encit 2020

ABCM Associação Brasileira de Engenharia e Ciências Mecânicas

18th Brazilian Congress of Thermal Sciences and Engineering
November 16–20, 2020 (Online)

ENC-2020-0346
CORRELATIONS REVIEW FOR THE SLUG LIQUID HOLDUP PREDICTION IN INTERMITTENT GAS-LIQUID FLOWS

Gabriel de Freitas Barboza[*]
Pedro Leineker Ochoski Machado[†]
Luiz Eduardo Melo Lima[‡]
Department of Mechanics, Federal University of Technology—Paraná—, Ponta Grossa, PR 84017-220, Brazil
[*]gabrielfreittasb@gmail.com, [†]pedmac@alunos.utfpr.edu.br, [‡]lelima@utfpr.edu.br

Abstract. *In the petroleum industry, the production and transportation of oil and gas is a classic example of a multiphase flows' occurrence. In turn, the gas-liquid flows do generally classified into three primary patterns: dispersed, separated, and intermittent. The latter consists of a unit cell which does divide into two regions that alternate along the pipe: an aerated liquid piston (slug region) and an elongated gas bubble in parallel with a thin liquid film (bubble region). The slug region aeration process is quite complex, difficulting its modeling. However, it is possible to estimate the slug liquid holdup from several correlations available in the literature. Thus, this study aims to present a comparative analysis of some of these correlations used to predict the slug liquid holdup. The correlations analyzed are calculated and compared against experimental data also available in the literature to check their limitations and accuracy. The results obtained in this study should demonstrate which correlations present more satisfactory results, although they are limited to the experimental data used for the realized comparison.*

Keywords: *two-phase flow, modeling, liquid holdup*

1. INTRODUCTION

The multiphase flows occurrence is observed in many industrial applications, e.g., in the petroleum industry, where oil and gas are produced from wellbores and transported through pipelines to the processing facilities (Shoham, 2006). The phases' spatial distribution defines a general classification of the gas-liquid flow in three primary patterns: dispersed, separated, and intermittent. The intermittent flow does form by the alternation of a slug or dispersed flow region (aerated liquid piston) followed by a bubble or separated flow region (elongated gas bubble in parallel with a thin liquid film), according to the unit cell concept proposed by Wallis (1969).

Several models are used to predict the film thickness in the bubble region as well as the phases' fractions and the pressure gradient of the unit cell. These models are dependent on parameters related to the nature of this flow pattern, e.g., the bubble nose velocity, the slug frequency, and the slug liquid holdup (i.e., the liquid fraction within the aerated piston) (Dukler and Fabre, 1994). The piston aeration process in the slug region is quite complicated and, consequently, makes modeling difficult. However, it is possible to estimate the slug liquid holdup from several correlations from the literature (Taitel and Barnea, 1990).

On the other hand, the slug liquid holdup in the intermittent flow can be measured experimentally, provided that appropriate instrumentation does use. However, for flows prediction achievement using simulators based on mechanistic models, e.g., the unit cell model by Taitel and Barnea (1990), it is frequently necessary to apply correlations that provide a reasonable estimate of the slug liquid holdup, among others parameters (Dukler and Fabre, 1994).

The limitations imposed by the operational conditions used to the development of the correlations constitute a barrier to allow the application of these correlations in a generalized way. Thus, correlation analysis is an alternative that can be used to assist in choosing one for a given application (Lima and Rosa, 2014).

According to Mishima and Ishii (1984), as well as Brauner and Barnea (1986), the piston collapse is attributed to excessive aeration, which may result in the short pistons formation. A mighty wake effect, created by the proximity of adjacent elongated bubbles, destabilizes the piston and destroys it when the gas fraction increases to a limiting value. This mechanism is one of responsible for the pattern transitions: slug to churn (Jayanti and Brauner, 1994) or slug to annular (Jamari *et al.*, 2008). Thus, there must be an applicability range for the slug liquid holdup correlations where no pattern transitions occur.

Dukler and Fabre (1994) discussed the requirement of an independent method to predict the slug liquid holdup to the solution of the averaged mass and momentum equations. They presented some data published and models proposed for radial and axial distributions of the slug liquid holdup, both vertical and horizontal tubes. It was observed quite large gradients in the local slug liquid holdup in the axial direction within the aerated piston. Besides, the models analyzed showed a dependence on superficial velocity and density of the gas, as well as the turbulence level and viscosity of the liquid, but the interfacial tension has a small effect.

Hale *et al.* (2005) verified the homogeneous assumption in the slug liquid holdup prediction for horizontal and almost horizontal flow cases of slug flow using an experimental circuit. The slug liquid holdup was determined using γ-tomography measurements. The results comparisons showed satisfactory agreement between the homogeneous unit cell model and experimental data for mixture superficial velocities above 6 m/s. At lower mixture superficial velocities, the model results under-predicts the experimental data for slug liquid holdup.

Lima and Rosa (2014) performed a comparative analysis of the wall shear models to the correlations for effective viscosity, slug frequency, and slug liquid holdup, by comparing the predicted pressure gradients as a function of the correlations' combination against two sets (vertical and horizontal) with 25 pairs experimental data for slug flows obtained by Lima (2011). Their results demonstrated a significant dependence on the correlations combination of the slug frequency and slug liquid holdup for closure in the phenomenological model.

