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EXPERIMENTAL STUDY OF TWO-PHASE SLUG FLOW THROUGH AN UPWARD VERTICAL TO HORIZONTAL TRANSITION

Maikon Bressani
Ricardo Augusto Mazza
Mechanical Engineering Faculty, State University of Campinas, São Paulo, Brazil
maikon_b@hotmail.com
mazza@fem.unicamp.br

Abstract. *The two-phase slug flow is extremely affected by gravity, however most of the related studies focus on flow analysis with constant inclination pipes. The influence of the elbow in vertical to horizontal transitions is not well-known despite its importance in pipeline systems. This work's objective is to study the influence of this kind of transition in the main slug flow parameters: the liquid slug and bubble lengths, translational bubble's velocity, among others. In order to accomplish this, an experimental setup was developed with an upward vertical section connected to a horizontal one by a 90º elbow of long radius. Impedance probes before and after the elbow were used to measure the slug flow parameters. The elbow was also instrumented with impedance probes making it possible to measure the bubble's velocity and the other parameters along the elbow in various positions. In all test cases there were no significant influence of the centrifugal force into slug flow parameters along the transition, which is consistent with the previous literature for inclined pipes. The presence of the transitions doesn´t significantly affect the translational bubble's nose velocity and bubble's lengths. There was a little influence in the liquid slug length.*
Keywords: *Slug flow, Flow through bends, Two-phase flow, Bubble velocity*

1. INTRODUCTION

Two phase slug flow patterns have been studied since the 60´s because of their important industrial applications such as in hydrocarbons transport and production, vaporization and condensation in thermal plants and refrigeration systems, emergency core cooling of nuclear reactors, heat and mass transfer in chemical reactors (Fabre and Line, 1992) and in cryogenic engineering (Hua *et al.*, 2009). This pattern is characterized by a long bubble followed by a liquid slug, as shown in Fig.1. There is a liquid film below the long bubble and its profile depends on the gravity force among other parameters. The liquid slug may or may not have small disperse gas bubbles as may the liquid film. One of the most important characteristics of this pattern is that all parameters are not constant in time and space. All parameters have a distribution around a mean value even with gas and liquid flow rates being constant. The main parameters in the slug flow are the bubbles nose and the liquid slug dispersed bubble velocities, the liquid holdup in the bubble and in the liquid slug region, the bubble and the liquid slug length (L_B and L_S respectively), the frequency (f) and the pressure drop along the pipe.

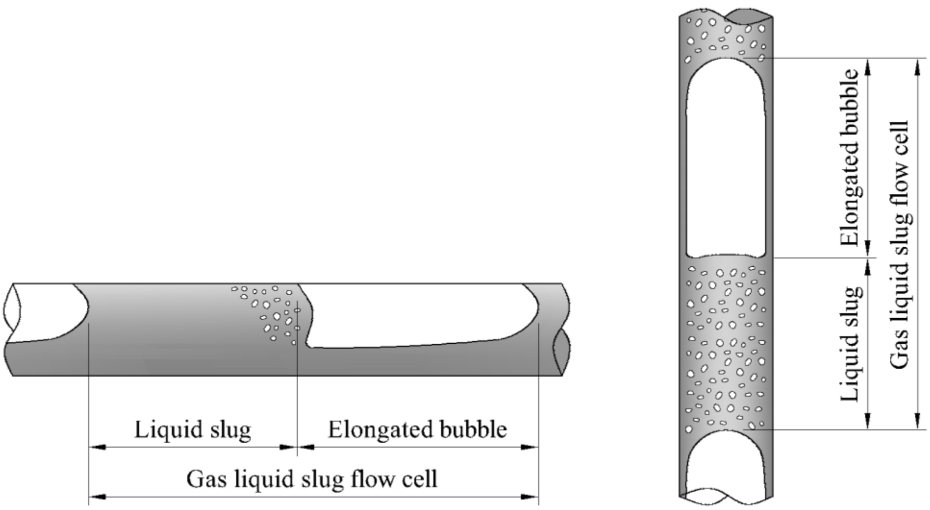

Figure 1. Gas liquid slug flow cell (L_U) composed by liquid slug (L_S) e elongated bubble (L_B)

