Yaqub et al. (2020c)	Air-water-oil	152.4	0	890	0.838	X	X			
Ren et al. (2021)	Air-water-oil	50	0 and 90°	832	0.0098	X	X		X	
Husein et al. (2021)	Air-water-oil	41	0	841	0.028	X*	X*			
Kjolaas et al. (2022)	Nitrogen-water-oil	97.18	90	838.8	0.003	X	X	X	X	
Zhou (2023)	Air-water-oil	50.8	0	785.6	0.00136	X*		X	X	
Zhai et al. (2025)	Air-water/glycerol mixture-oil	20	0	810	0.0146	X			X	
Boeije et al. (2026)	SF6-water- Exxsol D60	98.7	+1, +25, +45, +75, and +90	No details	No details	X*				
				809	0.00156	X*	X*	X	X	

*refers to studies where gas–liquid flow regime classification was employed.

hydrodynamics of highly viscous three-phase flows and contributes to extending the currently available knowledge beyond the predominantly horizontal and low-viscosity conditions reported in the literature.

2. Experimental setup and methodology

2.1. Experimental facility

The experimental campaign was carried out in the “Multiphase Flow Laboratory” of the Department of Energy at Politecnico di Milano. The experimental apparatus was designed to ensure a high degree of configurational flexibility, enabling operation in both horizontal and inclined layouts. Furthermore, the facility allows investigation of different fluid combinations, namely air–water, air–oil, water–oil, and air–water–oil systems (Franchi et al., 2023). In this work the three-phase combination air–water–oil at ambient temperature and atmospheric pressure is treated. The pipes have an internal diameter of 40 mm, they are made of Plexiglas® and the sections are connected by flanges and fixed on the top of an aluminum structure. The pressure test and the quick-closing valves sections are placed 6 m (150 diameters) downward of the multiphase injector, which is located at the top, to assure a fully developed flow. The quick-closing valves section is placed at the lowest level. The total length of the inclined section is 10.40 m, while the maximum height from the horizontal frame is 2.70 m as reported in Fig. 1.

2.2. Fluids

The test fluids used in the current study are: compressed air available from a distribution line at max. 10 bar, tap water from the municipal network (pH 7.3, conductivity 508 $\mu\text{S}/\text{cm}$ at 20°C, hardness 26°F, Total dissolved solids (TDS) at 180°C 364 mg/L) and a stable emulsion of water and Milpar 220 mineral oil. The physical properties of the three fluids, at ambient temperature and atmospheric pressure, are reported in Table 3.

2.3. Air circuit

The air comes from the compressed air line of the laboratory in the Department of Energy. Air pressure is regulated with a manometer placed above the flow-meter and set to 2 bar. The flow-meter is used to regulate the air flow, in particular the value considered for this study are [2000; 4000; 6000] NL/h. The actual flow-rate is obtained from:

$$Q_a = Q_{ref} \sqrt{\frac{P_{ref} \cdot P_{eff} \cdot T_{ref}}{P_{cond}^2 \cdot T}} \quad (4)$$

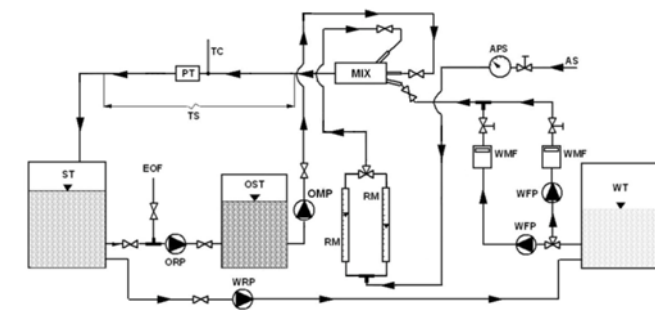


Fig. 1. Schematic diagram of the experimental setup, APR Air Pressure Regulation, AS Air Supplying line, CS Capacitance Sensor, EOF External Oil Feeding, GW Glass Window, M Manometer, MIX phase inlet Mixer, OMP Oil Metering Pump, ORP Oil Recovering Pump, OST Oil Supply Tank, PT Pressure Transducer, RM Rotameter, ST Separator Tank, TC Thermocouple, TS Test Section, WFP Water Feeding Pump, WMF Water Magnetic Flowmeter, WRP Water Recovering Pump, WT Water Tank.

Table 3

Fluids rheological properties.

Fluid	Density [kg/m^3]	Viscosity [$\text{Pa}\cdot\text{s}$]
Air	1.194	$1.81 \cdot 10^{-5}$
Water	997.5	0.001
Oil	890	0.93

Where Q_{ref} is the air flow-rate at the reference temperature (i.e., 293 K) and reference pressure (i.e., 1.01325 bar), whereas p_{eff} is the absolute pressure at the air inlet, measured with a dedicated pressure gauge (SETRA model 230, with full scale 6.89 kPa (1 psi), accuracy $\pm 0.5\%$ of the full scale), p_{cond} is the pressure within the conduit, i.e., the average value of the 5 measured pressure values (see subsequent section for specifications), and T is the measured temperature within the lab.

2.4. Water circuit

The water is stored in a tank (WT), with maximum capacity of 5 m^3 and it is pumped to the injection section by using a centrifugal pump (WFP). The water flow-rate is measured using a magnetic flow meter (Endress + Hauser Promag 30 FT15E, 0.5 – 6 $\text{m}^3/\text{h} \pm 0.5 \text{ m}^3/\text{h}$).

2.5. Oil circuit

The oil is stored in a 0.5 m^3 tank (OST), and it is pumped to the injection section by using a gear pump. An inverter sets and regulates the speed of the gear pump and so the flow rate of oil (Table 4).

2.6. Air–water–oil injection section

The controlled introduction of the three-phase mixture into the test section is a critical determinant of both the flow pattern development and the experimental reproducibility. The injection assembly is constructed from high-grade hydraulic PVC. To ensure system integrity, the gas phase is delivered via a non-return valve to prevent backflow. The liquid phase injection utilizes a specialized coaxial configuration: oil is introduced through the central conduit, while water is injected at 25° inclination into the annular space. These phases converge within a specialized nozzle prior to entering the primary flow line. This modular component is fabricated from material consistent with the main piping and features an adaptable geometry to accommodate varying pipe diameters. (Fig. 2).

2.7. Test section

The tests section consists of 5 pipes in series, with a downward inclination of 15°, made of polymethyl methacrylate (PMMA), commercially known as Plexiglas®. The first three sections are dedicated to flow pattern development in order to make reliable measurements, then there is the pressure drop measurement section, as well as the photographic section, which also includes the quick-closing valves. Attached to the photographic section are two mirrors, placed behind the tube and inclined 90° to each other, so that two complementary views (top and bottom) of the pipe are taken, along with the central one. To perform the flow pattern visualization, a high-speed camera is used. Specifically, the pictures are taken with a NIKON D4 camera with a

Table 4

Calibration of oil flow rate and superficial velocity.