To minimize the necessity of empirical correlations typically required to model the slug dynamics, Issa and Galleni (2015) presented an extension of the "slug capturing" technique to vertical slug flow. This approach uses the one-dimensional two-fluid model to predict slug flow behavior and has the advantage of being nearly entirely mechanistic. The results obtained by the model were compared with experimental data and showed satisfactory agreement.

Thus, the study aims to realize a comparison analysis of some correlations available in the literature to estimate the slug liquid holdup. The correlations results are compared against experimental data also available in the literature to check their limitations and accuracy to predict slug liquid holdup. The correlations accuracy should be presented in terms of the relative deviation modulus, RMS, etc., resulting from a computational code written in MATLAB® language.

2. LITERATURE REVIEW

This section presents details about the intermittent flow description and the slug liquid holdup correlations analyzed in this study.

2.1 Intermittent flow description

First, a brief description of the intermittent flow is given, which is represented schematically by Fig. 1, considering a mixture of gas (G) and liquid (L) flowing in a pipe of length L, diameter D, and inclination θ. The aerated piston exhibits velocity J and length L_S, exerting a wall shear stress τ_{WS}, and its dispersed gas bubbles present velocity U_B. The liquid fraction within the aerated piston, or slug liquid holdup, is represented by ϕ_S, and the liquid's velocity is U_S. The gas contained in the elongated bubble, with velocity U_T, displays velocity U_C, exerting a wall shear stress τ_{WC}. Also, in the elongated bubble region, the thin film with a fraction ϕ_F has a length L_F, thickness H_F, and velocity U_F, exerting a wall shear stress τ_{WF}. The interfacial shear stress is τ_I. The wetted perimeters by the gas S_C and liquid S_F, as well as the interfacial perimeter S_I, are shown at the pipe cross-section detail. A_C and A_F represent the areas occupied by gas and liquid, respectively (Carvalho and Lima, 2018).

The piston aeration process is a very complex phenomenon, so understanding and modeling are still in development. For a better representation of related phenoms, modeling proposals often assume the aerated piston divided into two regions: the elongated bubble's wake and the piston body. Guet *et al.* (2006) present an original modeling proposal for these phenomena. However, it becomes necessary for the solution of an eleven equations system. By definition, the slug liquid holdup ϕ_S corresponds to the ratio between the volume occupied by the liquid and the total piston volume as expressed by Eq. (1):

$$\phi_S = \frac{1}{L_S} \int_0^{L_S} \frac{A_S}{A} \mathrm{d}z_S \tag{1}$$

Where A_S is the cross-section area occupied by the liquid in the piston region, A is the pipe cross-section area, and z_S is the axial coordinate along with the piston length.

Despite disregard the radial and axial distributions of liquid in the piston, several empirical correlations are often used to estimate the slug liquid holdup. These correlations usually express ϕ_S as a function of the mixture superficial velocity J, as a mean value for the entire piston.

2.2 Slug liquid holdup correlations

For the refined oil flow, Gregory *et al.* (1978) obtained data from 167 experimental tests that were acquired using capacitance sensors. Therefore, from a curve adjustment of the slug liquid holdup as a function of the mixture superficial velocity, they have developed an empirical correlation that can be rewritten to include the pipe diameter effects. However, a dimensional inconsistency is present in their definition.

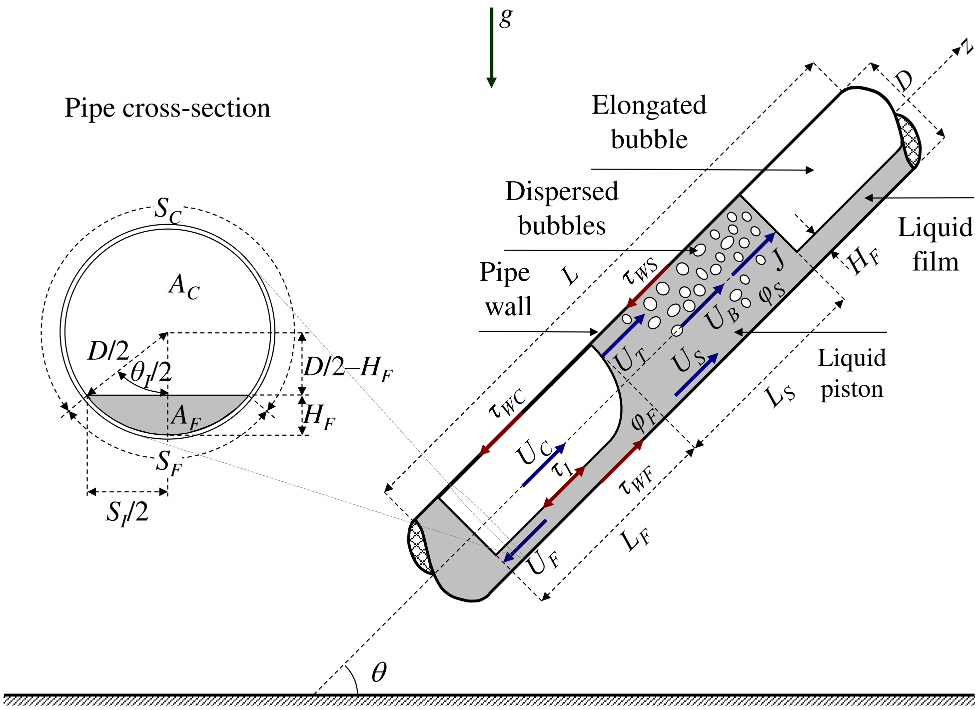

Figure 1. Schematic representation of the intermittent flow and its variables

From Gregory *et al.* (1978) experimental data, Malnes (1982) has proposed a modification in the original correlation of the Gregory *et al.* (1978) that includes additional parameters as surface tension and other fluids' properties, expressed by dimensionless numbers.

