

## ENCIT-2018-0251

# A REVIEW OF FREQUENCY CORRELATIONS FOR THE INTERMITTENT GAS-LIQUID FLOW IN HORIZONTAL PIPES

**Gislaine Letícia Carvalho**

**Luiz Eduardo Melo Lima**

Federal University of Technology – Paraná, Academic Department of Mechanics  
Monteiro Lobato Avenue, km 4, Jardim Carvalho, 84016-210, Ponta Grossa, Paraná, Brazil  
leticia.glc52@gmail.com, lelima@utfpr.edu.br

**Abstract.** *Gas-liquid two-phase flows are found in several industrial processes and in nature, which in turn can be classified into three main patterns: dispersed, separated and intermittent. Intermittent flow is characterized as a combination of a dispersed flow region, an aerated liquid piston, and a separate flow region, elongate gas bubble in parallel with a liquid film, thereby constituting a unit cell, which flows along a pipe with a certain frequency. This frequency is considered one of the fundamental characteristic of this flow type. Thus, in the present work, it is proposed to carry out a study concerning the models (correlations) available in the literature to estimate the intermittent flow frequency. The frequency correlations analyzed in this study are calculated and compared against experimental data also available in the literature for horizontal pipes, in order to verify which are more accurate, as well as their limitations for any applications. The results obtained in this analysis showed that although some frequency correlations have satisfactory results, it is not yet possible to apply them comprehensively, taking into account the different experimental configurations that may occur, such as variations in pipe diameters and fluid properties.*

**Keywords:** *two-phase flow, modeling, slug, frequency, correlations.*

## 1. INTRODUCTION

The multiphase flows are characterized by the presence of two or more immiscible phases or components and they may present themselves in the following combinations: gas-solid, gas-liquid, liquid-solid, liquid-liquid, liquid-liquid-gas and others (Vicencio, 2013). Being the two-phase flow of gas and liquid one of the simplest and most common case found in several industrial processes.

According to the way each phase is distributed in space, the flow can be classified in three main patterns: dispersed, separated and intermittent. Which in turn, these main patterns can be sub-classified according to the peculiarities of the arrangements formed. The intermittent flow (or slug flow) is characterized by the alternation of a dispersed flow region (an aerated liquid piston) followed by a separated flow region (elongate gas bubble in parallel with a liquid film), being this set denominated unit cell (Wallis, 1969), which interact kinematically and dynamically along the flow in the pipe. The regions of aerated liquid piston exhibit a large amount of liquid with small dispersed bubbles and represents a barrier between two adjacent elongated gas bubbles (Rodrigues, 2009).

Gas-liquid two-phase flows occur in several industrial applications, for example in chemical, oil and nuclear industry, in geothermal power plants and others (Shoham, 2006). In the oil industry, the fluids (gas and oil) mixture exiting the reservoir is transported through pipelines to the stationary production unit, where the phases are separated and processed. Part of the route done by this mixture can occur in the intermittent pattern, thus the study of this type of flow has become increasingly important because of the long distances this mixture must travel.

Due to intermittency nature of the slug flow, occurs variations in the phase fractions and in the mixture pressure that should be predicted in the processing plant, as well as its sizing criteria in projects, because at a certain moment there is the coming of just liquid, in the form of a piston, and at another moment the coming of a large amount of gas, in the form of an elongated bubble.

The alternation frequency of the regions formed by the liquid piston and elongated gas bubble in a specific section of the production line can generate vibrations, which if not monitored correctly, may cause resonance, besides to compromising the safety of installations. For this reason, it is of great importance to model the slug flow and the understanding of the phenomena that occur to predict anomalies and avoid damages or waste of production (Rodrigues, 2009).

Another important aspect associated to the intermittent flow frequency is its influence on the length of the unit cell (aerated liquid piston and elongated gas bubble), which in turn influences the magnitudes of the contributions of friction and gravitational in the mixture pressure gradient (Lima and Rosa, 2014, 2015), that should be predicted to the project, sizing, and operations of production equipment.

In many cases, the frequency of the intermittent flow can be measured experimentally, provided that appropriate instrumentation is used. However, for flow prediction achievement using simulators, which are often based on mechanistic models, for example, Taitel and Barnea (1990) model, it becomes necessary to apply sub-models or correlations that provide a reasonable estimate of the intermittent flow frequency. The problem is that many of these correlations, for the frequency estimate of intermittent flow available in the literature, have limitations imposed by the empirical conditions which were developed. Thus, the aim of this work is to realize a comparative analysis of correlations available in the literature for estimating the intermittent flow frequency against experimental data also available in the literature, in order to identify which are more accurate, as well as their limitations of applications, and how they behave when applied in different conditions of those in which they were obtained.

## 2. CORRELATIONS FOR FREQUENCY CALCULATION

In this section is presented a theoretical review of the correlations for intermittent flow frequency, as well as the analyzed correlations definitions.

### 2.1 Theoretical review of the correlations

Several correlations have been developed to predict the intermittent flow frequency, varying from simple algebraic correlations, such as Gregory and Scott (1969) and Heywood and Richardson (1979), up to more complex correlations taking into account pipe length and important mechanistic variables, such as Hill *et al.* (1990) and Hill *et al.* (1994).