Frequency [Hz]	Q_o [m^3/h]	J_o [m/s]
30	2.52	0.56
40	3.23	0.71
50	4.12	0.91
60	4.79	1.06

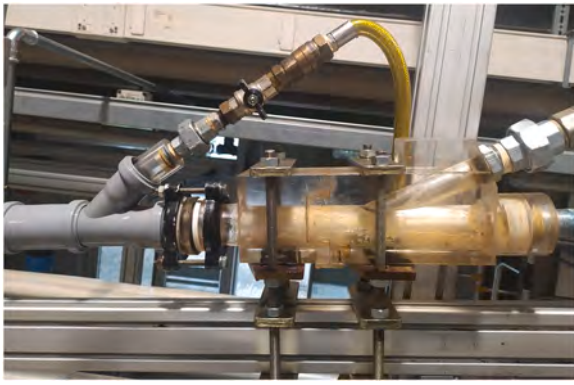


Fig. 2. Three-phase injector and detail of water-oil injector.

NIKKOR 60 mm f/2.8 G Micro lens, setting an exposure time of 1/6400 s with a F-stop of f/16. Finally, pressure drop measurements are performed using a differential piezo-resistive pressure transducer (C230, Setra System, 0–5.5 V, 0.5–10.05 kPa, $\pm 0.25\%$ FS) installed on a 2 m test section equipped with five pressure taps. The signals are acquired through a data acquisition board and processed using LabView® and Excel®.

2.8. Quick-closing valve method

The void fractions are measured with the quick-closing valves method. The procedure has been calibrated during previous experimental campaigns showing good results and repeatability (Colombo et al., 2015).

2.9. Procedure

The experimental runs are performed by setting the desired water, oil, and air flow-rates and then letting the flow develop, 48 velocity triplets are set as combinations of the values reported in Table 5.

Once the initial setup is complete, pressure drop experiments are conducted. Pressure measurements are collected sequentially from the five taps positioned along the 2 m test section. For each fluid velocity condition, a minimum of five trials is carried out to ensure repeatability. As discussed in the results and discussion section, the pressure measurements confirm that the flow is fully developed in the test section.

2.10. Uncertainty analysis

Superficial velocities: The value of air flow rate in the pipeline (see Eq. (4)) depends on a set of independent measured quantities: the set value on the flowmeter (Q_{ref}), the flowmeter working pressure (p_{eff}), the average test section pressure (p_{cond}) and temperature (T); therefore, partial derivatives with respect to these variables have to be computed and evaluated at the known values of the measured quantities.

The combined uncertainty E_{Q_a} results equal to:

$$E_{Q_a} = \sqrt{\left(\frac{\partial Q_a}{\partial Q_{ref}} E_{Q_{ref}}\right)^2 + \left(\frac{\partial Q_a}{\partial p_{eff}} E_{p_{eff}}\right)^2 + \left(\frac{\partial Q_a}{\partial p_{cond}} E_{p_{cond}}\right)^2 + \left(\frac{\partial Q_a}{\partial T} E_T\right)^2} \quad (5)$$

Finally, superficial velocities uncertainties E_{J_a} , E_{J_w} and E_{J_o} are computed as:

$$E_{J_a} = \frac{E_{Q_a}}{\Omega} \quad (i) \quad E_{J_w} = \frac{E_{Q_w}}{\Omega} \quad (ii) \quad E_{J_o} = \frac{E_{Q_o}}{\Omega} \quad (iii) \quad (6)$$

Pressure: Pressure measures are obtained as time averaged values over an acquisition time interval t ; therefore, the uncertainty E_{p_i} is computed as:

$$E_{p_i} = \frac{E_{transducer}}{\sqrt{f_s t}} \quad (7)$$

Where f_s is the board sampling frequency, so that the product $f_s t$ is the number of samples n . The uncertainty of the pressure gradient is taken equal to the value of the standard error σ_b associated to the slope of the regression straight line.

Void fraction: The uncertainty associated with the void fraction measurement is mainly related to the determination of the phase volumes trapped between the quick-closing valves. The free-surface level is measured with a ruler, resulting in a maximum reading uncertainty of ± 1 mm. The cross-sectional area is affected by the uncertainty in the inner diameter of the Plexiglas tube, assumed equal to the manufacturer's dimensional tolerance ± 0.5 mm.

Table 6 reports the percentage measurements uncertainties for the main quantities of interest.

3. Results and discussion

3.1. Flow regimes

In the present study, the identification of three-phase flow regimes is carried out by analyzing flow images collected at the top, side, and bottom of the pipe, following the terminology proposed by Keskin et al. (2007). As explained in Section 1, this flow regime classification approach is based on the identification of gas–liquid and liquid–liquid two-phase flow regimes. For gas–liquid flow regimes, Keskin et al. (2007) considered stratified flow (which includes both smooth and wavy stratified flows), intermittent flow (including plug and slug flows), dispersed bubble flow, and annular flow. In contrast, the liquid–liquid flow regimes include stratified flow, dual continuous flow, oil-in-water dispersion, and water-in-oil dispersion.

Under the experimental conditions investigated in the present study, three flow regimes were identified, namely:

3.1.1. Stratified–dual continuous (ST–DC) (Fig. 3a)

This flow regime is characterized by a gas layer flowing above the liquid phases with an undulated interface. Meanwhile, the oil and water phases flow separately, being divided by an interface where water droplets are dispersed in a continuous oil phase above, while oil droplets are dispersed in a continuous water phase below.

3.1.2. Stratified–water continuous (ST–WC) (Fig. 3b)

Oil is present as an emulsion in a continuous water phase. The oil-in-water (O/W) emulsion flows below a continuous gas phase, and the gas–liquid interface is relatively wavy.

3.1.3. Intermittent–water continuous (IN–WC) (Fig. 3c)

The flow is characterized by an alternating passage of elongated bubbles above a continuous oil-in-water dispersion, followed by liquid slugs of the same nature occupying the entire pipe cross-section.