Based on a flow of natural gas and its condensate, Ferschneider (1983) developed a slug gas fraction (or slug liquid holdup) correlation that considers the fluids' properties in a 146 mm internal diameter pipe with an inclination varying from 0° to 4° with the horizontal.

For the development of a correlational model, Barnea and Brauner (1985) assumed a fully developed horizontal flow, with the gas in the piston behaving like dispersed bubbles, and using a balance between the breaking and coalescing forces of bubbles, calculated the gas fraction at the transition between the intermittent and dispersed flows, using the Taitel and Dukler (1976) model for the transition condition. Their correlation is a function of the mixture's superficial velocity. Showed satisfactory results when compared against data from Gregory *et al.* (1978).

In the development of a slug liquid holdup model for horizontal flows, Marcano *et al.* (1998) utilized a second-degree polynomial. The obtained correlation is a function of the mixture's superficial velocity.

Later, Gomez *et al.* (2000) used 283 experimental data from six different sources for the development of a slug liquid holdup correlation. The data utilized include several fluids and varying diameters and inclinations of the pipe. According to Su and Metcalfe (1997), the action of surface tension on the variation of slug liquid holdup is insignificant compared to the viscosity's effects. Therefore, the proposed correlation incorporates the mixture superficial velocity, the fluids' viscosities, and the diameter and inclination of the pipe. The Nuland (1999) data did not use on their correlation development. These data were used to compare their correlation's results, which showed the mean value of the relative deviation modulus of 14.2%.

Utilizing the same principle of Barnea and Brauner (1985), where the gas in the piston behaves like dispersed bubbles, Zhang *et al.* (2003) proposed a correlation model for the slug liquid holdup, through a balance between the turbulent kinetic energy of the liquid phase and the energy of the dispersed bubbles free surface. Their model considers the dispersed bubbles as spherical, further the shear stress influence on the pipe wall, and the *momentum* transfer between piston and film, which varies with the inclination, so the inclusion of this parameter increases their correlation's accuracy for inclination differents. Film velocity and fractions are parameters required for model closure.

The results collected for Zhang *et al.* (2003) correlation were compared with experimental data obtained by capacitance sensors, considering different inclinations and diameters, and presenting a satisfactory agreement with the experimental data for mixture superficial velocities larger than 0.1 m/s.

From 410 experimental data of horizontal flow, Al-Safran (2009) proposed a correlational model for slug liquid holdup. His correlation is dependent on a dimensionless parameter named *momentum* transfer rate between piston and film and depends on velocities of mixture, liquid, and gas, further the film fraction. His correlation was obtained using non-linear regression. For validation, data from Kokal (1987) was utilized.

Based on high viscosity fluids flow in a 50.8 mm internal diameter pipe, Kora *et al.* (2011) have developed a correlation for slug liquid holdup that employs forces of inertia, gravity, and viscous by using the viscosity and Froude numbers.

A slug liquid holdup correlation was established by Xu (2013) using 271 experimental data sets, where 228 data sets are for Newtonian fluids and the remainder for non-Newtonian fluids. His correlation is a function of the Reynolds number of the liquid phase and the pipe inclination.

Motivated by the small number of studies showing the viscosity effects on the liquid fraction in the piston, Al-Safran *et al.* (2015) proposed a correlational model for the slug liquid holdup for high viscosity fluids in horizontal flows. For this study, the liquid fraction data in the piston were acquired using capacitance sensors. From the dimensionless numbers found by Wallis (1969), using Buckingham's Pi theorem, to calculate the inertial and viscous forces in their model, the results obtained were compared with experimental high viscosity data acquired by Nuland (1999) and presenting a mean value of the relative deviation modulus of 11.35%.

From 68 experimental tests, Al-Ruhaimani *et al.* (2018) developed a correlation for slug liquid holdup, utilizing the inverse viscosity number to account for the fluid properties. Data were acquired based on vertical flows for pipe with an internal diameter of 50.8 mm. Following the Al-Ruhaimani *et al.* (2018) study, Abdul-Majeed and Al-Mashat (2019) proposed a model for slug liquid holdup applied to viscous fluids, but including horizontal, inclined, and vertical flow. From a quick closing valve system and capacitance sensors, the experimental data did obtain. Four correlations were developed, ranging from 0° to 90°, which in turn were used to produce a unified model that includes all inclinations. The model is a function of the Froude and viscosity numbers, i.e., as a function of fluids' properties, pipe diameter and inclination, and mixture superficial velocity. The model results were validated against data from Nuland (1999), with 89 data sets, Kora *et al.* (2011), with 144 data sets, both for horizontal, and Al-Ruhaimani *et al.* (2018), with 68 data sets, for vertical. Thus, they noted that the proposed model presents better results compared to the correlations used in its development.