Gregory and Scott (1969) developed a model to calculate the intermittent flow frequency. Using a 19 mm inner diameter pipe and carbon dioxide and water as fluids, the authors conducted an experiment which they could to obtain frequency data measured by two techniques, one through visual observations, where the number of unit cell were counted passing in a specific point in the test section in a measured time period with a stopwatch, and the other through counting the number of unit cells pressure pulses recorded by the pressure measurement system in a certain time period. Both measurement methods were considered satisfactory. The authors demonstrated that there is a direct dependence of the frequency with the liquid superficial velocity and an indirect dependence in relation to the pipe diameter.

Following the same concepts of Gregory and Scott (1969), Heywood and Richardson (1979) correlated the mean frequency with the mixture Froude number, diameter and volumetric fraction of liquid for an experiment carried out in a 42 mm inner diameter pipe and an air-water mixture. By of the gamma ray absorption method, it was realized a scanning of a vertical pipe cross-section, which it was possible to obtain the Power Spectral Density (PSD) of the liquid fraction to determine the mean values of the thickness of the liquid film and liquid fraction in the piston, as well as the frequency and the unit cell length. The mean frequency was estimated to be the maximum frequency value obtained from PSD.

Nydal (1991) performed an experimental analysis using an air-water mixture as the test fluid in pipes with diameters ranging from 31 mm to 90 mm. From this analysis, the author proposed a correlation based on the liquid flow rate, arguing that the intermittent flow frequency depends strongly on the liquid superficial velocity and depends weakly on the gas superficial velocity (Hernandez-Perez *et al.*, 2010; Schulkes *et al.*, 2011).

Jepson and Taylor (1993) observed that the pipe diameter has great influence on the flow characteristics, such as frequency, length, velocity and pressure gradient. According to the authors, the most part of the studies are for smaller diameters pipes, therefore, their experiment was performed using a 30 mm inner diameter pipe for an air-water mixture and the results obtained were compared with the existing data for 25.4 mm and 51.2 mm inner diameters pipe. It was observed that the frequency decreases as the liquid superficial velocity decreases and that occurs an increase when the pipe diameter increases, for a given gas superficial velocity value.

Manolis *et al.* (1995) acquired experimental data for frequency, in high pressure, in a horizontal pipe and using the air-water mixture as the test fluid. The frequency was estimated through by counting the number of unit cells passing at a fixed point during a certain time period. Gokcal *et al.* (2009) state that the results of this experiment show that there is no significant pressure effect on the intermittent flow frequency, and when the experimental data are compared with Gregory and Scott (1969) correlation, the results present poor agreement, except for lower frequency values. In spite of, the proposed correlation, developed modifying the Gregory and Scott (1969) correlation, presented better prediction when compared with experimental data for high pressure.

The Shell correlation (Zabaras *et al.*, 1999; Al-Safran, 2009) was obtained from a curve fitting for the Heywood and Richardson (1979) experimental data, using five dimensionless parameters. Although the Shell correlation doesn't have functional dependence with an inclination angle, it showed a good concordance with sloped pipe data acquired by the company "Shell" in an air-water flow system in a 101.6 mm inner diameter pipe.

Investigating to develop a correlation, Fossa *et al.* (2003) used an air-water mixture as test fluids in a horizontal test section with 12 m long, which pressure and gas fraction measurements were obtained. The pipes used in the experiment had 40 mm and 60 mm inner diameter and the data collected presented a satisfactory result against literature data of several authors. The authors suggested a new method through of an algorithm that consists in the statistical mean values gas fractions analysis, in the cross-section, obtained through ring type impedance probes to obtain information about the

main flow characteristics of the flow, such as the unit cell frequency. The method could be validated by comparison among calculated parameters, through collected data for the gas fraction, and measured data, through scanned images and cross-correlation procedures, presenting a relative maximum deviation of about 15%.

Shea *et al.* (2004) developed a correlation obtained from a curve fitting for field data that strongly depends on the mixer's axial distance to the measuring position. The study carried out by authors indicates satisfactory agreement among data measured in the laboratory and data obtained from the field (Al-Safran, 2009).

Wang *et al.* (2007) conducted an experiment in a horizontal test section 133 m long, in a 50 mm inner diameter pipe and an air-water mixture. The unit cell frequency, as well as other hydrodynamic parameters, was determined along the test circuit for a range of input flow rates using two pairs of conductivity probes located away from the pipe inlet. Through the experiment, they realized that the average frequency increases as the liquid superficial velocity increases, however, it depends weakly on the gas superficial velocity. The correlations proposed by Wang *et al.* (2007) and Fossa *et al.* (2003) were written in the dimensionless form using the Strouhal number and, although both were developed based in experiments using test sections with different lengths, both presented satisfactory results.