3.2. Flow maps

In Fig. 4a, the observed flow regimes are plotted using J_o vs J_w plot for $J_a = 0.75$ m/s. The ST–DC regime occurs in the region of low J_o and J_w , whereas increasing J_L leads to the disappearance of the dual continuous interface in favor of the water-continuous regime. In this region, ST–WC and IN–WC occupy the zones of low and high J_w , respectively. Furthermore, increasing J_a reduces the extent of the ST–DC region and promotes a transition toward intermittent flow, as shown in Figs. 4b, c. Consequently, the proportion of operating conditions classified within the slug flow regime increases from 37.5% to 68.75% as J_a increases from 0.75 to 2.25 m/s. These observations highlight the complex interplay among the flow rates of the three phases and the

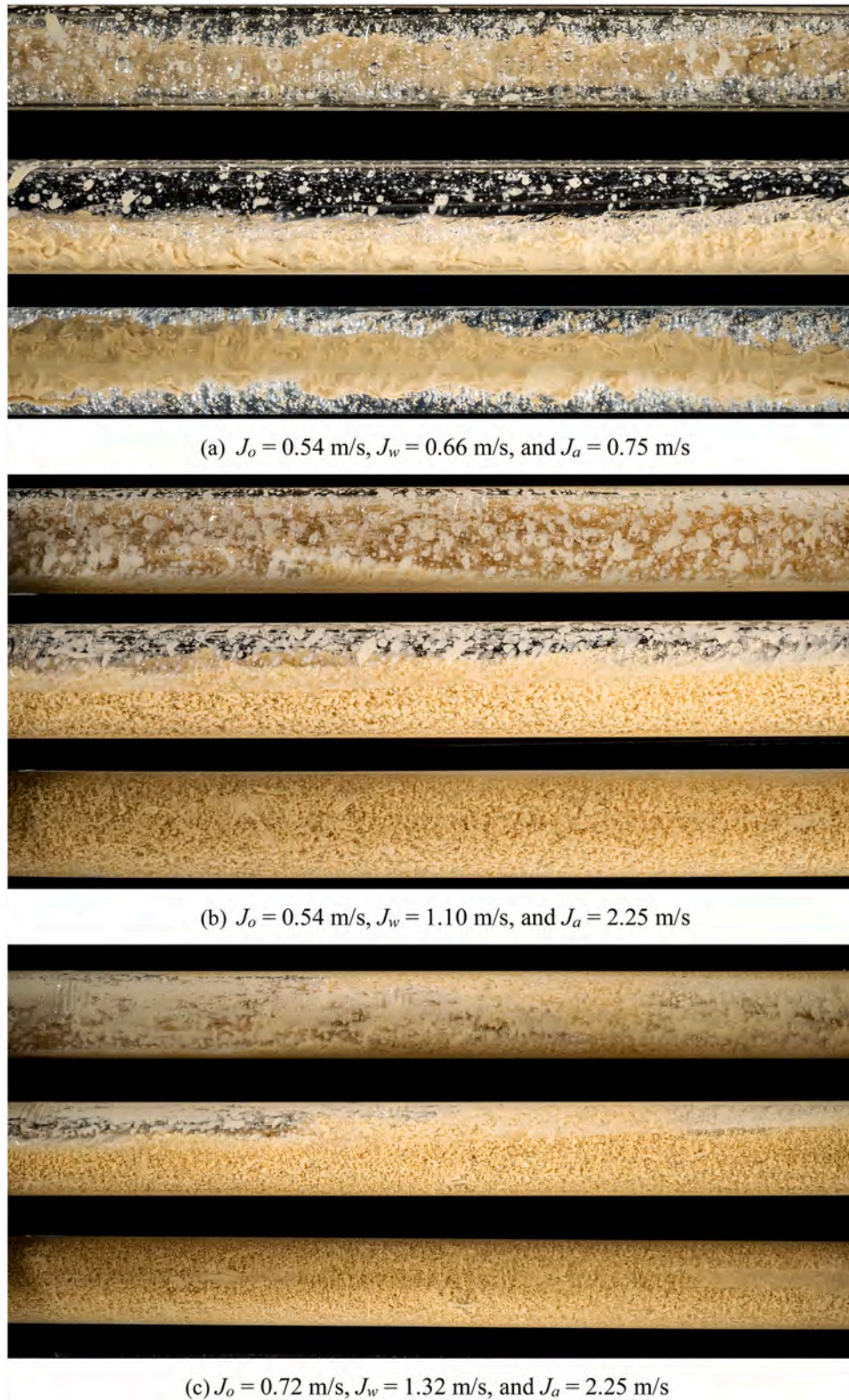


Fig. 3. Images of observed flow regimes (a) Stratified-Dual Continuous (ST-DC); (b) Stratified-Water Continuous (ST-WC); and (c) Intermittent-Water Continuous (IN-WC). For each flow condition, the first, second, and third image represent the top, side, and bottom views, respectively. Flow direction: from right to left.

resulting gas–liquid and liquid–liquid interfacial dynamics.

Following the flow regime mapping approaches employed notably by Keskin et al. (2007), Dehkordi et al. (2019a), and Yaqub et al. (2020c), the observed flow regimes for $WC = 0.55$ are plotted as a function of J_l and J_a (Fig. 5). It can be clearly observed that the ST–DC

regime occupies the region of low J_l . As J_l increases, the liquid–liquid interface transitions to a water-continuous configuration prior to the onset of gas–liquid slugging.

Table 5
Operating conditions.

J_a [m/s]	J_w [m/s]	J_o [m/s]
0.75	0.66	0.54
1.50	0.88	0.72
2.25	1.10	0.89
	1.32	1.07

Table 6
Percentage measurement uncertainties of the main quantities.

Percentage uncertainty	Minimum	Maximum
J_a	2%	7%
J_w	2%	5%
J_o	2%	5%
$-dp/dx$	1%	5%

3.3. Void fraction

In a multiphase flow, the phases generally flow at different velocities, which generates slip between them and, consequently, leads to an accumulation of one phase at the expense of the other within the pipe. For gas-liquid two-phase flow, the gas holdup, commonly referred to as void fraction, is used to characterize the nature of the flow, whether it is homogeneous, inertia-driven, or gravity-driven (Ghajar, 2020). These three regimes correspond to cases where the average gas velocity is equal to, greater than, or lower than the average liquid velocity, respectively (Ghajar, 2020; Arabi et al., 2026).

Assuming that the air-oil-water three-phase flow can be approximated as a gas-liquid two-phase flow, with the oil-water mixture behaving as a homogeneous liquid phase, the nature of the flow can be estimated by plotting the void fraction as a function of the air input fraction calculated using:

$$\lambda_a = \frac{J_a}{J_m} \quad (8)$$

where the mixture velocity J_m is defined as follows:

$$J_m = J_a + J_w + J_o \quad (9)$$

Such a representation (Fig. 6) shows that the vast majority of data points lie below the bisector corresponding to homogeneous flow ($\alpha = \lambda_a$). This region is therefore characterized by inertia-driven flow. Interestingly, these points correspond to $J_a = 1.50$ and 2.25 m/s. On the other hand, the experimental conditions recorded at $J_a = 0.75$ m/s exhibit a gravity-driven/homogenous flows behavior.

