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Physically-based models for predicting the bubbly-to-slug flow transition in vertical downward gas–liquid two-phase flow

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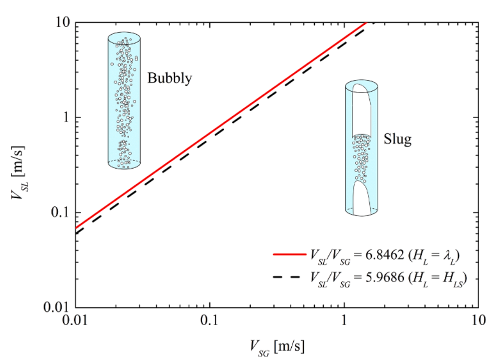
HIGHLIGHTS

- Novel models are proposed to predict the bubbly-to-slug flow transition in vertical downward gas-liquid two-phase flow.
- Two distinct approaches are employed, each based on a separate physical phenomenon associated with the transition.
- The resulting transition lines are nearly identical, confirming the internal consistency of the two approaches.
- Models' validation against a large experimental database (9.53 mm ≤ D≤ 80 mm) show highly satisfactory agreement.

GRAPHICAL ABSTRACT



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ABSTRACT

Accurately predicting flow regime transitions remains one of the key challenges in multiphase flow systems, with significant implications for design, safety, and operational reliability. In this study, novel models are introduced to predict the bubbly-to-slug flow transition in vertical downward gas–liquid flows. The transition to bubbly flow is defined in such a way that it reflects the disappearance of slug-like flow structures, offering a more intuitive physical interpretation of the underlying mechanisms. Two independent and physically meaningful criteria are proposed: (i) the onset of homogeneous flow behavior and (ii) the vanishing of the Taylor bubble. Based on these criteria, analytical expressions are derived using recent correlations for global and slug liquid holdups.

The resulting transition lines are nearly identical, underscoring the internal consistency and robustness of the proposed methodology. The models' performances were validated against an extensive experimental database from the literature and covering a broad range of pipe diameters (9.53 mm ≤ D≤ 80 mm). They showed excellent agreement with observed transitions in most cases, confirming their predictive accuracy.

1. Introduction

Gas–liquid two-phase vertical downward flow is notably encountered in applications such as water injection in petroleum reservoirs (Bouyahiaoui et al., 2024), gas condensate pipelines (Aliyu et al., 2016), carbon capture and storage (Hammer et al., 2021; Arabi et al., 2025c), heat exchangers, boilers and cooling systems (Wada et al., 2025; Ayegba et al., 2024, 2025), nuclear thermal hydraulics (Lokanathan and Hibiki, 2018), and in some chemical engineering processes (Roustan et al.,

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Nomenclature

D	Pipe diameter [m]
Eo	Eötvos number [-]
f_M	Friction factor [-]
Fr_L	Liquid Froude number [-]
H_L	Liquid holdup [-]
H_{LS}	Slug liquid holdup [-]
H_{LTB}	Taylor bubble liquid holdup [-]
L_{LS}	Liquid slug length [m]
L_{SU}	Slug unit length [m]
L_{TB}	Taylor bubble length [m]
V_G	Average gas velocity [m.s^{-1}]
V_L	Average liquid velocity [m.s^{-1}]
V_{SG}	Gas superficial velocity [m.s^{-1}]
V_{SL}	Liquid superficial velocity [m.s^{-1}]
Y_L	Dimensionless parameter [-]

Greek letters

λ_L	Input liquid fraction [-]
μ_L	Liquid viscosity [Pa.s]
ρ_G	Gas density [kg.m^3]
ρ_L	Liquid density [kg.m^3]
σ	Surface tension [N.m^{-1}]