From a dimensional analysis using Buckingham's Pi theorem, Archibong-Eso *et al.* (2019) defined the slug liquid holdup as a function of the viscosity, Froude, and Reynolds numbers, and the fluids' properties. Then, utilizing data from an electrical capacitance tomography, developed an empirical correlation applicable to viscous fluids. Their model covers a viscosity range of 0.189 Pa.s to 8.0 Pa.s and has a mean value of the relative deviation modulus of 0.07% compared to correlations proposed by Gregory *et al.* (1978), Malnes (1982), Kora *et al.* (2011), and Al-Safran *et al.* (2013).

The correlations of Zhang *et al.* (2003) and Al-Safran (2009) require a numerical solution to a film model. These models did not select for the present analysis due to the difficulty and the computational cost of obtaining this kind of solution. Thus, in this study were employed only linear algebraic correlations.

2.2.1 Correlations' summary

Table 1 summarizes the main characteristics of the models analyzed in this study: diameter, inclination, mixture superficial velocity, and fluids. This characteristics include pipe diameter and inclination, mixture superficial velocity, and fluids employed. The correlations are identified as C1 (Gregory *et al.*, 1978), C2 (Malnes, 1982), C3 (Ferschneider, 1983), C4 (Barnea and Brauner, 1985), C5 (Marcano *et al.*, 1998), C6 (Gomez *et al.*, 2000), C7 (Kora *et al.*, 2011), C8 (Xu, 2013), C9 (Al-Safran *et al.*, 2015), C10 (Al-Ruhaimani *et al.*, 2018), C11 (Abdul-Majeed and Al-Mashat, 2019), and C12 (Archibong-Eso *et al.*, 2019).

Table 1. Characteristics of the correlations analyzed in this study

Correlation	D / [mm]	θ / [°]	J / [m/s]	Fluids
C1	25.8 and 51.2	0	0.118 to 17.692	Air and refined oil
C2	25.8 and 51.3	0	0.118 to 17.693	Air and refined oil
C3	146	0 to 4	–	Natural gas and condensate
C4	–	0 to 90	–	–
C5	–	0	–	–
C6	51 and 203	0 to 90	–	Various fluids
C7	50.8	0	0.21 to 4.32	Air and viscous oil
C8	25.8 and 60	0 to 75	0.1 to 20	Various fluids
C9	50.8	0	0.2 to 4.3	Air and mineral viscous oil
C10	50.8	90	0.52 to 1.76	–
C11	80 and 100	0 to 90	0.2 to 4.14	Air and lubricant oil
C12	25.4 and 76.2	0	0.13 to 7.21	Air and viscous oil

Additionally, Tab. 2 presents the mathematical expressions that represent each of the correlations described in Tab. 1 to help understand the models' functional dependence.

Table 2. Definition of the correlations analyzed in this study

Correlation	ϕ_S
C1	$\left[1+(J/8.66)^{1.39}\right]^{-1}$
C2	$1-\left(1+\frac{83\sqrt{\Delta\rho/\rho_L}}{\mathrm{Eo}^{1/4}\mathrm{Fr}}\right)^{-1}$
C3	$\left[1+\mathrm{Eo}^{0.2}\mathrm{Fr}^2/50\right]^{-2}$
C6	$\exp\left[-\left(2.48\times10^{-6}\mathrm{Re}+0.45\theta\right)\right]$
C7	$\begin{cases}1 & \text{if } \mathrm{Fr}N_\mu^{0.2}\leq 0.15\\ 1.012\exp\left(-0.085\mathrm{Fr}N_\mu^{0.2}\right) & \text{if } 0.15<\mathrm{Fr}N_\mu^{0.2}<1.5\\ 0.9473\exp\left(-0.041\mathrm{Fr}N_\mu^{0.2}\right) & \text{if } \mathrm{Fr}N_\mu^{0.2}\geq 1.5\end{cases}$
C8	$\left[1+(J/9.514)^{1.274}\right]^{-1}$
C9	$0.85-0.075\psi+0.057\sqrt{\psi^2+2.27}$ [a]
C10	$\frac{0.266}{\sqrt{\mathrm{FrRe}}}+0.912$
C11	$1.016-0.000611\theta+(0.000124\theta-0.0195)\,\mathrm{Fr}N_\mu^{-0.2}$
C12	$1-0.0336\mathrm{Fr}N_\mu^{0.11}$

[a] Where: $\psi=\mathrm{Fr}N_\mu^{0.2}-0.89$.

As shown in Tab. 2, the Eötvös number, Eo, the mixture Froude number, Fr, the mixture Reynolds number, Re, the viscosity number, N_μ, among others parameters, are used to expressed the correlations, and its definitions are given by Eqs. (2), (3), (4), and (5).

$$\mathrm{Eo}=gD^2\Delta\rho/\sigma \quad (2)$$

$$\mathrm{Fr}=J/\sqrt{gD\Delta\rho/\rho_L} \quad (3)$$

$$\mathrm{Re}=JD/\nu_L \quad (4)$$

$$N_\mu=\mu_L\left[g\Delta\rho/\left(\rho_L^2\sigma^3\right)\right]^{1/4} \quad (5)$$

Where g is the gravitational acceleration, ρ is the density, μ is the dynamic viscosity, ν is the kinematic viscosity, σ is the surface tension, and the densities difference is $\Delta\rho=\rho_L-\rho_G$.