Ghajar (2020) showed that, for gas-liquid two-phase flow, buoyancy-driven flow appears in downward orientations when $Fr_a < 0.1$, where Fr_a denotes the gas Froude number. This dimensionless number expresses the ratio between gas inertia and gravity and is calculated as:

$$Fr_a = \sqrt{\frac{\rho_a}{\rho_l - \rho_a}} \frac{J_a}{\sqrt{gD\cos\theta}} \quad (10)$$

where θ and ρ_l refer to the pipe inclination and the liquid density, respectively. This latter is defined as the weighted average of the water and oil densities, with the water cut used as the weighting factor:

$$\rho_l = WC\rho_w + (1 - WC)\rho_o \quad (11)$$

Under the conditions investigated in the present work, the buoyancy-to-inertia-driven flow transition is found to occur at a lower Fr_a (between 0.044 and 0.087) than the critical value reported by Ghajar (2020). Additional experimental data will help define this critical value with greater precision.

The drift-flux model is a widely used approach for modeling multi-

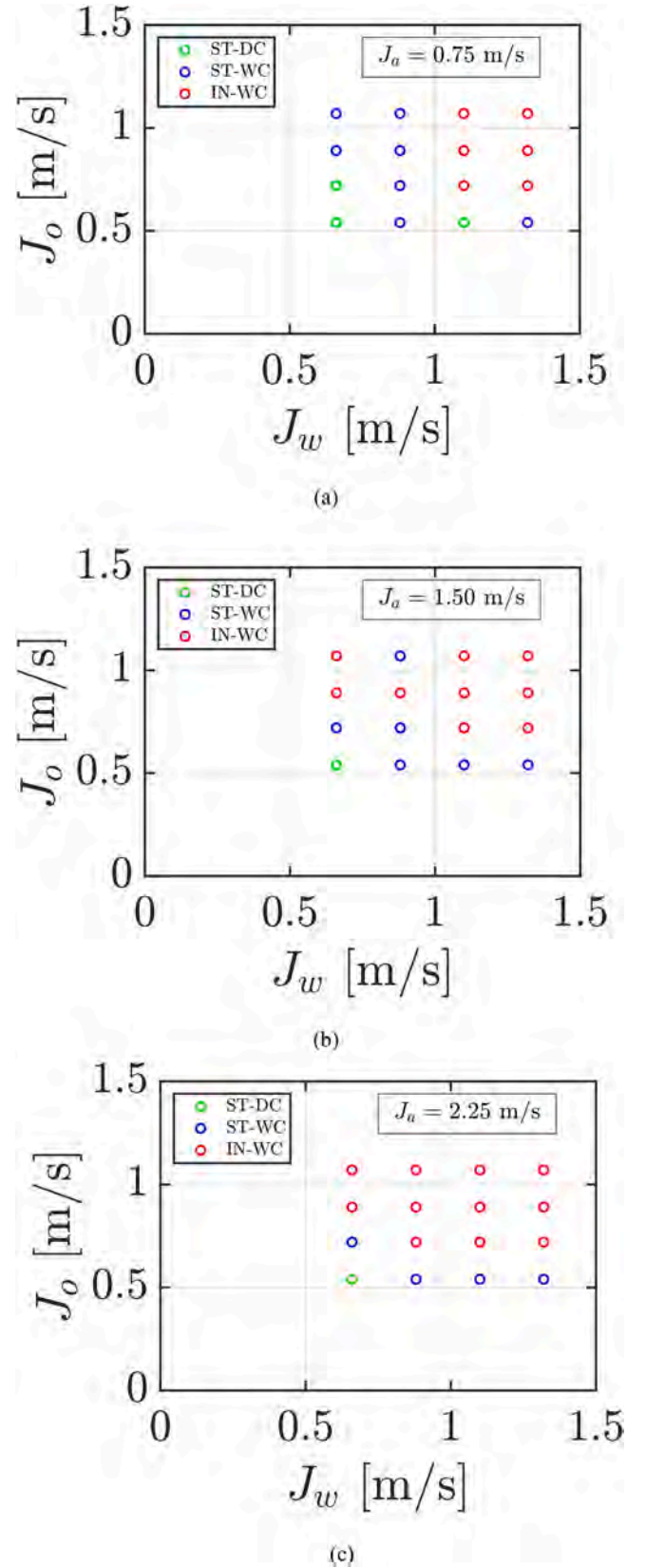


Fig. 4. Plot of flow regimes observed using J_o vs J_w for different J_a .

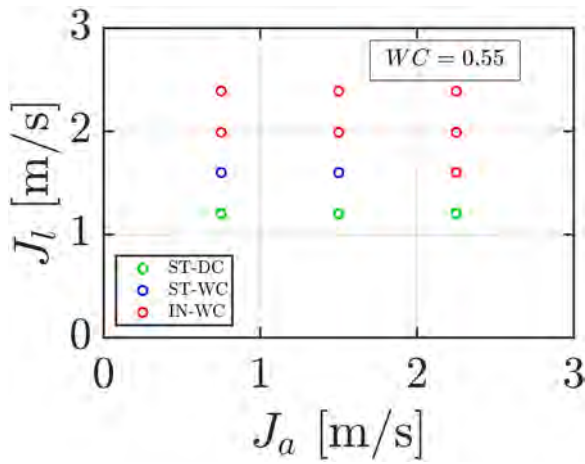
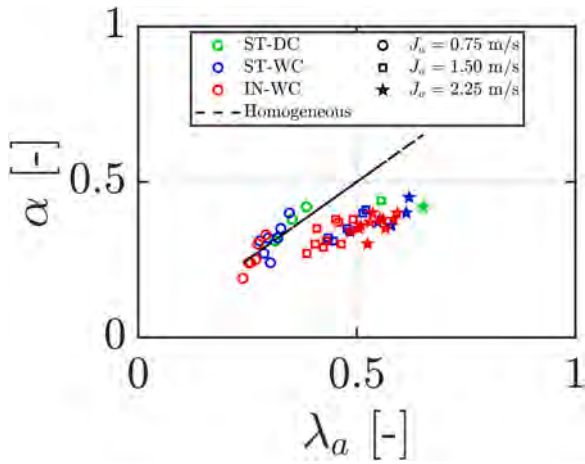
Fig. 5. Plot of flow regimes observed using J_l vs J_a for $WC = 0.55$.