Abreviation

ID	Inner diameter

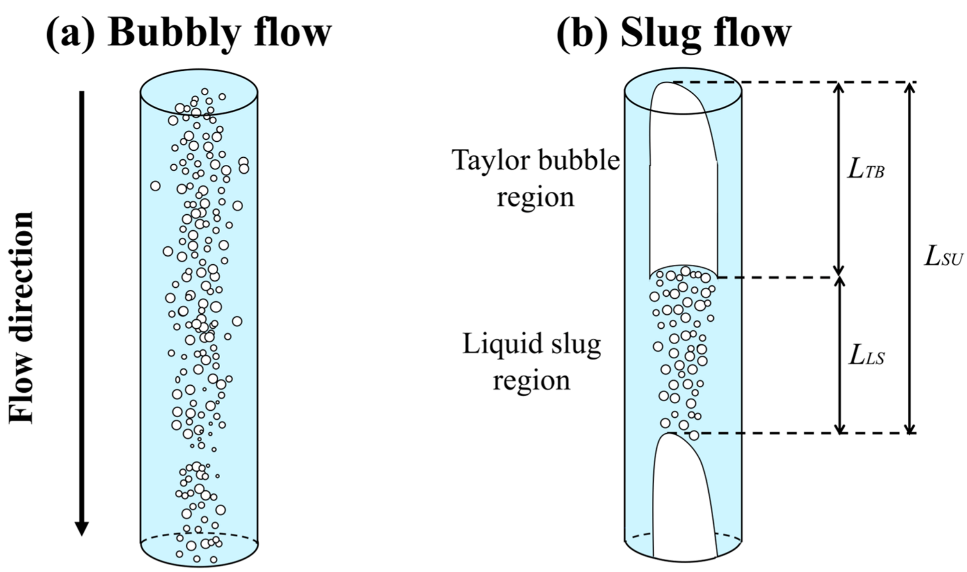

Fig. 1. Schematic of gas-liquid vertical downward bubbly and slug flows.

Table 1
Reported ranges of critical liquid holdup values for the bubbly-to-slug flow transition, as identified in previous experimental studies.

Authors and year	Pipe diameter [mm]	Range of liquid holdup of the bubble-to-slug flows transition
Usui and Sato (1989)	24	0.81-0.84
Jiang and Rezkallah (1993)	9.525	0.73-0.77
Xue et al. (2016)	25	0.66-0.72

1992; Marrocos et al., 2024). Although this flow configuration has been investigated since the 1960s, notably in the pioneering works of Hughmark (1963) and Golan and Stenning (1969), it remains comparatively less explored and understood than the vertical upward flow (Arabi et al., 2025b).

In the vertical downward two-phase flow, four dominant flow regimes are typically identified: bubbly, slug, churn-turbulent, and annular (Qiao et al., 2017). Each regime exhibits a distinct interfacial configuration, which significantly influences the underlying hydrodynamic behavior that are directly relevant to industrial design, performance, and reliability. Illustrations of bubbly and slug flow patterns observed in vertical downward configurations are presented in Fig. 1. In bubbly flow, the gas phase is dispersed as small, discrete bubbles within

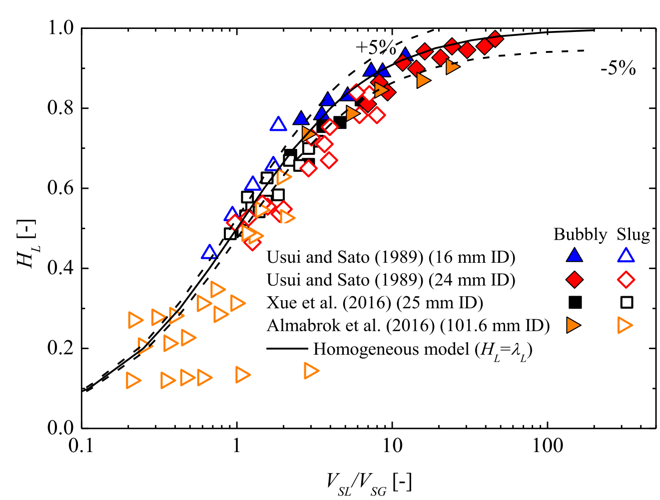

Fig. 2. Global liquid holdup measured by various authors in bubbly and slug flow regimes, plotted as a function of the liquid-to-gas superficial velocity ratio.

a continuous liquid phase. Note that this regime was referred to as dispersed bubble flow by Barnea et al. (1982), among others. In contrast,

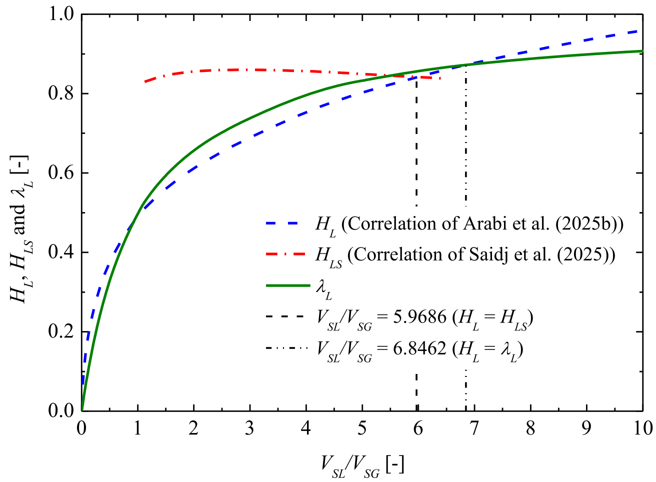

Fig. 3. Evolution of global liquid holdup, slug liquid holdup and homogenous liquid holdup as a function of liquid-to-gas liquid superficial velocity ratio.