Gokcal *et al.* (2009) carried out a study in a horizontal tube to show the liquid viscosity effect in the intermittent flow frequency. In the experiment, an air and mineral oil mixture were used, at different temperatures. The test section had 18.9 m of total length, being a section 9.15 m long with a transparent acrylic pipe, which allows visual observations, and another section 9.75 m long of steel pipe, to work with inlet pressures of up to 100 psig, being both pipes 50.8 mm inner diameter. Due to the liquid viscosity to depend strongly on the temperature, a heating-cooling system was used to ensure accurate temperature control, is set in the oil tank to the desired value before each test. The frequency was calculated by counting the numbers of unit cells passing through sensors and dividing them by the time period of test execution. Four laser sensors and two capacitance sensors were used in the acrylic test section. The values obtained in both devices were compared to ensure quality in the experiment results, which indicated good agreement in the measurements of the capacitance sensors and laser, besides the results confirmation through visual observations. The results also showed that the frequency increases with the increase of the liquid viscosity, therefore, it was concluded that the frequency depends strongly on the liquid viscosity and was correlated using the inverse viscosity dimensionless number.

Using air and water mixture, Zhao *et al.* (2013) performed a study to verify the viscosity effect in the intermittent flow frequency. The experiment was conducted in two horizontal test sections, one with 5.5 m long and 26 mm inner diameter pipe, for viscosities of 3.5 Pa·s and 7.5 Pa·s, and another section with 17 m long and 74 mm inner diameter pipe, for viscosities of 1.0 Pa·s, 3.5 Pa·s and 6.0 Pa·s. Frequency data were obtained by means of liquid fraction data processing on Electrical Capacitance Tomography (ECT) sensors. The results showed that as the viscosity increases, the frequency also increases, depending strongly on the liquid viscosity, the liquid flow rate, and the pipe diameter. Higher values of frequency are obtained when there are higher values of viscosity and liquid superficial velocity and smaller diameter pipe values. The proposed correlation was obtained from a modification in the Schulkes *et al.* (2011) correlation and provides good results for turbulent gas flow in a laminar liquid flow. On the other hand, the Schulkes *et al.* (2011) correlation diverges for turbulent gas flow cases.

Al-Safran (2016) proposed a correlation using a Poisson model probabilistic to calculate the frequency. The model requires the mean frequency value as input data, thus, multiple linear regression functions were developed based on 473 data points collected from the literature for several geometric conditions, operational and properties physical of the fluids. This mean frequency was correlated with diameter, liquid superficial velocity and the slip factor (ratio between gas velocity and liquid velocity). According to the author, any other correlation already developed could be used to calculate the average frequency. From a database acquired in an experiment by Woods *et al.* (2006), Al-Safran (2016) validated his model and adjusted the correlation using 95% confidence intervals, whose deviation was reduced from a range of 40% and 50% to 15%, for liquid superficial velocities of 1.2 m/s and 0.4 m/s, respectively. The author verified that the frequency decreases as the gas superficial velocity increases and the correlation is more accurate in frequency predictions when there're high or low gas superficial velocities, rather than intermediate velocities.

Table 1 presents a summary of the main characteristics and conditions in which the frequency models analyzed in this work were developed.

## 2.2 Definition of the frequency correlations

The intermittent flow analysis is usually done using the unit cell concept defined by Wallis (1969). Fig. 1 shows a slug flow schematic representation in a pipe of length  $L$ , diameter  $D$ , and inclination  $\theta$ . The liquid piston region, with velocity  $J$  and length  $L_S$ , exerts a wall shear stress  $\tau_{W,S}$  and the gas bubbles dispersed in this piston present velocity  $U_B$ . The liquid fraction in the piston is represented by  $\phi_S$  and the liquid velocity in the piston corresponds to  $U_S$ . In the elongated bubble region, the liquid film with a fraction  $\phi_F$  has a length  $L_F$ , thickness  $H_F$ , and velocity  $U_F$ , exerting a wall shear stress  $\tau_{W,F}$ . The gas contained in the elongated bubble, of velocity  $U_T$ , present velocity  $U_C$ , exerting a wall shear stress  $\tau_{W,C}$ . The interfacial shear stress is represented by  $\tau_I$ . At the pipe cross-section detail, there are the wetted perimeters by the gas  $S_C$  and by liquid  $S_F$ , as well as the interfacial perimeter  $S_I$ . The areas occupied by gas and liquid are represented by  $A_C$  and  $A_F$ , respectively.

Table 1. Information about the frequency models analyzed in this study.

Correlation	Author	$D$ / [mm]	Fluids
C1	Gregory and Scott (1969)	19	CO <sub>2</sub> -water
C2	Heywood and Richardson (1979)	42	Air-water
C3	Nydal (1991)	31–90	Air-water
C4	Jepson and Taylor (1993)	300	Air-water
C5	Manolis <i>et al.</i> (1995)	78	Air-water
C6	Shell (Zabaras <i>et al.</i> , 1999)	42	Air-water
C7	Fossa <i>et al.</i> (2003)	40 and 60	Air-water
C8	Shea <i>et al.</i> (2004)	-	-
C9	Wang <i>et al.</i> (2007)	50	Air-water
C10	Gokcal <i>et al.</i> (2009)	50.8	Air-oil
C11	Zhao <i>et al.</i> (2013)	26 and 74	Air-oil
C12	Al-Safran (2016)	25–203	Various