Fig. 6. Void fraction versus air input fraction.

phase flow, to consider the nonuniform radial-phase distribution and the local relative velocity between phases (Hibiki, 2019; Liu et al., 2020; AlSaif and Al-Sarkhi, 2024). Although the drift-flux model was originally developed for vertical upward gas-liquid flow by Zuber and Findlay (1965), it has been successfully applied to various multiphase flow systems, including liquid-liquid two-phase flow (Franchi et al., 2023) and gas-liquid-liquid three-phase flow (Lahey et al., 1992). Assuming that the oil and water phases are homogeneous and flow at the same velocity, the air velocity (V_a) can be expressed as:

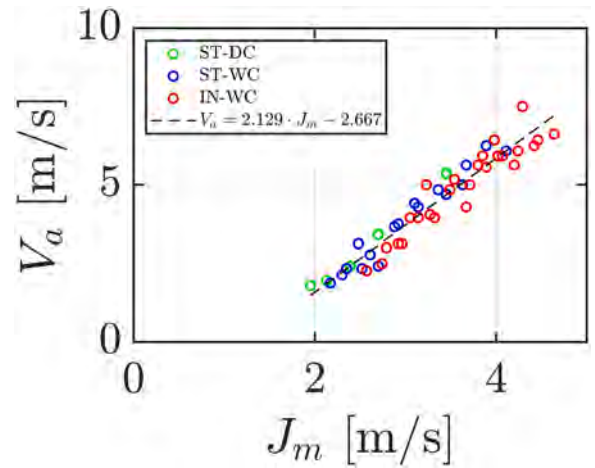
$$V_a = C_0 J_m + V_d \quad (12)$$

Here, C_0 , and V_d denote the distribution parameter, and drift velocity, respectively. V_a is calculated as follows:

$$V_a = \frac{J_a}{\alpha} \quad (13)$$

According to Eq. (12), the distribution coefficient and the drift velocity can be determined by applying a linear fit to the results plotted in a V_a versus J_m plot (Zuber and Findlay, 1965). As shown in Fig. 7, the results obtained for the three flow regimes are well correlated by a straight line, with $C_0 = 2.1$ and $V_d = -2.7$ m/s. The negative drift velocity is expected for downward flow, as buoyancy forces oppose the motion and retard the flow. It is worth noting that the negative value of the drift velocity has also been reported by Lahey et al. (1992) for horizontal slug flow with a continuous water phase.

Recently, Arabi et al. (2025b) successfully correlated the void

Fig. 7. Plot of V_a as function of J_m .

fraction in vertical downward gas-liquid flow by employing the $(1-\alpha)/(J_l/J_a)$ vs λ_l coordinate system, where λ_l denotes the liquid input fraction, defined as:

$$\lambda_l = 1 - \lambda_a = \frac{J_l}{J_m} \quad (14)$$

As shown in Fig. 8, this representation allows all the data obtained across the three flow regimes to collapse onto a single trend. By applying a two-variable power-law fit is obtained, with all data points lying within $\pm 15\%$:

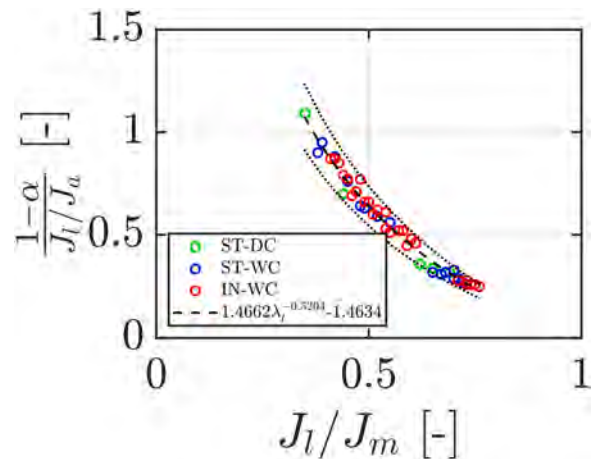
$$\frac{(1-\alpha)J_a}{J_l} = 1.4662\lambda_l^{-0.5204} - 1.4634 \quad (15)$$

The quality of the fit is confirmed by the low *SSE* and *RMSE* values, together with a high coefficient of determination: *SSE* = 0.0430, R^2 = 0.9819, *DFE* = 45, and *RMSE* = 0.0309.

Thus, the void fraction can be predicted as:

$$\alpha = 1 - \left[\frac{J_l}{J_a} (1.4662\lambda_l^{-0.5204} - 1.4634) \right] \quad (16)$$

This correlation predicts the void fraction with an average relative error and an average absolute relative error of -1.78% and 9.81% , respectively.

Fig. 8. Plot of $(1-\alpha)/(J_l/J_a)$ as function of λ_l , the dashed lines represent the boundaries at $\pm 15\%$.

3.4. Pressure drop

As explained in Section 2, the pipe is equipped with five pressure transducers distributed along its length to monitor the axial pressure evolution. Representative examples of normalized pressure drop profiles ($\Delta p_{\text{normalized}} = \frac{P - P_{\min}}{P_{\max} - P_{\min}}$) is presented in Fig. 9. It can be observed that the pressure varies linearly along the pipe, indicating a uniform pressure gradient and confirming that the flow is fully developed over the measurement section.

The frictional pressure gradient can be determined by subtracting the calculated hydrostatic pressure gradient from the total pressure gradient obtained from the static pressure profiles (Eq. (17)) (Bouyahiaoui et al., 2024). It should be noted that this formulation assumes that the pressure drop due to acceleration is negligible (Beggs and Brill, 1973; Bouyahiaoui et al., 2024) further considering that the flow is adiabatic and without mass transfer between the phases.

$$\left(-\frac{dp}{dx}\right)_f = \left(-\frac{dp}{dx}\right)_g - \left(-\frac{dz}{dx}\right)_t \quad (17)$$

The gravitational pressure drop gradient is calculated as follows:

$$\left(-\frac{dp}{dx}\right)_g = \rho_m g \quad (18)$$

with

$$\rho_m = \alpha \rho_a + (1 - \alpha) \rho_l \quad (19)$$

Traditionally, the frictional two-phase pressure drop gradient is correlated with the Separated Flow Model (SFM) which is based on two-phase flow multiplier ($\Phi_{l,2p}^2$) calculated as:

$$\Phi_{l,2p}^2 = \frac{\left(-\frac{dp}{dx}\right)_f}{\left(-\frac{dp}{dx}\right)_l} \quad (20)$$

Generally, the two-phase flow multiplier is correlated with the Lockhart-Martinelli parameter given as:

$$X = \sqrt{\frac{\left(-\frac{dp}{dx}\right)_l}{\left(-\frac{dp}{dx}\right)_a}} \quad (21)$$

with

$$\left(-\frac{dp}{dx}\right)_l = \frac{f_l \rho_l J_l^2}{2D} \quad (22)$$

$$\left(-\frac{dp}{dx}\right)_a = \frac{f_a \rho_a J_a^2}{2D} \quad (23)$$

Here, f_l and f_a denote the liquid and gas friction factors, respectively. In this study, we use the correlation proposed by Fang et al. (2011) to calculate the friction factor in turbulent flow. Moreover, the laminar-to-turbulent transition is assumed to occur at $Re = 1055$ (Bouyahiaoui et al., 2024). Accordingly, the friction factors for the liquid and gas phases are given as follows:

$$f_l = \begin{cases} \frac{64}{Re_l} & \text{for } Re_l \leq 1055 \\ 0.25 \left[\log \left(\frac{150.39}{Re_l^{0.98865}} - \frac{152.66}{Re_l} \right) \right]^{-2} & \text{for } Re_l > 1055 \end{cases} \quad (24)$$