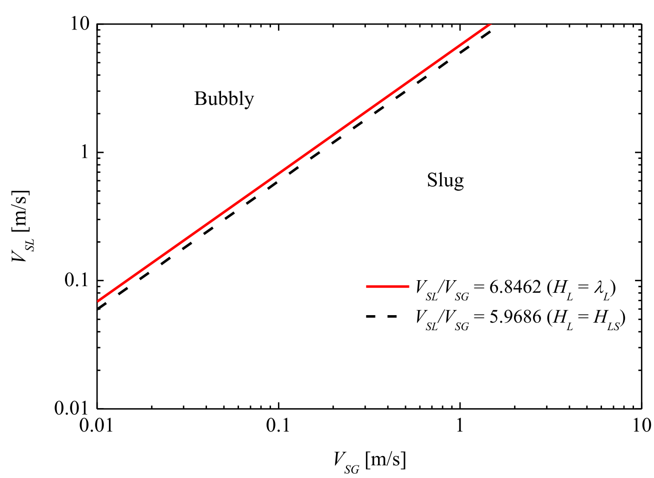

Fig. 4. Plot of the two bubbly-to-slug flow transition models in a V_{SL} vs V_{SG} plot.

slug flow is characterized by an alternating sequence of large Taylor bubbles, surrounded by a thin liquid film attached to the pipe wall, and liquid slugs, which contain small entrained gas bubbles. This structural feature explains why the liquid slug is traditionally considered as a bubbly/dispersed bubbles flow for modeling purposes (Barnea and Brauner, 1985; Andreussi et al., 1993a; Zhang et al., 2003a, 2003b; Mohammadi et al., 2019). Slug flow characteristic lengths are typically described by the parameters: liquid slug length (L_S), Taylor bubble length (L_{TB}), and slug unit length (L_{SU}). In addition, cross-sectional area fractions occupied by the liquid phase within the liquid slugs and within the Taylor bubbles are referred to as the slug liquid holdup (H_{LS}) and the Taylor bubble liquid holdup (H_{LTB}), respectively.

As discussed by Bouyahiaoui et al. (2024) and Arabi et al. (2025b), several authors have conducted comparative studies on flow regimes and the behavior of both global and local parameters in vertical upward and vertical downward flows. These comparisons highlight fundamental differences between the two configurations, which are mainly attributed to the opposing influence of buoyancy forces on inertial forces. This opposition significantly affects various flow regimes, particularly bubbly and slug flows.

For instance, gas bubbles tend to migrate toward the center of the pipe and exhibit rotational motion as the liquid superficial velocity increases in bubbly downward flow (Qiao et al., 2017, 2022). This behavior, referred to as the "coring" phenomenon (Hibiki et al., 2004), is explained by lift forces that tend to move the bubbles toward the center of the pipe (Hanratty, 2013). In slug flow, the buoyancy force affects the slip velocities inside the liquid slugs between dispersed bubbles and continuous liquid flow, which, according to Sekoguchi et al. (1996), has an impact on the shape of Taylor flow. The latter may exhibit an asymmetrical shape, as noted by Sekoguchi et al. (1996) and Aql and Al-Safran (2024) among others. This asymmetry explains why the distribution coefficient is less than unity in this pipe orientation, as reported by Martin (1976) and Aql and Al-Safran (2024). Saidj et al. (2025) further explained that the Taylor bubble translates at a lower velocity than the liquid slugs, causing the trailing slug to discharge onto the preceding Taylor bubble. Such interactions, along with the motion of entrained gas bubbles within the liquid slug, alter the slug aeration mechanism, making it distinct from that in vertical upward flow.