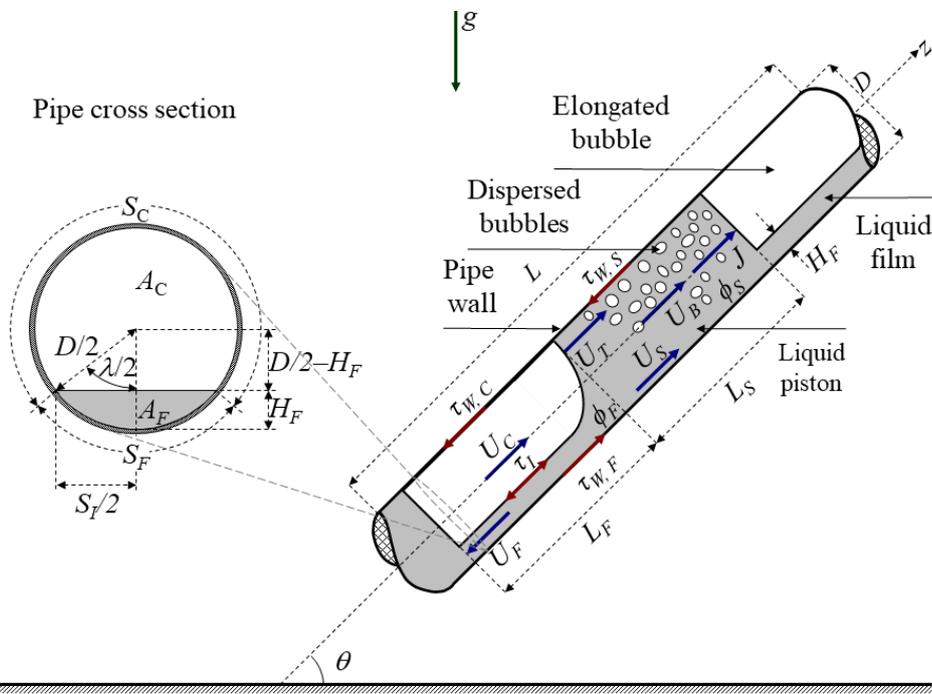


Figure 1. Schematic representation of the unit cell in the intermittent flow and its variables; adapted from Lima (2011).

The frequency  $f$  of the unit cell is defined as the ratio of the elongated bubble velocity  $U_T$  by the unit cell length  $L_F + L_S$ , according to Eq. (1):

$$f = \frac{U_T}{L_F + L_S} \quad (1)$$

The intermittence factor  $\beta$  is defined as a times or lengths fraction referring to the regions constituting the unit cell. According to Bueno (2010), the intermittence is not periodic neither in time nor space. Thus, in average terms, represents the occurrences of the liquid piston and the elongated bubble. The intermittence factor  $\beta$  is expressed in terms of the elongated bubble length (or liquid film)  $L_F$  and the liquid piston  $L_S$ , according to Eq. (2):

$$\beta = \frac{L_F}{L_F + L_S} = \frac{L_F}{U_T/f} \quad (2)$$

There are several models available in the literature for frequency estimate in function of known parameters. Tab. 2 presents the definitions of the correlations for frequency estimate for each author. The sub-indexes  $G$  and  $L$  are used to represent the gas and liquid phase, respectively. The absence of the sub-index refers to the mixture.

Table 2. Correlations for frequency calculation.

Correlation	$f$ / [Hz]
C1	$0.0226 \left[ \lambda_L \left( \frac{19.75}{gD} + Fr^2 \right) \right]^{6/5}$
C2	$0.0434 \left[ \lambda_L \left( \frac{2.02}{D} + Fr^2 \right) \right]^{1.02}$
C3	$0.088 \left[ Fr \left( \frac{1.5}{J} + \lambda_L \right) \right]^2$
C4	$\lambda_L \left( \frac{4.76 \times 10^{-3} J^2 + 0.035 J}{D} \right)$
C5	$0.0037 \left[ \lambda_L \left( \frac{25}{gD} + Fr^2 \right) \right]^{9/5}$
C6	$\sqrt{\frac{g}{D}} \left\{ Fr_{min} + 0.73 Fr_L^{2.34} \left[ (Fr_G + Fr_L)^{0.1} - 1.17 Fr_L^{0.064} \right]^2 \right\}$
C7	$\frac{J_G}{D} \left( \frac{0.044 \lambda_L}{1 - 1.71 \lambda_L + 0.70 \lambda_L^2} \right)$
C8	$0.47 \left( \frac{J_L^{3/4}}{D^{6/5} L_i^{0.55}} \right)$
C9	$\frac{J_G}{D} \left( \frac{0.05 \lambda_L}{1 - 1.675 \lambda_L + 0.768 \lambda_L^2} \right)$
C10	$2.816 \frac{J_L}{D} N_\nu^{-0.612}$
C11	$\frac{J}{D} [\Psi(\lambda_L) \Phi(Re_L, Re_G)]$
C12	$\exp(1.51 - 17.04 D + 0.77 \ln J_L - 0.181 \ln \bar{S})$