3. METHODOLOGY

This section presents some details about the correlations' analysis procedure and a brief description of the experimental data used in this comparison study.

3.1 Analysis procedure

The correlations accuracy is based on the determination of the mean value of the relative deviation modulus, ϵ_R, between the calculated (calc.) and measured (meas.) values to slug liquid holdup, ϕ_S. Also, the Root Mean Square (RMS) of the relative deviations is given, referring to the set of N experimental tests. Equations (6) and (7) express the ϵ_R and RMS definitions, respectively:

$$\epsilon_R=\frac{1}{N}\sum\left|\frac{\phi_S^{\text{calc.}}-\phi_S^{\text{meas.}}}{\phi_S^{\text{meas.}}}\right| \quad (6)$$

$$\mathrm{RMS}=\sqrt{\frac{1}{N}\sum\left(\frac{\phi_S^{\text{calc.}}-\phi_S^{\text{meas.}}}{\phi_S^{\text{meas.}}}\right)^2} \quad (7)$$

To calculate the results of each correlation and its auxiliary variables, as well as of the mean value of the relative deviation modulus and RMS, was using a computer code developed in MATLAB® language.

3.2 Experimental data

In this comparative analysis, the experimental data obtained by Souza (2013) was used. Their experiments were performed using an air-water mixture in a vertical test section of 306 diameters long and 26 mm internal diameter. Two separate circuits of air and water were carried to a mixer to form the two-phase flow. In the sequence, the air-water mixture passed through an acrylic test section, where the measurements were carried out at $77D$ and $257D$ downstream of the mixer. In these measuring stations, the intermittent flow was monitored through impedance sensors connected to a data acquisition system, used to obtain and process the data. After leaving the test section, the mixture is discharged into a vertical tube 75 mm internal diameter, which acts as an air-water separator. Table 3 shows the phases' superficial velocities and slug liquid holdup for each experimental test acquired by Souza (2013) experiments.

Table 3. Experimental tests realized by Souza (2013)

Test / [#]	J_L / [m/s]	J_G / [m/s]	ϕ_S
1	0.30	0.28	0.88
2	0.31	0.57	0.84
3	0.30	0.83	0.75
4	0.60	0.27	0.91
5	0.61	0.55	0.86
6	0.61	0.80	0.79
7	0.61	1.09	0.76
8	0.92	0.53	0.86
9	0.90	0.82	0.81
10	0.91	1.10	0.77
11	1.20	0.82	0.81
12	1.21	1.07	0.79
13	1.20	1.25	0.76

For the calculations performed with the correlations analyzed, the pressure of 945 mbar and the temperature of 25 °C were used to obtain the fluid's properties. The air density was taken considering it as an ideal gas.

4. RESULTS AND DISCUSSIONS

This section presents the results obtained from the analysis performed for the calculated values of each correlation of slug liquid holdup in comparison to the experimental data collected by Souza (2013). Table 4 shows the mean value of the relative deviation modulus and RMS for each correlation analyzed.

Table 4. Mean value of the relative deviation modulus and its RMS for the correlations analyzed in this study

Correlation	ϵ_R / [%]	RMS / [%]
C1	12.78	13.83
C2	10.76	11.89
C3	13.73	14.91
C4	19.35	20.35
C5	19.44	20.43
C6	45.57	45.64
C7	18.80	19.68
C8	12.10	13.18
C9	18.62	19.49
C10	12.46	14.11
C11	16.45	17.35
C12	18.17	19.12

The results obtained are also presented graphically in Fig. 2. In all graphs, the abscissa and ordinate axes represent the slug liquid holdup measured and calculated, respectively. The diagonal dashed line represents the occurrence of none relative deviation, 0%, and the other near dashed lines represent the relative deviation limits of $\pm 20\%$. Each graph contains sets of three correlations grouped according to the mean value of the relative deviation modulus to make easy the comparison.