Gas-liquid vertical downward flow still presents unresolved complexities. To the best of the author's knowledge, the model proposed by Roustan et al. (1992) remains the only one-dimensional mechanistic model developed specifically for vertical downward flow to predict both global liquid holdup and pressure drop. Since mechanistic models are generally inherently dependent on the prevailing flow regime (Xiao et al., 1990, Arabi et al., 2025a,2025c), accurately identifying the transition between different flow regimes, particularly between bubbly and slug flow, is of critical importance. A closer examination of the bubbly-to-slug flow transition model developed by Usui (1989) reveals that it assumes a fixed critical global liquid holdup (H_L) for this transition, equal to 0.825. On the other hand, Lokanathan and Hibiki (2018) stated that the bubbly flow disaspears when $H_L = 0.945$. However, experimental results reported in the literature, as summarized in Table 1, indicate that this transition actually occurs over a range of liquid holdup values rather than at a single and sharply defined point. Consequently, using a fixed critical value of liquid holdup to model this transition can be considered questionable and may not capture the true variability observed in experiments.

In this short communication, we propose new models for predicting the bubbly-to-slug flow transition. The models are based on analyzing two key physical phenomena that characterize such transition and is constructed using recently developed predictive correlations available in the literature. To assess its validity, the proposed transition model is compared against experimental observations reported in the open literature.

2. Analysis and model development

Gas-liquid two-phase flows can be broadly classified into two main categories: homogeneous and non-homogeneous flows. In homogeneous flow, both phases travel at the same velocity, implying no slip between the gas and liquid phases. In contrast, non-homogeneous flow involves a velocity difference between the phases and can be further classified as either inertia-driven or buoyancy-driven flow. These correspond to conditions where the average gas velocity exceeds the average liquid velocity ($V_G > V_L$) and average liquid velocity exceeds the average gas velocity ($V_L > V_G$), respectively (Ghajar, 2020).

The existence of slippage between the phases can be identified by analyzing parameters such as the slip ratio, slip velocity, or slippage number, or by examining the relationship between liquid holdup and either the input liquid fraction (λ_L, as defined in Eq. 1) or the superficial velocity ratio (V_{SL}/V_{SG}) (Arabi et al., 2021).

$$\lambda_L = \frac{V_{SL}}{V_{SL} + V_{SG}} \tag{1}$$

In Fig. 2, we present the experimental results of liquid holdup measured for bubbly and slug flows by Usui and Sato (1989), Xue et al. (2016) and Almabrok et al. (2016) as a function of V_{SL}/V_{SG}. The figure clearly illustrates that the data corresponding to bubbly flow exhibits a behavior consistent with homogeneous flow ($H_L = \lambda_L$). For the vast