Davies and Taylor (1950) and Nicklin (1962) begun the slug flow studies measuring the rise velocity of an isolated bubble through stagnant and flowing liquids, respectively. Their studies were restricted to vertical tubes. Bendiksen (1984) extended the studies to inclined ones. All these works had their main focus on the elongated bubble rise velocity determination. A review regarding bubble rise velocity could be found in Fabre (2003), Fabre and Line (1992) and Viana *et al*., (2003). The first slug flow modelling was proposed by Dukler and Hubbard (1975). This model used a periodic unit cell to predict the pressured drop and the averaged film holdup in horizontal and slightly inclined tubes, among other parameters. A most complete model was presented by Taitel and Barnea (1990) and Fernandes *et al.*, (1983) extended the model to vertical tubes. A comparative review among the different models was done by Mazza *et al.*, (2010) and the authors found that the key parameter on the model performance is the bubble velocity. All the unit cell model capture only the average value of the slug flow parameter. To capture the parameters distributions it is necessary to use a slug tracking model. This class of model employs a Lagrangian approach to tracks every unit cell boundary as they evolve downstream the pipe. There are developed slug tracking models to horizontal (Barnea and Taitel, 1993 and Taitel and Barnea, 1998), slightly inclined (Cook and Behnia, 2000a and Rosa *et al*., 2015) and hilly terrain pipes (Zheng *et al*., 1994; Nydal and Barnejee, 1996; Taitel and Barnea, 2000 and Al-safran *et al*., 2004). The slug tracking models are extremely dependent on the closure relationship, mainly the bubble velocity correlations. Experimental data regarding slug flow parameters in pipes have been published since the 70's. There is experimental data in horizontal pipes for bubble velocity and bubble and liquid slug lengths (Wang *et al*., 2007; Nydal *et al*., 1992 and Cook and Behnia, 2000b); frequency (Wang *et al*., 2007; Greskovich and Shrier, 1972; Tronconi, 1990; Bertola and Cafaro, 2001 and Zabaras *et al*., 2000); bubble and liquid slug void fraction (Lewis *et al*., 2002 and Nydal *et al*., 2007). Ujang *et al*., (2006) studied the formation process and Rosa *et al*., (2004) included the effect of viscosity. Bueno (2010) studied the main slug flow parameters like bubble and liquid slug, bubble´s noise velocity, frequency and coalescence ratio for inclined ducts experimentally. The authors present the average and distributions for all parameters.

The slug flow industrial application occurs mainly in horizontal, vertical and inclined pipe. However, pipelines have valves, manifolds, reservoirs inlets and outlets, transitions like elbows, expansions, contractions, etc. Although these elements represent a few portion of the total length, their influence on the flow behavior is representative. Therefore, it is important to better understand the flow behavior on such elements to achieve an accurate design project. In the last decades a few studies have been conducted about such elements. For example, Al-Safran *et al*., (2008), Al-Safran *et al*., (2005) and E. Al-Safran *et al*., (2004) used a slug tracking model to study the slug flow behavior on hilly terrain and Kim *et al*., (2010), Benbella *et al*., (2009) and Spedding and Benard (2007) measured the pressure drop on slug flows in a 90º elbow. Also, Aung and Yuwono (2013) performed a similar study for bubble flow. Thus, the flow parameter identification on two phase transitions is an important research field that should be explored.

The main objective on this paper is to analyze the influence of a 90° vertical to horizontal elbow bend in the slug flow parameters. Impedance sensors were used to measure the slug flow parameter like bubble velocity, bubble and liquid slug length and frequency, among others; before, after and through the 90° elbow. The measurements are compared with reported data, especially with Nicklin (1962) and Bendiksen (1984).

2. EXPERIMENTAL SETUP

A schematic diagram of the experimental setup and the 90° vertical to horizontal elbow is shown in Fig. 2. The vertical and the horizontal test sections were made with 26 mm internal diameter transparent Plexiglass pipes. Their lengths were 2,800 and 1,000 mm, respectively. The 90° elbow was made with a seamless stainless steel tube with the same internal diameter and radius of curvature of 142 mm (r/D = 5.5). The working fluids were air and tap water and one Y type mixer was located at bottom of the vertical section, 2,278 mm (≅88D) before the elbow. The flow rates were measured by an electromagnetic flowmeter by Krohne (Optiflux 2000 C/6 with minimum 0.5% accuracy) and an ordinary gas rotameter by Omega calibrated against a Drum-type gas meter by Ritter (TG50/6 with 0.1% accuracy). Two measuring stations with a twin set of double wire impedance probes axially spaced 112,5 mm were used, one before and other after the elbow. Every station had a Validyne differential pressure transducer (DP15 with 0.25% accuracy). One measured the pressure drop throughout the two stations and along the elbow. The other measured the pressure at the vertical station and had one tap open to the atmosphere. Along the elbow there were five wire impedance probes spaced by 37.2 mm (15º degree along the symmetry radius). All the probes consisted of a 0.6 mm wire stretched along the pipe diameter and fixed at wall tube with a leakage seal and an electrical isolation system. The impedance probe picks up electrical liquid properties near it and the high and low voltage is associated to the liquid and the gas phase respectively (Huang *et al*., 2008). The signals resembled square waves shifted in time due the probe´s spacing and each bubble´s nose velocity was determined by the time interval between them. The analogic signal for each probe was sampled at 3 kHz, digitized and stored by a National Instruments data acquisition system. A post processing system determined the nose´s velocity of each bubble at vertical, at horizontal and along the 90° elbow combining properly the signal of two consecutives probes. The bubble and liquid lengths, the frequency and the coalescence tax were determined by the same post processing system. The uncertainty analysis shown that bubble´s nose velocity, frequency, coalescence tax, bubble and liquid slug lengths errors was less than 12%.