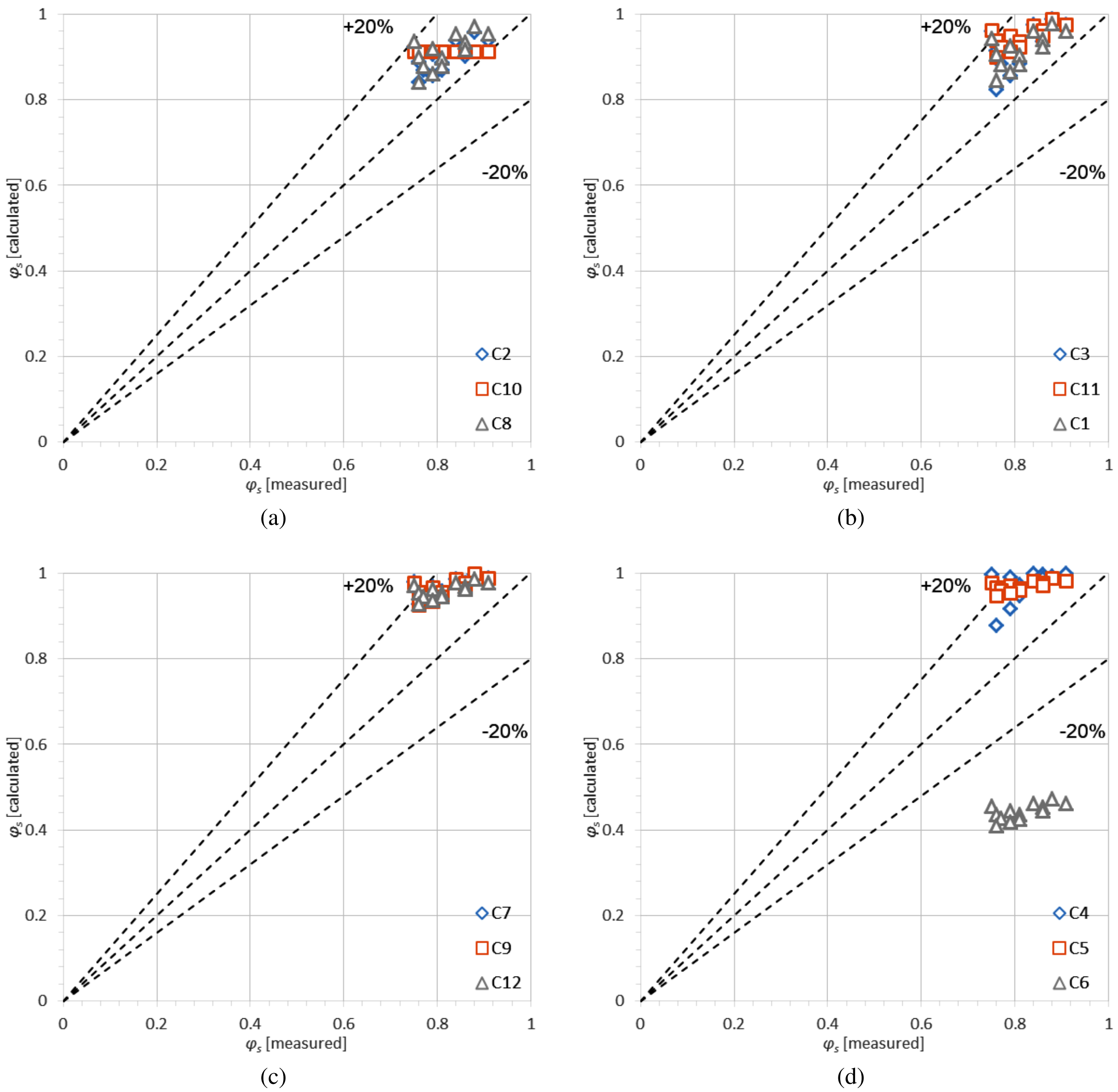

Figure 2. Numerical-experimental comparison of the slug liquid holdup correlations: (a) C2, C10 and C8; (b) C3, C11 and C1; (c) C7, C9 and C12; (d) C4, C5 and C6

The correlations that presented the lowest mean values of the relative deviation modulus are C2, C8, and C10, being represented graphically in Fig. 2a. Although developed for horizontal flow, the C2 correlation showed a satisfactory agreement with the experimental vertical flow data, with the lowest mean value of the relative deviation modulus.

Correlations C1, C3, and C11 performed satisfactorily, keeping the mean values of the relative deviation modulus below 17%, as shown in Fig. 2b. Correlation C1 covers horizontal flows, whereas correlation C3 was developed covering horizontal and slightly inclined flows. Therefore, the mean values of the relative deviation modulus and its RMS obtained for these correlations are justified. For the correlation C11, there is a difference between the diameter used in the model proposed and the experimental data of Souza (2013) used in this analysis.

Figure 2c shows the correlations C7, C9, and C12, which present the mean values of the relative deviation modulus below 20%. These correlations are applicable for horizontal flows, so this is the expected behavior.

The correlations C4, C5, and C6 shown in Fig. 2d presented the highest mean values of the relative deviation modulus. The correlation C6 demonstrated the worst agreement with experimental data, with 45% of the relative deviation modulus value. The divergence presented is still discrepant and the model showed ineffective for the experimental data used in the comparison. The correlation C6 was developed utilizing data that covers vertical flow,however, there were no comparisons with other data sets that included flow at 90°. Therefore, the need for a more extensive data set for correlation development is one of the justifications for the result obtained.

5. CONCLUSIONS

In the present study, were analyzed some correlations for the slug liquid holdup. The experimental data of the slug liquid holdup acquired by Souza (2013) for vertical flow were used to the analysis. Thus, it was possible to verify the accuracy of each correlation analyzed against reference data, evaluating the models' behavior when applied under different conditions from those adopted in its development. The correlations C2 (Malnes, 1982) and C8 (Xu, 2013), even being developed for flow conditions different from the experimental data, presented the best performances.

The most significant relative deviation values result from the fact that several conditions were applied to obtain the experimental data sets for the development of each correlation. From the analysis performed, it was possible to verify which models maintained a satisfactory performance when comparing with data of different nature, keeping the mean values of the relative deviation modulus less than 20%. The correlation C6 (Gomez *et al.*, 2000) is an exception, which presented a considerable disagreement with the experimental data used as a reference.

Similar analyses can be performed to include more correlations from literature as well as to use a more comprehensive set of experimental data under various conditions (diameters, inclinations, fluids, velocities, etc.).

6. ACKNOWLEDGEMENTS

The authors thank the Federal University of Technology—Paraná—for the resources made available.

7. REFERENCES

Abdul-Majeed, G.H. and Al-Mashat, A.M., 2019. "A unified correlation for predicting slug liquid holdup in viscous two-phase flow for pipe inclination from horizontal to vertical". *SN Applied Sciences*, Vol. 1, No. 1. ISSN 2523-3971. DOI 10.1007/s42452-018-0081-0.