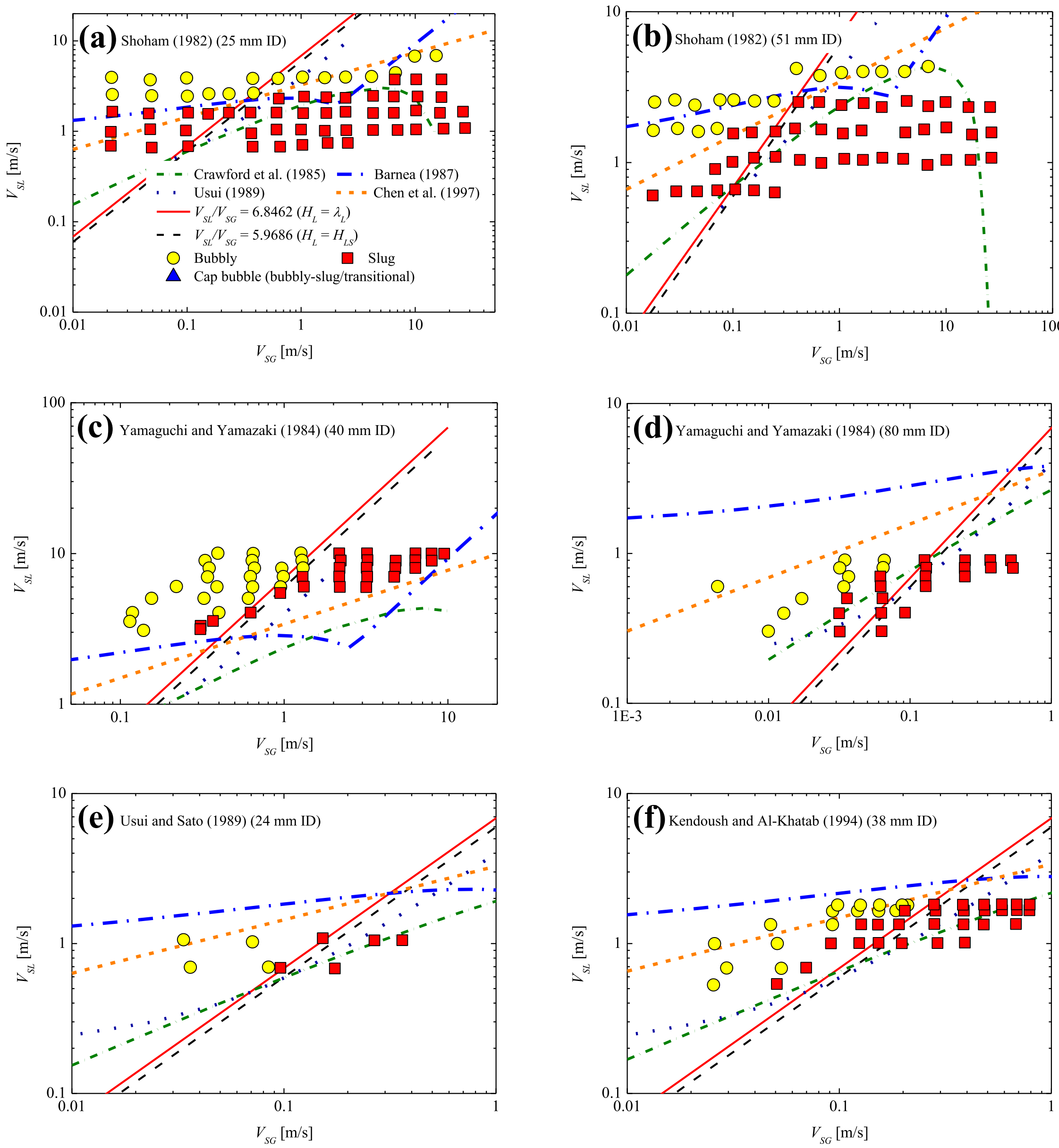

Fig. 5. Comparison of the prediction of the proposed and the existing bubbly-to-slug flows transition models with various experimental observations reported in the literature.

majority of data points, the deviation between measured liquid holdup and the input liquid fraction curve remains within ±5 %, a margin that is slightly lower than the typical uncertainty ranges associated with commonly used measurement techniques, as summarized recently in Arabi et al. (2025b). An examination of Fig. 2 reveals that the bubbly-to-slug flow transition corresponds to a broader transition from homogeneous to non-homogeneous flow. Therefore, based on this plot, one can reasonably claim that the slug flow emerges from bubbly flow when:

$$H_L = \lambda_L \quad (2)$$

As discussed in Section 1, slug flow consists of two distinct structures, the Taylor bubble and the liquid slug, each characterized by different liquid holdup values. The average liquid holdup within a slug unit can be calculated using Eq. 3 (Fernandes et al., 1983; Sylvester, 1987; Xiao et al., 1990; Andreussi et al., 1993b; Shoham, 2005).

$$H_L = \frac{L_{LS}}{L_{SU}} H_{LS} + \frac{L_{TB}}{L_{SU}} H_{LTB} \quad (3)$$

Considering that the fact that the liquid slug region can be viewed as bubbly/dispersed bubble flow according to Barnea and Brauner (1985), Brauner and Barnea (1986) and Zhang et al. (2003a), the transition to bubbly flow can be interpreted as the disappearance of the Taylor bubble region (Zhang et al., 2003a, 2003b). In this scenario, all the gas is transported in the form of dispersed bubbles within the continuous liquid phase. From Eq. 3, this transition can also be identified when:

$$H_L = H_{LS} \quad (4)$$

For gas-liquid vertical downward flow, Arabi et al. (2025b) recently developed a correlation for predicting global liquid holdup (Eq. 5). This correlation was validated against a comprehensive database encompassing a wide range of fluid mixtures, pipe diameters, flow regimes, and operating conditions. The authors reported that their model