$$f_a = \begin{cases} \frac{64}{Re_a} & \text{for } Re_a \leq 1055 \\ 0.25 \left[\log \left(\frac{150.39}{Re_a^{0.98865}} - \frac{152.66}{Re_a} \right) \right]^{-2} & \text{for } Re_a > 1055 \end{cases} \quad (25)$$

where Re_l and Re_a denote the Reynolds numbers of the liquid and gas phases, respectively, and are calculated as follows:

$$Re_l = \frac{\rho_l J_l D}{\mu_l} \quad (26)$$

$$Re_a = \frac{\rho_a J_a D}{\mu_a} \quad (27)$$

Eq. (27) involves the liquid viscosity, which, like the liquid density, may be determined by linearly interpolating between the viscosities of water and oil, as follows:

$$\mu_l = WC\mu_w + (1 - WC)\mu_o \quad (28)$$

As noted by Pan (1996), Hall (1993) reported that this approach leads to incorrect predictions of the liquid viscosity. It was therefore suggested to employ the correlations of Hartschek (1928); Richardson (1933), and Brinkman (1952), given in Eqs. (29)-(31), respectively.

$$\mu_l = \frac{\mu_{cont}}{1 - \lambda_{dis}^{0.33}} \quad (29)$$

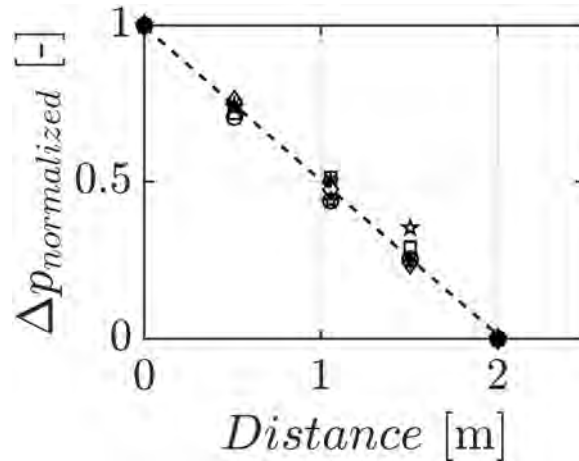


Fig. 9. Evolution of static pressure along the measurement section for five repeated tests.

$$\mu_l = \mu_{cont} e^{2.5\lambda_{dis}} \quad (30)$$

$$\mu_l = \frac{\mu_{cont}}{(1 - \lambda_{dis})^{2.5}} \quad (31)$$

Here, μ_{cont} and λ_{dis} refer to the viscosity of the continuous phase and the phase fraction of the dispersed phase, respectively. In our experiments, the water is the continuous phase while the oil is the dispersed phase which means that $\mu_{cont} = \mu_w$ and $\lambda_{dis} = OC$.

On the other hand, it is common in petroleum engineering to consider for water continuous flow the following equation for liquid viscosity:

$$\mu_l = \mu_w \quad (32)$$

The evolution of the liquid viscosities given by the five formulas (Eqs. (28)-(32)) are depicted in Fig. 10 as function of water cut. Note that we plotted only the range of the WC observed in our present experiments (0.382-0.710). One can see clearly the linear interpolation gives several magnitude higher values. The correlations of Hartschek (1928); Richardson (1933), and Brinkman (1952) give relatively close values in the range of WC depicted.

By considering the liquid phase as water-oil mixture with averaged properties, the three-phase flow multiplier can be expressed as:

$$\Phi_{L,3P}^2 = \frac{\left(-\frac{dp}{dx}\right)_{f,3P}}{\left(-\frac{dp}{dx}\right)_l} \quad (33)$$

In Fig. 11, the frictional pressure drop data are presented in terms of the three-phase flow multiplier $\Phi_{L,3P}$ as a function of X , using different formulations for the liquid viscosity. The values of $\Phi_{L,3P}$ are consistent across most models, except for the linear interpolation model, which yields values below unity, implying a three-phase pressure drop lower than that of the liquid mixture alone. This is physically questionable, given the turbulence of the gas phase and its complex interactions with the liquid phase, including the formation of interfacial waves and slugging, already discussed in Section 3.2. This result further confirms the limitations of the linear interpolation approach already reported by Pan (1996). Moreover, significant dispersion is observed in all cases. This indicates that a single fit cannot adequately represent all the data, thereby highlighting the limitations of the SFM approach for the present case, regardless of the liquid viscosity model employed. Consequently, an alternative approach is required to correlate the frictional pressure drop gradient.

In Fig. 12, the frictional pressure drop results are plotted using the dimensionless numbers P_m and Fr_m , defined as:

$$P_m = \frac{D \left(-\frac{dp}{dx}\right)_{f,3P}}{\frac{1}{2} \rho_m J_m^2} \quad (34)$$

$$Fr_M = \sqrt{\frac{\rho_l}{\rho_l - \rho_a}} \frac{J_m}{\sqrt{g D \cos \theta}} \quad (35)$$

It is worth noting that these dimensionless numbers have been successfully employed to correlate the total pressure drop in vertical downward gas-liquid flow by Bouyahiaoui et al. (2020) and more recently by Arabi et al. (2025b).

Fig. 12 clearly shows that the data obtained across the three observed flow regimes collapse onto a single curve. The results can be successfully correlated using the following correlation:

$$P_m = 1.9205 Fr_m^{-3.3038} + 0.0085 \quad (36)$$

The statistical parameters of the fit were obtained as follows: $SSE = 0.0005$, $R^2 = 0.8625$, $DFE = 40$, and $RMSE = 0.0036$.

It can be observed from the plot that this correlation predicts the majority of data points within $\pm 15\%$. Moreover, the experimental measurements of the frictional pressure drop are predicted with an average relative error and an average absolute relative error of -4.57% and 15.50% , respectively.

3.5. Characteristic frequencies

The three reported flow regimes exhibit fluctuations characterized by a specific frequency, referred to as the characteristic frequency (f_c). These characteristic frequencies can be considered as the dominant frequencies observed in frequency spectra (Wijaynta et al., 2023; Höhn et al., 2024; Cenzi et al., 2026). In the present study, the dominant frequencies were extracted from the Power Spectral Density (PSD) analysis of pressure time series collected from the five pressure transducers placed along the pipe. Fig. 13 displays the axial evolution of the characteristic frequencies for six experimental conditions corresponding to different values of J_o , J_w , and J_a . Though the values fall in a similar variation range at all the pressure taps, only the frequencies measured at the fifth one were considered for further analysis being the farthest (i.e. the least affected) from the injection point.

Mantilla (2008) and Al-Sarkhi et al. (2012) have shown that the characteristic frequencies of gas-liquid two-phase flow can be well correlated using the Strouhal number based on the liquid superficial velocity (St_l) and the modified Lockhart-Martinelli parameter (X'). These two parameters are defined by Eq. (37) and Eq. (38), respectively.