In the correlations presented in Tab. 2, the phase superficial velocity,  $J_k$ , represents the velocity that a phase would have if flowed alone in the pipe. It is defined as the ratio between the phase volumetric flow rate  $Q_k$  and the area  $A$  of the pipe cross-section:

$$J_k = \frac{Q_k}{A} \quad (3)$$

The mixture superficial velocity,  $J$ , corresponds to the velocity of the mixture volume center. It is defined as the sum of phase superficial velocities:

$$J = J_L + J_G \quad (4)$$

The phase homogeneous fraction,  $\lambda_k$ , represents the ratio between the volume occupied by a phase and the mixture volume, considering that the phases have the same velocity, and can be determined by the ratio between the phase superficial velocity and mixture superficial velocity:

$$\lambda_k = \frac{J_k}{J} \quad (5)$$

The mixture Froude number,  $Fr$ , represents the ratio between the inertial and gravitational forces. It is defined in terms of the mixture superficial velocity, pipe diameter, and gravitational acceleration  $g$ :

$$Fr = \frac{J}{\sqrt{gD}} \quad (6)$$

Similarly, the phase Froude number,  $Fr_k$ , is defined in terms of the phase superficial velocity, pipe diameter, and gravitational acceleration:

$$Fr_k = \frac{J_k}{\sqrt{gD}} \quad (7)$$

The mixture Reynolds number,  $Re$ , represents the ratio between of inertial and viscous forces. It is defined in terms of mixture superficial velocity, liquid density  $\rho_L$ , liquid dynamic viscosity  $\mu_L$ , and pipe diameter:

$$Re = \frac{J D \rho_L}{\mu_L} \quad (8)$$

Similarly, the phase Reynolds number,  $Re_k$ , is defined in terms of the pipe diameter, superficial velocity, density and dynamic viscosity of the phase.

$$Re_k = \frac{J_k D \rho_k}{\mu_k} \quad (9)$$

Correlation C6 considers a minimum Froude number,  $Fr_{min}$ , as a limit value of the liquid Froude number for the correlation adjustment:

$$Fr_{min} = 0.048 Fr_L^{0.81} \quad (10)$$

In correlation C10, the inverse viscosity dimensionless number,  $N_\nu$ , relates the buoyancy force to the viscous force, is defined as:

$$N_\nu = \frac{\sqrt{g D^3 (1 - \rho_G / \rho_L)}}{\nu_L} \quad (11)$$

The dimensionless function of the phases fractions,  $\Psi(\lambda_L)$ , is defined in correlation C11 according to:

$$\Psi(\lambda_L) = 0.016 \lambda_L (2 + 3 \lambda_L) \quad (12)$$

Still, in correlation C11, the dimensionless function of the phases Reynolds number,  $\Phi(Re_L, Re_G)$ , is valid only for the laminar liquid flow ( $Re_L \leq 4000$ ), according to:

$$\Phi(Re_L, Re_G) = \begin{cases} 10.836 Re_L^{-0.337} & \text{if } Re_G \leq 4000 \\ 6.40 Re_L^{-0.141} & \text{if } Re_G > 4000 \end{cases} \quad (13)$$

The slip factor,  $\bar{S}$ , presents in correlation C16, is defined as the ratio between the gas and liquid local velocities, which can be calculated in terms of the liquid dynamic viscosity and its reference value,  $\mu_{L,0} = 1 \text{ Pa}\cdot\text{s}$ , and the ratio of the gas and liquid superficial velocities:

$$\bar{S} = 1 + 1.95 \left( \frac{\mu_L}{\mu_{L,0}} \right)^{0.01} \left( \frac{J_G}{J_L} \right)^{3/2} \quad (14)$$

### 3. ANALYSIS METHOD OF THE FREQUENCY CORRELATIONS

The correlations accuracy analysis, presented in Tab. 2, is based on the determination of the relative deviation modulus mean value  $\epsilon_R$  between the calculated (calc.) and measured (meas.) values for frequency,  $f$ , and the determination of the RMS (Root Mean Square) of the relative deviations, referring to the  $N$  experimental points, whose definitions are given according to Eqs. (15) and (16), respectively:

$$\epsilon_R = \frac{1}{N} \sum \frac{|f_{calc.} - f_{meas.}|}{f_{meas.}} \quad (15)$$

$$\text{RMS} = \sqrt{\frac{1}{N} \sum \epsilon_R^2} \quad (16)$$

For calculation of each correlation and their auxiliary variables as well as of the mean values of the relative deviation modulus and its RMS, a spreadsheet developed in the ©Microsoft Excel 2016 was used.

The experimental data used in this work for correlations comparisons were obtained from the work of Bueno (2010), which carried out the experiments using air and water as a mixture in a test section of 306 diameters of extension and 26 mm inner diameter. The experimental apparatus basically consists at the flow in two separate circuits of air and water that are carried to a mixer to form the two-phase flow, which in the sequence passes through the acrylic test section, where the measurements were carried out in two different stations, one  $77D$  and another one  $257D$ , downstream of the mixer. At these stations, the intermittent flow was monitored through impedance sensors connected to a data acquisition system, used to obtain the frequency values. After going through the test section, the mixture is discharged into a vertical tube 75 mm inner diameter which acts as an air and water separator. Tab. 3 presents the intervals of the variables determined in the experiments carried out by Bueno (2010).

Table 3. Variables intervals determined experimentally by Bueno (2010).