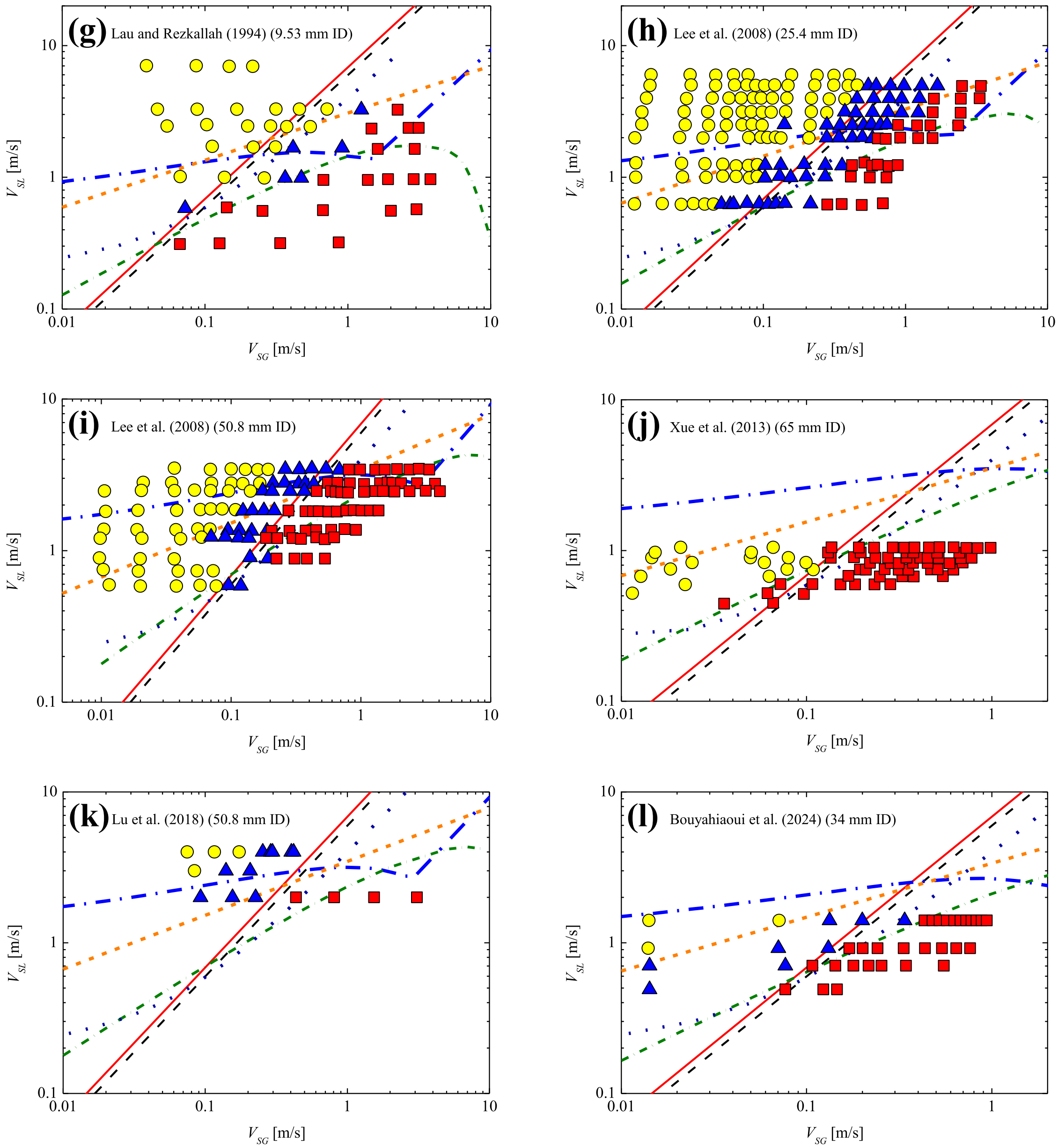

Fig. 5. (*continued*).

demonstrates superior reliability compared to existing correlations developed for vertical downward flow.

$$H_L = \frac{V_{SL}}{V_{SG}}\left(\lambda_L^{-0.4804} - 1\right)^{0.765} \tag{5}$$

It is important to note that the authors specified that when $H_L \geq 1$, the liquid holdup should be taken as equal to the input liquid fraction.