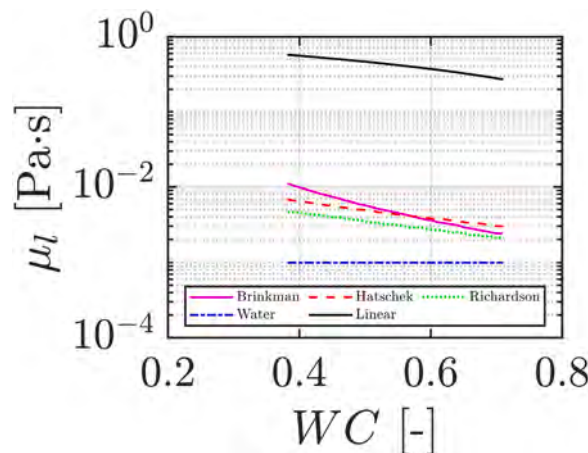


Fig. 10. Plot of μ_l as function of WC calculated with the different formulas.

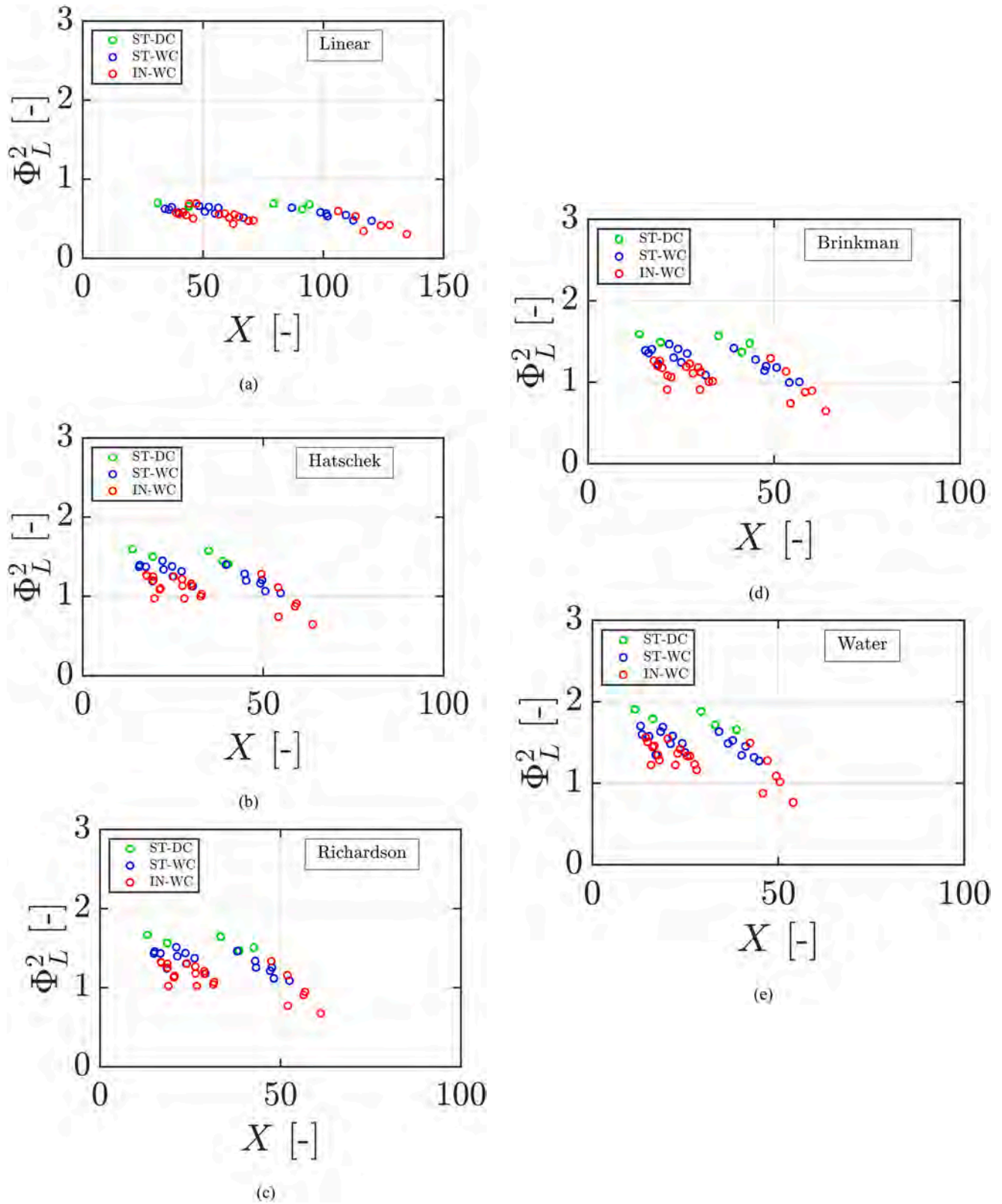


Fig. 11. Plot of $\Phi_{L,3P}^2$ as function X for different calculated values of μ_i .

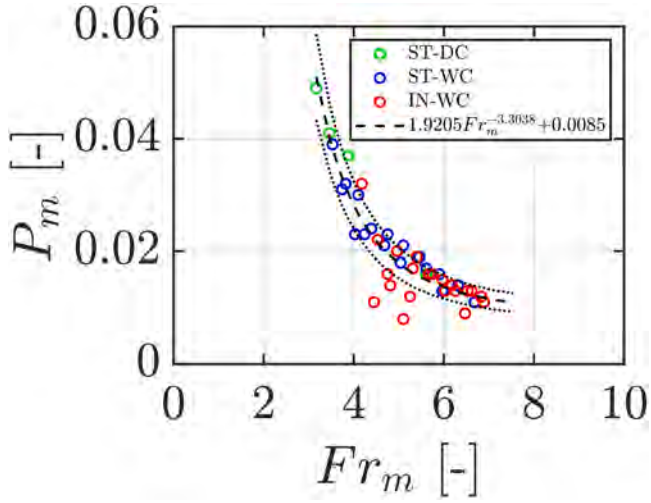


Fig. 12. Plot of PM^* as function of Fr_m , the dashed lines represent the boundaries at $\pm 15\%$.