$J_G$ / [cm/s]	$J_L$ / [cm/s]	$P$ / [mbar]	$f$ / [Hz]	$N$
30.2–185.9	29.0–121.0	982–1058	0.46–3.88	10

The fluids properties necessary to calculate the frequency were obtained from Fox *et al.* (2006, Tab. A8, p. 719) for the operational conditions in which the experiments were carried out: atmospheric pressure of  $P_{atm} = 947 \text{ mbar}$  and ambient temperature  $T = 25 \text{ }^\circ\text{C}$ . The air density is estimated from the ideal gas state equation, considering this ambient temperature and the local absolute pressure at each experimental test.

#### 4. RESULTS AND DISCUSSION

In Figure 2, are presented the results in the two graphs form, both of them in terms of Strouhal number ( $St \equiv fD/J_G$ ) for measured and calculated frequency values. Each graph present six correlations whose the RMS values are most near. The abscissa axis represents the dimensionless measured frequency and the ordinate axis represents the dimensionless calculated frequency. In the graphs were established ranges of  $-30\%$  and  $+30\%$ , considered as satisfactory limits for the deviations analyzed.

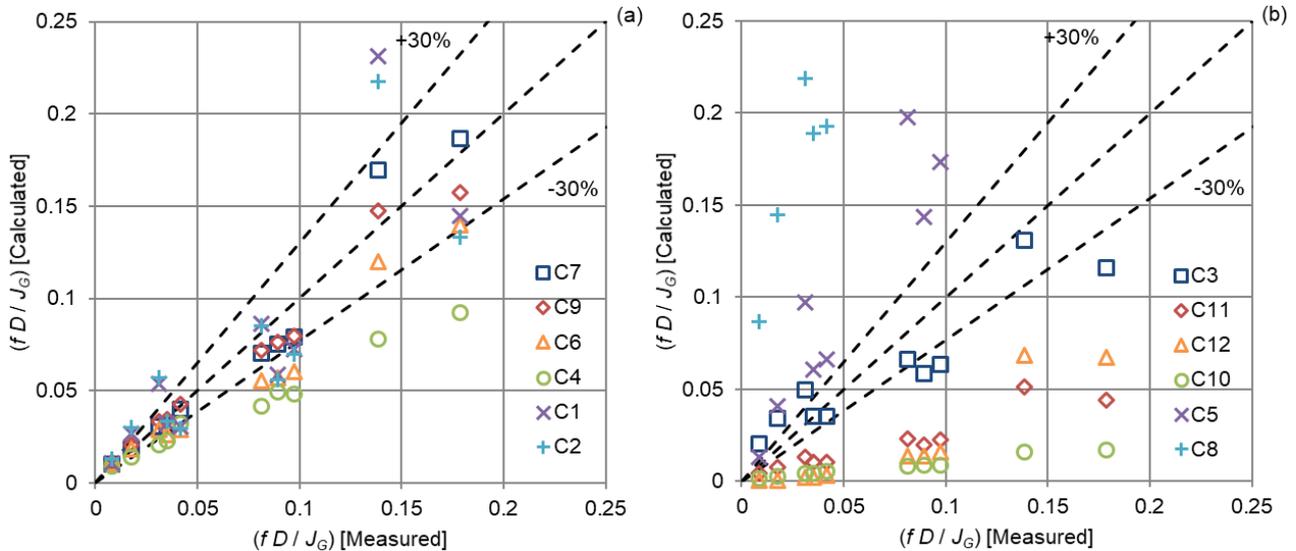


Figure 2. Comparison between the calculated and measured frequency dimensionless values for air-water flow in a 26 mm diameter horizontal tube.

According to the graph “a” in Fig. 2, for horizontal flows, the correlations that presented the most satisfactory results were C7 and C9, presenting its points within the limits established, which the calculated and measured values of frequency presents approximate values. Correlations C6, C4, C1, and C2 also presented good results, although some localized points appear outside the established deviation ranges of  $\pm 30\%$ . In the graph “b”, presented in Fig. 2, both of correlations present unsatisfactory results, because, with the exception of correlation C3, all others present the points outside the  $\pm 30\%$  limit range.

From the analysis of relative deviations and RMS values in Tab. 4 for calculated and measured values for frequency, the correlations that presented values inside  $\pm 30\%$  limit were C7, C9, and C6.

Table 4. Relative deviations and RMS values for frequency correlations.

Correlation	$\epsilon_R$	RMS
C1	33.95	40.26
C2	38.99	46.06
C3	43.71	46.06
C4	35.56	38.24
C5	128.34	155.26
C6	23.96	26.60
C7	11.67	13.97
C8	456.41	504.31
C9	12.77	15.96
C10	87.81	87.87
C11	67.51	68.17
C12	84.15	85.45

As shown in Tab. 4, correlations C1 and C2 presented values most close to RMS and both were developed for horizontal flows. The authors who developed these correlations adopted a similar way to define them, using the flow velocity for a minimum frequency observed in the experiment, but considering different fluids and pipe diameters. The velocities used were 6 m/s and 4.8 m/s for C1 and C2, respectively. Greskovich and Shrier (1972) studied the correlation proposed by Gregory and Scott (1969) for large diameters and, according to the authors, this correlation is not suggested for larger diameters than those used in the experiment.