Al-Ruhaimani, F., Pereyra, E., Sarica, C., Al-Safran, E. and Torres, C., 2018. "Prediction of slug-liquid holdup for high-viscosity oils in upward gas/liquid vertical-pipe flow". *SPE Production & Operations*, Vol. 33, No. 2, pp. 281–299. ISSN 1930-1855. DOI 10.2118/187957-PA.

Al-Safran, E., Kora, C. and Sarica, C., 2013. "Prediction of liquid volume fraction in slugs in two-phase horizontal pipe flow with high viscosity liquid". In *Proceedings of the 16th International Conference on Multiphase Production Technology, Cannes, France*. BHR Group, OnePetro, Richardson, TX, USA. Document ID BHR-2013-H4.

Al-Safran, E., 2009. "Prediction of slug liquid holdup in horizontal pipes". *Journal of Energy Resources Technology*, Vol. 131, No. 2. ISSN 0195-0738. DOI 10.1115/1.3120305.

Al-Safran, E., Kora, C. and Sarica, C., 2015. "Prediction of slug liquid holdup in high viscosity liquid and gas two-phase flow in horizontal pipes". *Journal of Petroleum Science and Engineering*, Vol. 133, pp. 566–575. ISSN 0920-4105. DOI 10.1016/j.petrol.2015.06.032.

Archibong-Eso, A., Okeke, N.E., Baba, Y., Aliyu, A.M., Lao, L. and Yeung, H., 2019. "Estimating slug liquid holdup in high viscosity oil-gas two-phase flow". *Flow Measurement and Instrumentation*, Vol. 65, pp. 22–32. ISSN 0955-5986. DOI 10.1016/j.flowmeasinst.2018.10.027.

Barnea, D. and Brauner, N., 1985. "Holdup of the liquid slug in two phase intermittent flow". *International Journal of Multiphase Flow*, Vol. 11, No. 1, pp. 43–49. ISSN 0301-9322. DOI 10.1016/0301-9322(85)90004-7.

Brauner, N. and Barnea, D., 1986. "Slug/Churn transition in upward gas-liquid flow". *Chemical Engineering Science*, Vol. 41, No. 1, pp. 159–163. ISSN 0009-2509. DOI 10.1016/0009-2509(86)85209-5.

Carvalho, G.L. and Lima, L.E.M., 2018. "A review of frequency correlations for the intermittent gas-liquid flow in horizontal pipes". In *Proceedings of the 17th Brazilian Congress of Thermal Sciences and Engineering (ENCIT), Águas de Lindóia, SP, Brazil*. UNICAMP and EESC-USP, Brazilian Association of Engineering and Mechanical Sciences (ABCM), Rio de Janeiro, RJ, Brazil. DOI 10.26678/abcm.encit2018.cit18-0251. Paper ID ENCIT-2018-0251.

Dukler, A.E. and Fabre, J., 1994. "Gas-liquid slug flow: knots and loose ends". *Multiphase Science and Technology*, Vol. 8, No. 1-4, pp. 355–469. ISSN 0276-1459. DOI 10.1615/multscientechn.v8.i1-4.80.

Ferschneider, G., 1983. "Ecoulements diphasiques gaz-liquide à poches et à bouchons en conduites". *Revue de l'Institut Français du Pétrole*, Vol. 38, No. 2, pp. 153–182. ISSN 0020-2274. DOI 10.2516/ogst:1983010. Oil & Gas Science and Technology.

Gomez, L.E., Shoham, O. and Taitel, Y., 2000. "Prediction of slug liquid holdup: horizontal to upward vertical flow". *International Journal of Multiphase Flow*, Vol. 26, No. 3, pp. 517–521. ISSN 0301-9322. DOI 10.1016/s0301-9322(99)00025-7.

Gregory, G.A., Nicholson, M.K. and Aziz, K., 1978. "Correlation of the liquid volume fraction in the slug for horizontal gas-liquid slug flow". *International Journal of Multiphase Flow*, Vol. 4, No. 1, pp. 33–39. ISSN 0301-9322. DOI 10.1016/0301-9322(78)90023-x.

Guet, S., Decarre, S., Henriot, V. and Liné, A., 2006. "Void fraction in vertical gas-liquid slug flow: influence of liquid slug content". *Chemical Engineering Science*, Vol. 61, No. 22, pp. 7336–7350. ISSN 0009-2509. DOI

10.1016/j.ces.2006.08.029.

Hale, C.P., Hewitt, G.F., Manolis, I.G., Mendes, M.A., Richardson, S.M. and Wong, W.L., 2005. "Experimental and analytical studies of gas entrainment phenomena in slug flow in horizontal and near horizontal pipes". *Multiphase Science and Technology*, Vol. 17, No. 1-2, pp. 147–168. ISSN 0276-1459. DOI 10.1615/multscientechn.v17.i1-2.80.

Issa, R.I. and Galleni, F., 2015. "Mechanistic simulation of slug flow in vertical pipes using the one-dimensional two-fluid model". *Multiphase Science and Technology*, Vol. 27, No. 2-4, pp. 229–245. ISSN 0276-1459. DOI 10.1615/multscientechn.v27.i2-4.90.