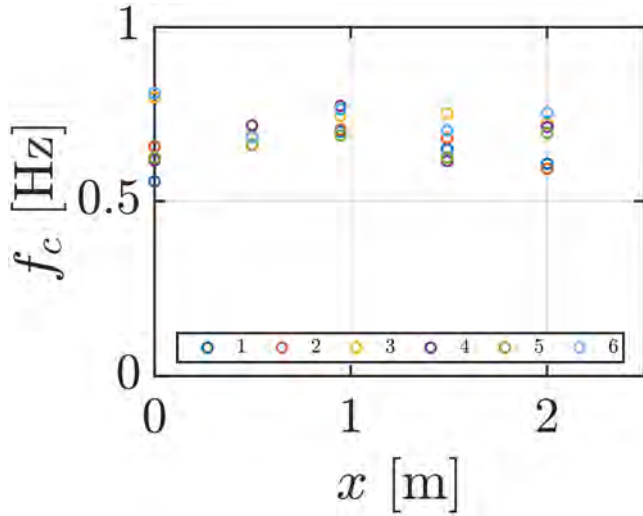


Fig. 13. Evolution of static pressure along the measurement section. (1): $J_l = 0.54$ m/s; $J_w = 0.66$ m/s and $J_a = 2.25$ m/s; (2): $J_l = 0.54$ m/s; $J_w = 0.88$ m/s and $J_a = 2.25$ m/s; (3): $J_l = 0.54$ m/s; $J_w = 1.10$ m/s and $J_a = 2.25$ m/s; (4): $J_l = 0.72$ m/s; $J_w = 0.66$ m/s and $J_a = 1.50$ m/s; (5): $J_l = 0.72$ m/s; $J_w = 0.88$ m/s and $J_a = 1.50$ m/s; (6): $J_l = 0.72$ m/s; $J_w = 1.10$ m/s and $J_a = 1.50$ m/s.

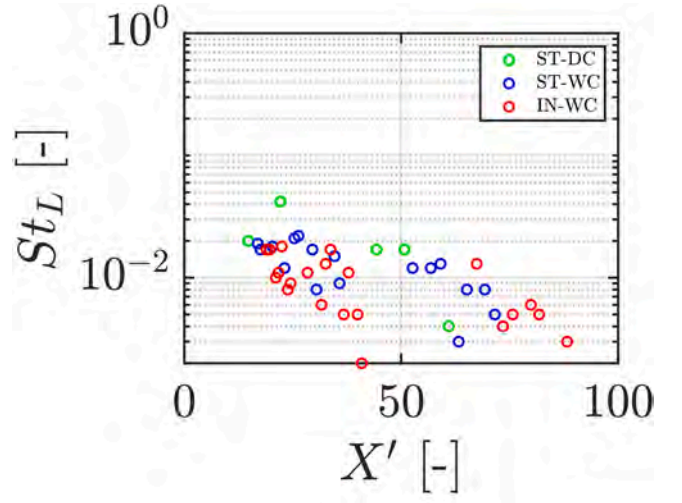
$$St_l = \frac{f_c D}{J_l} \quad (37)$$

$$X' = \frac{Fr_l}{Fr_g} \quad (38)$$

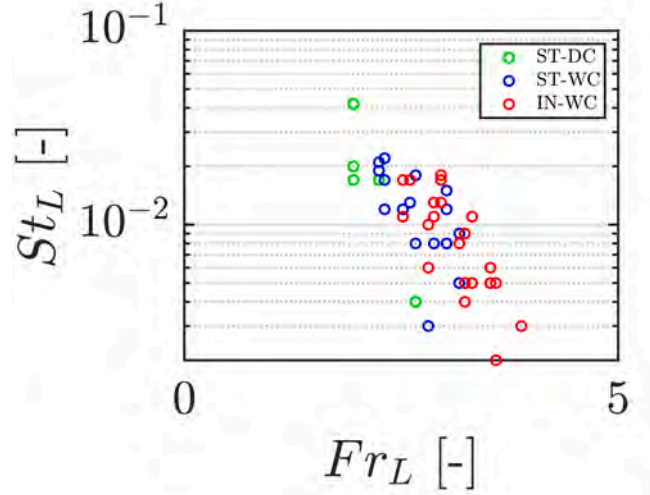
Here, Fr_l denotes the liquid Froude number, defined as follows:

$$Fr_l = \sqrt{\frac{\rho_l}{\rho_l - \rho_g}} \frac{J_l}{\sqrt{g D \cos \theta}} \quad (39)$$

From Fig. 14a, the measured characteristic frequencies plotted as St_l versus X' show that ST-DC generally exhibits the highest values of dimensionless characteristic frequency, whereas the lowest values are obtained for slug flow (IN-WC). This result is physically consistent, since interfacial waves occur at higher frequencies than slugging events. However, it also is to be noted that the data show high dispersion, which makes it difficult to identify a clear general trend, even when the different flow-regime categories are considered.



(a)



(b)

Fig. 14. Plot of St_l as function of (a) X' and (b) Fr_l .

In Fig. 14b, the characteristic frequency results obtained in the present study are plotted in terms of St_l versus Fr_l . Although this representation leads to a reduced dispersion of the data, it still indicates that classical dimensionless parameters developed for gas–liquid two-phase flow are not adequate to predict the characteristic frequency behavior for the present configuration. This finding highlights that the presence of a second liquid phase, together with the complex interactions discussed previously, prevents the direct application of gas–liquid two-phase flow scaling laws and emphasizes the need for new physically based models specifically developed for three-phase flows.

4. Conclusions

This study presents a comprehensive experimental investigation of air–water–high-viscosity oil three-phase flow in a 15° downward-inclined pipe of 40 mm ID, addressing key gaps in the current literature related to downward configurations and high-viscosity fluids.

Three distinct flow regimes, ST-DC, ST-WC, and IN-WC, were identified based on flow visualization. These flow regimes are based on gas–liquid and liquid–liquid interfacial dynamics. The flow regimes were mapped using different coordinate systems.

The analysis of void fractions showed that the flow can be classified

into inertia-driven, homogenous, and gravity-driven regimes. The transition to gravity-driven flow is governed by the gas superficial velocity. In addition, a new void fraction correlation was developed, providing satisfactory predictions with low error levels.

Frictional pressure drop analysis demonstrated that the traditional separated fluid model is not sufficient to represent the full dataset due to significant dispersion. Improved scaling was achieved using alternative dimensionless groups, leading to the development of a new empirical correlation capable of predicting the data with satisfactory accuracy.

The study of characteristic frequency, obtained from pressure signal analysis, revealed that classical scaling approaches fail to capture the observed trends in three-phase flow.

Overall, this work contributes to the development of a comprehensive experimental database of key design parameters, introduces new modeling approaches for three-phase flows in inclined downward pipes, and highlights the limitations of applying modeling approaches originally developed for gas-liquid two-phase flows to this type of multiphase flow. Future research should extend the database to encompass a broader range of liquid viscosities, pipe inclinations, and fluid systems, while developing physically based models capable of accurately describing the complex interactions governing three-phase flows. Such advances will provide a stronger foundation for the design, optimization, and flow assurance of oil production and transportation systems involving high-viscosity three-phase flows.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors acknowledge the use of OpenAI's GPT-5.3 to enhance the language and clarity of this manuscript. The tool was exclusively used to refine phrasing, improve coherence, and ensure effective communication, without altering the scientific content.

CRediT authorship contribution statement

Igor Matteo Carraretto: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abderrahouf Arabi:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Luigi Pietro Maria Colombo:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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