Correlation C3 presented values little above of 30% for RMS. This correlation was developed for horizontal pipes and the author used data from various pipe diameters, including one of 31 mm inner diameter, which is close to that one used by Bueno (2010).

Correlation C4 was developed from data obtained for a 300 mm inner diameter pipe since the author proposed a model that covered data of large diameters pipe.

Correlation C5 presented an RMS value above of 100%. This correlation was adapted from the Gregory and Scott (1969) model, however, for a minimum velocity of 5 m/s, a diameter three times greater than that used in this analysis and high-pressure air-water flow data.

The proposed model by correlation C6 was developed for data of Heywood and Richardson (1979), for a 42 mm inner diameter horizontal pipe and compared with data from an inclined pipe of 101.6 mm inner diameter, in which presented good agreement. For this study, the RMS value was below the range of 30%.

The model for frequency calculation given by correlation C7 presented the most satisfactory result, with RMS value of 13.97%. In this model, the authors presented the frequency in terms of the Strouhal number and as a function of the homogeneous liquid fraction, which was obtained from a curve fit for horizontal flow data and compared with data from other authors for different diameters, presenting slight deviation.

Correlation C8, obtained from a curve fit, takes into account the pipe length; however, for the present analysis, it is presented the RMS value above 200%. In the experiment carried out to develop it, the pipe length used may be different from that used in this work and, therefore, presents these significant deviations for the calculated frequency, which is inversely proportional to this length.

Correlation C9 was also written in terms of Strouhal number, similar to correlation C7, presenting satisfactory results for the calculated frequency with RMS value of 15.96%.

Correlation C10 model was developed using data from an air-oil mixture, in order to study the viscosity effect in the frequency. For this study, using air-water mixture, the RMS value corresponds to 87.87%. As there are not many correlations based on higher liquid viscosity values, this may be a limited correlation at this point.

Correlation C11 presented RMS value above 60%. To develop it, Zhao *et al.* (2013) used a higher viscosity liquid than that one used in this study. This correlation is valid only when the liquid is laminar, but for the data of Bueno (2010), the liquid behaved as turbulent, which may explain the divergences found in this results.

Al-Safran (2016) developed correlation C12 based on flow data with several different characteristics. The RMS value presents was above 80% and, according to the author, this correlation presents greater precision for higher and lower values of superficial gas velocities and not for intermediate values, as well as the data used in this work.

## 5. CONCLUSIONS

In this present work, a comparative analysis was performed between some correlations existing in the literature to calculate the intermittent flow frequency. The analysis was realized by comparing with experimental frequency data available in the literature. With the comparison between the models, it was possible to verify which are more accurate and how they behave when used in an application with different conditions than those in which they were developed.

The results presented in this study demonstrate that is possible to use various frequency correlations, whose presented lower deviations. The correlations proposed by Fossa *et al.* (2003) and Wang *et al.* (2007) presented the better results, both were written in terms of Strouhal number and presents approximate and satisfactory results, with low deviations.

Each correlation was proposed based on a data set that is restricted to that conditions in which they were developed. Most of these correlations may present acceptable results for data from an experiment with different characteristics, however, some models when applied in others conditions may presents results with significant deviations, especially when there is a more limited database. Some authors have attempted to develop models that cover more diverse data in relation the phase flow rates, viscosity, and diameters, although, some these models have not proved to be the most efficient in this analysis.

As a suggestion for future work, the correlations can be compared using a larger database for larger diameters and with other work fluids, as a way of verifying their application to flows with higher liquid viscosity, since there are few models developed for this situation. In addition, the search for a more accurate and comprehensive model for estimating the intermittent flow frequency can be performed from the acquisition and analysis of more experimental data.

## 6. ACKNOWLEDGMENTS

The authors thank the Federal University of Technology – Paraná for the support received for the development of this work and the participation in this event.