Recently, Saidj et al. (2025) proposed a model for slug liquid holdup in vertical downward flow (Eq. 6). This correlation, developed using experimental data obtained in a 34 mm ID pipe over the range of $1.12 \leq V_{SL}/V_{SG} \leq 6.54$, is based on insights from prior analyses conducted by Al-Sarkhi et al. (2024) and Al-Sarkhi and Fdleseed (2024).

$$H_{LS} = \frac{\lambda_L}{\left(\frac{2.0767}{1+\left(\frac{V_{SL}}{V_{SG}}\right)^{-0.4649}}\right) - 0.4287} \tag{6}$$

To determine the critical values of V_{SL}/V_{SG} at which the conditions defined by Eq. 2 and Eq. 4 occur, we plotted the evolution of homogeneous liquid holdup, global liquid holdup, and slug liquid holdup, as predicted by the correlations of Arabi et al. (2025b) and Saidj et al. (2025), respectively, as a function of V_{SL}/V_{SG} in Fig. 3. As shown in the figure, the homogeneous liquid holdup curve intersects the global liquid holdup curve at $V_{SL}/V_{SG} = 6.8462$, while the slug liquid holdup becomes equal to the global liquid holdup at $V_{SL}/V_{SG} = 5.9686$. Based on these two physical conditions, the bubbly-to-slug flow transition can be expressed as:

$$V_{SL} = 6.8462\ V_{SG} \tag{7}$$

$$V_{SL} = 5.9686\ V_{SG} \tag{8}$$

The proximity of the two critical V_{SL}/V_{SG} values explains why the corresponding transition lines appear nearly indistinguishable in the V_{SL} vs V_{SG} plot shown in Fig. 4. This result highlights the internal consistency of the proposed approach and reinforces the reliability of the two correlations developed by Arabi et al. (2025b) and Saidj et al. (2025).

Table 2
Prediction successful rates in % of the bubbly-to-slug flow transition models*.

Data source	Number of evaluated points	Proposed model ($H_L = \lambda_L$)	Proposed model ($H_L = H_{LS}$)	Crawford et al. (1985)	Barnea (1987)	Usui (1989)	Chen et al. (1997)
Shoham (1982) (25 mm)	65	73.85	75.38	66.15	**90.77**	73.85	86.15
Shoham (1982) (51 mm)	61	77.05	77.05	73.77	90.16	75.41	**95.08**
Yamazaki and Yamaguchi (1984) (40 mm)	50	90.00	**94.00**	48.00	48.00	84.00	48.00
Yamazaki and Yamaguchi (1984) (80 mm)	30	80.00	76.67	**93.33**	66.67	76.67	70.00
Usui and Sato (1989) (24 mm)	9	**100.00**	77.78	77.78	55.56	77.78	88.89
Kendoush and Al-Khatab (1994) (38 mm)	44	**84.09**	77.27	65.91	63.64	75.00	79.55
Lau and Rezkallah (1995) (9.53 mm)	42	90.48	90.48	90.48	88.10	**97.62**	90.48
Lee et al. (2008) (25.4 mm)	112	**100.00**	**100.00**	89.29	72.32	**100.00**	88.39
Lee et al. (2008) (51.8 mm)	114	**100.00**	97.37	79.82	69.30	92.98	90.35
Xue et al. (2013) (65 mm)	75	93.33	90.67	**94.67**	77.33	90.67	81.33
Lu et al. (2018) (50.8 mm)	8	**100.00**	**100.00**	87.50	**100.00**	**100.00**	**100.00**
Bouyahiaoui et al. (2024) (34 mm)	32	**100.00**	93.75	93.75	90.63	93.75	**100.00**
All database	642	**90.97**	89.41	79.91	75.23	87.85	84.58

* Bold numbers indicate, for each dataset, the best prediction.

3. Evaluation of the proposed and existing models

The proposed bubbly-to-slug flow transition models were evaluated using a comprehensive database of experimental observations collected for air-water mixture by various authors. The existing bubbly-to-slug flow transition models proposed by Crawford et al. (1985), Barnea (1987), Usui (1989) and Chen et al. (1997), summarized in Appendix A, were also included in the evaluation. In Fig. 5, the transition boundaries predicted by the six models are plotted alongside the experimental data, which span a wide range of pipe diameters (9.53 mm to 80 mm). The comparison shows a high level of agreement for the proposed models, demonstrating their reliability and predictive capability in capturing this flow transition.

The accuracy of the proposed models is particularly evident in the datasets of Lau and Rezakallah (1995), Lee et al. (2008), Lu et al. (2018), and Bouyahiaoui et al. (2024), all of which treat the bubbly-to-slug flow transition as a distinct regime, albeit with different terminologies. Particular attention should be given to the excellent agreement obtained for the two datasets reported by Lee et al. (2008), as shown in Fig. 5h and Fig. 5i. Unlike most studies, in which flow identification is based on visual observation, these authors employed an objective classification method using a neural network-based algorithm fed by void-fraction time series acquired with an impedance void meter. This approach significantly reduces the subjectivity typically associated with traditional visual flow regime identification methods, whether performed through direct observation or high-speed video analysis (Zhang et al., 2023).