Jamari, S., Hale, C.P., Hewitt, G.F. and Richardson, S.M., 2008. "Studies of the slug-annular regime transition in two-phase flow in horizontal pipes". *Multiphase Science and Technology*, Vol. 20, No. 1, pp. 1–24. ISSN 0276-1459. DOI 10.1615/multscientechn.v20.i1.10.

Jayanti, S. and Brauner, N., 1994. "Churn flow". *Multiphase Science and Technology*, Vol. 8, No. 1-4, pp. 471–521. ISSN 0276-1459. DOI 10.1615/multscientechn.v8.i1-4.90.

Kokal, S.L., 1987. *An experimental study of two phase flow in inclined pipes*. Ph.D. thesis, University of Calgary, Calgary, Alberta, Canada. DOI 10.11575/PRISM/14066. URL `http://hdl.handle.net/1880/23721`.

Kora, C., Sarica, C., Zhang, H.q., Al-Sarkhi, A. and Al-Safran, E., 2011. "Effects of high oil viscosity on slug liquid holdup in horizontal pipes". In *Proceedings of the Canadian Unconventional Resources Conference, Calgary, Alberta, Canada*. Society of Petroleum Engineers (SPE), OnePetro, Richardson, TX, USA. DOI 10.2118/146954-ms. Document ID SPE-146954-MS.

Lima, L.E.M., 2011. *Análise do modelo de mistura aplicado em escoamentos isotérmicos gás-líquido*. Ph.D. thesis, Faculdade de Engenharia Mecânica, Universidade Estadual de Campinas, Campinas, SP, Brazil. URL `http://repositorio.unicamp.br/jspui/handle/REPOSIP/264105`. In Portuguese.

Lima, L.E.M. and Rosa, E.S., 2014. "Comparative analysis of wall shear stress models to the drift-flux model applied to slug flow regime". *Journal of Petroleum Science and Engineering*, Vol. 122, pp. 371–383. ISSN 0920-4105. DOI 10.1016/j.petrol.2014.07.032.

Malnes, D., 1982. "Slug flow in vertical, horizontal and inclined pipe". Technical report, Institute for Energy Technology, Kjeller, Norway. Report IFE/KR/E-83/002.

Marcano, R., Chen, X.T., Sarica, C. and Brill, J.P., 1998. "A study of slug characteristics for two-phase horizontal flow". In *Proceedings of the International Petroleum Conference and Exhibition of Mexico, Villahermosa, Mexico*. Society of Petroleum Engineers (SPE), OnePetro, Richardson, TX, USA. DOI 10.2118/39856-ms. Document ID SPE-39856-MS.

Mishima, K. and Ishii, M., 1984. "Flow regime transition criteria for upward two-phase flow in vertical tubes". *International Journal of Heat and Mass Transfer*, Vol. 27, No. 5, pp. 723–737. ISSN 0017-9310. DOI 10.1016/0017-9310(84)90142-X.

Nuland, S., 1999. "Bubble fraction in slugs in two-phase flow with high viscosity liquids". In *Proceedings of the International Symposium on Two-phase Flow Modeling and Experimentation, Pisa, Italy*. Vol. 2, pp. 731–738.

Shoham, O., 2006. *Mechanistic modeling of gas-liquid two-phase flow in pipes*. Society of Petroleum Engineers (SPE), Richardson, TX, USA. ISBN 9781555631079.

Souza, M.A.S.F., 2013. *Caracterização experimental da fração de gás no escoamento vertical intermitente gás-líquido*. Ph.D. thesis, Faculdade de Engenharia Mecânica, Universidade Estadual de Campinas, Campinas, SP, Brazil. URL `http://repositorio.unicamp.br/jspui/handle/REPOSIP/264090`. In Portuguese.

Su, C. and Metcalfe, R.W., 1997. "Influences of liquid properties on gas entrainment at the bottom of a fixed bubble". In *Proceedings of the ASME Fluids Engineering Division Summer Meeting, Vancouver, British Columbia, Canada*. American Society of Mechanical Engineers (ASME), New York, NY, USA.

Taitel, Y. and Barnea, D., 1990. "Two-phase slug flow". In *Advances in Heat Transfer*, Elsevier BV, Vol. 20, pp. 83–132. DOI 10.1016/s0065-2717(08)70026-1.

Taitel, Y. and Dukler, A.E., 1976. "A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow". *AIChE Journal*, Vol. 22, No. 1, pp. 47–55. ISSN 1547-5905. DOI 10.1002/aic.690220105.

Wallis, G.B., 1969. *One-dimensional two-phase flow*. McGraw-Hill, New York, NY, USA. ISBN 9780070679429.

Xu, J.y., 2013. "A simple correlation for prediction of the liquid slug holdup in gas/non-Newtonian fluids: horizontal to upward inclined flow". *Experimental Thermal and Fluid Science*, Vol. 44, pp. 893–896. ISSN 0894-1777. DOI 10.1016/j.expthermflusci.2012.06.017.

Zhang, H.Q., Wang, Q., Sarica, C. and Brill, J.P., 2003. "A unified mechanistic model for slug liquid holdup and transition between slug and dispersed bubble flows". *International Journal of Multiphase Flow*, Vol. 29, No. 1, pp. 97–107. ISSN 0301-9322. DOI 10.1016/s0301-9322(02)00111-8.

8. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.