## 7. REFERENCES

- Al-Safran, E.M., 2009. "Investigation and prediction of slug frequency in gas/liquid horizontal pipe flow". *Journal of Petroleum Science and Engineering*, Vol. 69, No. 1, pp. 143–155.
- Al-Safran, E.M., 2016. "Probabilistic modeling of slug frequency in gas/liquid pipe flow using the Poisson probability theory". *Journal of Petroleum Science and Engineering*, Vol. 138, pp. 88–96.
- Bueno, L.G.G., 2010. *Estudo experimental de escoamentos líquido-gás intermitentes em tubulações inclinadas*. Master's Thesis, Universidade Estadual de Campinas, Campinas, São Paulo, Brazil. URL <http://repositorio.unicamp.br/jspui/handle/REPOSIP/263073>.
- Fossa, M., Guglielmini, G. and Marchitto, A., 2003. "Intermittent flow parameters from void fraction analysis". *Flow Measurement and Instrumentation*, Vol. 14, No. 4, pp. 161–168.
- Fox, R.W., McDonald, A.T. and Pritchard, P.J., 2006. *Introdução à mecânica dos fluidos*. LTC – Livros Técnicos e Científicos.
- Gokcal, B., Al-Sarkhi, A., Sarica, C., Al-Safran, E.M. *et al.*, 2009. "Prediction of slug frequency for high viscosity oils in horizontal pipes". In *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers.
- Gregory, G.A. and Scott, D.S., 1969. "Correlation of liquid slug velocity and frequency in horizontal cocurrent gas-liquid slug flow". *AIChE Journal*, Vol. 15, No. 6, pp. 933–935.
- Greskovich, E.J. and Shrier, A.L., 1972. "Slug frequency in horizontal gas-liquid slug flow". *Industrial & Engineering Chemistry Process Design and Development*, Vol. 11, No. 2, pp. 317–318.
- Hernandez-Perez, V., Abdulkadir, M. and Azzopardi, B.J., 2010. "Slugging frequency correlation for inclined gas-liquid flow". *World Academy of Science, Engineering and Technology*, Vol. 6, pp. 44–51.
- Heywood, N.I. and Richardson, J.F., 1979. "Slug flow of air-water mixtures in a horizontal pipe: determination of liquid holdup by  $\gamma$ -ray absorption". *Chemical Engineering Science*, Vol. 34, No. 1, pp. 17–30.
- Hill, T.J., Wood, D.G. *et al.*, 1990. "A new approach to the prediction of slug frequency". In *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers.
- Hill, T.J., Wood, D.G. *et al.*, 1994. "Slug flow: occurrence, consequences, and prediction". In *University of Tulsa Centennial Petroleum Engineering Symposium*. Society of Petroleum Engineers.
- Jepson, W.P. and Taylor, R.E., 1993. "Slug flow and its transitions in large-diameter horizontal pipes". *International Journal of Multiphase Flow*, Vol. 19, No. 3, pp. 411–420.
- Lima, L.E.M., 2011. *Análise do modelo de mistura aplicado em escoamentos isotérmicos gás-líquido*. Ph.D. Thesis, Universidade Estadual de Campinas, Campinas, São Paulo, Brazil. URL <http://repositorio.unicamp.br/jspui/handle/REPOSIP/264105>.
- 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: <http://dx.doi.org/10.1016/j.petrol.2014.07.032>. URL <http://www.sciencedirect.com/science/article/pii/S0920410514002319>.
- Lima, L.E.M. and Rosa, E.S., 2015. "Sensitivity analysis of the wall shear model to the correlations for frequency and slug holdup in the gas-liquid slug flow in pipes". *Advanced Materials Research*, Vol. 1104, pp. 61–67. ISSN 1662-8985. doi: [10.4028/www.scientific.net/AMR.1104.61](https://www.scientific.net/AMR.1104.61). URL <https://www.scientific.net/AMR.1104.61>.
- Manolis, I.G., Mendes-Tatsis, M.A. and Hewitt, G.F., 1995. "The effect of pressure on slug frequency on two-phase horizontal flow". In *The 2nd Conference on Multiphase Flow*. Kyoto, Japan.
- Nydal, O.J., 1991. *An experimental investigation on slug flow*. Ph.D. Thesis, University of Oslo, Oslo, Norway.
- Rodrigues, H.T., 2009. *Simulação numérica do escoamento bifásico gás-líquido no padrão de golfadas utilizando um modelo lagrangeano de seguimento de pistões*. Master's Thesis, Universidade Tecnológica Federal do Paraná, Curitiba, Paraná, Brazil.
- Schulkes, R. *et al.*, 2011. "Slug frequencies revisited". In *15th International Conference on Multiphase Production Technology*. BHR Group.
- Shea, R.H., Eidsmoen, H., Nordsveen, M., Rasmussen, J., Xu, Z. and Nossen, J., 2004. "Slug frequency prediction method comparison". In *Proceedings of the 4th North American Conference on Multiphase Technology*. pp. 227–237.
- Shoham, O., 2006. *Mechanistic modeling of gas-liquid two-phase flow in pipes*. Society of Petroleum Engineers.
- Taitel, Y. and Barnea, D., 1990. "Two-phase slug flow". *Advances in Heat Transfer*, Vol. 20, pp. 83–132.
- Vicencio, F.E.C., 2013. *Caracterização experimental do escoamento intermitente líquido-gás em tubulações horizontais*. Master's Thesis, Universidade Tecnológica Federal do Paraná, Curitiba, Paraná, Brazil.
- Wallis, G.B., 1969. *One-dimensional two-phase flow*. McGraw-Hill.
- Wang, X., Guo, L. and Zhang, X., 2007. "An experimental study of the statistical parameters of gas-liquid two-phase slug flow in horizontal pipeline". *International Journal of Heat and Mass Transfer*, Vol. 50, No. 11, pp. 2439–2443.
- Woods, B.D., Fan, Z. and Hanratty, T.J., 2006. "Frequency and development of slugs in a horizontal pipe at large liquid flows". *International Journal of Multiphase Flow*, Vol. 32, No. 8, pp. 902–925.

Zabaras, G.J. *et al.*, 1999. "Prediction of slug frequency for gas-liquid flows". In *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers.

Zhao, Y., Yeung, H. and Lao, L., 2013. "Slug frequency in high viscosity liquid and gas flow in horizontal pipes". In *16th International Conference on Multiphase Production Technology*. BHR Group.

## **8. RESPONSIBILITY NOTICE**

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