The prediction performance of the developed models, as well as the four existing ones, was also evaluated by counting, for each bubbly and slug flow dataset, the number of data points correctly predicted by each model. For each dataset, the performance of a given model is quantified by the ratio of successful predictions to the total number of experimental data points. This methodology, originally proposed by Pereyra et al. (2012), was more recently employed by Arabi et al. (2026). The success rates (in %) of the six transition models for each dataset are summarized in Table 2. It is clear that the proposed models provide the best predictions, with success rates of 90.97 % and 89.41 %, which are around 90 %, the threshold commonly used to qualify a prediction as excellent (Boutaghane et al., 2023). It is also noted that the model based on the disappearance of the homogenous behavior ($H_L = \lambda_L$) yields slightly better predictions than the model based on the disappearance of Taylor bubble ($H_L = H_{LS}$) criterion.

4. Concluding remarks and future works

The transition from slug to bubbly flow can be physically interpreted as occurring when the flow becomes homogeneous and the liquid holdup within the liquid slug equals the global liquid holdup. Based on these two conditions, new expressions for predicting the bubbly-to-slug flow transition were derived using the recent correlations proposed by Arabi et al. (2025b) and Saidj et al. (2025), which estimate the global and slug liquid holdups, respectively, for gas-liquid vertical downward flow. The predictive performance of the two transition models, whose results are notably close, were validated using a comprehensive experimental database spanning a wide range of pipe diameters. They also best performed comparatively to existing bubbly-to-slug flow transition models.

Although the predictions of the two models are reliable, they present certain limitations. Specifically, the assumption of a generally homogeneous behavior for vertical downward bubbly flow, adopted in the first model, requires validation against a larger database covering notably a wider range of pipe diameters. In addition, the correlation of Saidj et al. (2025), used for $H_{LS} = H_L$ criterion, was developed based on a single pipe diameter and a limited dataset of 38 data points. Improving this correlation, particularly by accounting for the effect of pipe diameter, would enable a more accurate prediction of the flow regime transition using this criterion.

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

The authors acknowledge the use of OpenAI's ChatGPT-4o and ChatGPT-5o 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

Abderraouf Arabi: Writing – original draft, Visualization, Validation, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Youssef Stiriba:** Writing – review & editing, Project administration, Visualization. **Jordi Pallares:** Writing – review & editing, Project administration, Funding acquisition.

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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Appendix A. Summary of existing bubbly-to-slug flow transition models for gas-liquid vertical downward flow

Authors and year	Model
Crawford et al. (1985)	$\frac{V_{SG}}{\sqrt{gD}} = 0.117\left(\frac{V_{SL}+V_{SG}}{\sqrt{gD}}\right)^{1.6}$
Barnea (1987)	(a) $2\left[\frac{0.4\sigma}{(\rho_L-\rho_G)g}\right]^{\frac{1}{2}} = \left[0.725+4.15\left(\frac{V_{SG}}{V_{SL}+V_{SG}}\right)^{\frac{1}{2}}\right]\left(\frac{\sigma}{\rho_L}\right)^{\frac{3}{5}}\left(\frac{2f_M}{D}(V_{SL}+V_{SG})^3\right)^{-\frac{2}{5}}$
	(b) $V_{SL} = 0.923V_{SG}$
Usui (1989)	$3.76\left(\frac{V_{SG}}{V_{SL}}\right)+\frac{1.28}{Fr_L Eo^{0.25}} = 1$
	with $Fr_L = \sqrt{\frac{\rho_L}{(\rho_L-\rho_G)}}\frac{V_{SL}}{\sqrt{gD}}$ and $Eo = \frac{(\rho_L-\rho_G)gD^2}{\sigma}$
Chen et al. (1997)	$V_{SL} = 12.65\frac{Y_L}{Eo^{0.5}}V_{SG}$
	with $Y_L = \frac{(\rho_L-\rho_G)g}{0.092\left(\frac{\rho_L V_{SL}D}{\mu_L}\right)^{-2}\frac{\rho_L V_{SL}^2}{D}}$

Data availability

No data was used for the research described in the article.

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