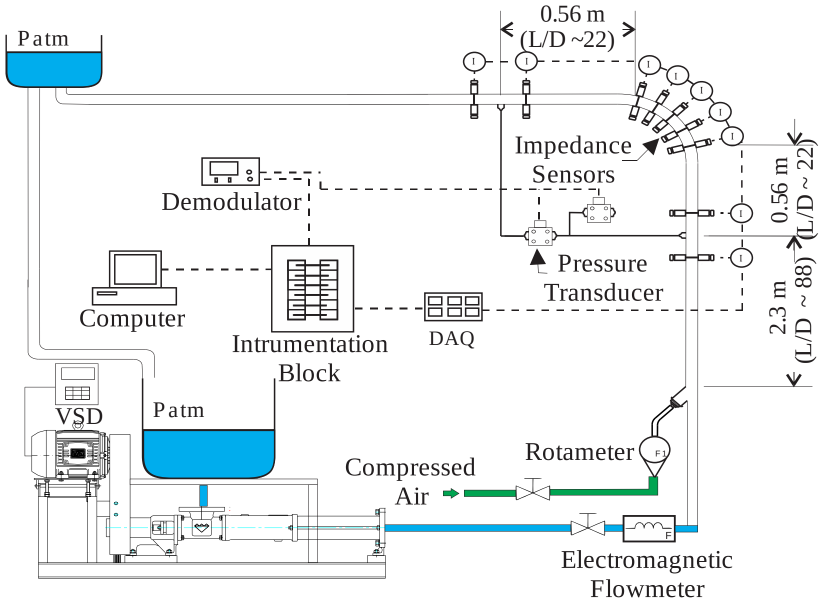

Figure 2. Schematic representation of the experimental apparatus

3. RESULTS

The experimental data set consists of four runs with operational conditions shown on Tab. 1. The liquid and the gas fluxes were chosen to assure slug flow in the vertical and horizontal sections with two Froude regimes. Two points in each Froude regime with different liquid and gas flow ratios were used. The liquid and gas volumetric fluxes, J_L and J_G, are defined by the ratio of volumetric flow rate of the respective phase by the pipe's cross-sectional area. All the data were acquired during 120 seconds and each run was repeated three time. In each test there is at least 200 bubbles passing through the probe. Therefore, the average data represents the mean of the minimum 600 elements and the sample size can be considered representative of the population.

Table. 1 – Experimental test grid and reference values

Run	J_L [m/s]	J_G [m/s]	$J = J_L + J_G$ [m/s]	$Fr = J/\sqrt{g.D}$	$Re = \rho_L.J.D/\mu_L$
#1	0.60	0.32	0.92	1.82	2.4 x 10^4
#2	0.30	0.64	0.94	1.86	2.4 x 10^4
#3	0.90	0.96	1.86	3.68	4.8 x 10^4
#4	1.20	0.64	1.84	3.64	4.8 x 10^4

3.1 Translational bubble´s nose velocities

Based on Nicklin´s (1962), Bendiksen (1984) shows that the translational bubble´s velocities in inclined tubes could be determined by:

$$V_B = C_0 J + C_\infty \sqrt{gD}\,, \tag{1}$$

where J is the mixture velocity, *g* is gravity, D is the pipe´s diameter, C_0 and C_∞ are constants as shown in Tab. 2. As shown, the C_0 and C_∞ are a function of the pipe inclination measured horizontally and were experimentally determined by Bendiksen (1984) in line with a constant inclination. This is different from a vertical 90° to horizontal elbow, but it is the only comparison relation currently available.

The experimental results are presented in Fig. 3 where the continuous lines represent the translational bubble´s nose velocity (V_B) calculated by Eq. (1). The vertical and horizontal measuring stations are represented by 90° and 0° in the abscissa, respectively. The other abscissa values represents the stations along the elbow. One can see that the velocity predicted by Tab. 2 constants are befitting with the experimental date shown in the Fig. 3. The major deviations occur in tests #2 and #3 and they are 12.7% and 8.5%, respectively. For the vertical station, there was excellent fit. The largest deviation was 4.8% for test #2. Bendiksen (1984) worked with inclined pipes and therefore only gravity changed with the inclination. In this paper, there is gravity and centripetal forces caused by the elbow´s curvature. The centripetal force induces secondary flows and changes the liquid velocity prolife in the liquid slug ahead of the bubble which could modify the C_0 parameter. In the presented tests, the centrifugal accelerations were 0.6 and 1.1 times the gravity and even the highest centrifugal velocity does not seem to affect the bubble´s velocity very much since the measurements were closed to Bendiksen (1984) predictions.

Table 2. Parameters for calculating the bubble translation velocity according with Bendiksen (1984)

	C_0	C_∞
$Re_J > 2000$	$Fr_J \geq 3.5 = 1.2$	$\frac{0.345}{\left(1+3805/Eo^{3.06}\right)^{0.58}}\sin\theta$
	$Fr_J < 3.5 = 1+0.2\sin^2(\theta)$	$\left(0.542-\frac{1.76}{Eo^{0.56}}\right)\cos\theta+\frac{0.345}{\left(1+3805/Eo^{3.06}\right)^{0.58}}\sin\theta$
$Re_J < 2000$	2.0	$\left(0.542-\frac{1.76}{Eo^{0.56}}\right)\cos\theta+\frac{0.345}{\left(1+3805/Eo^{3.06}\right)^{0.58}}\sin\theta$

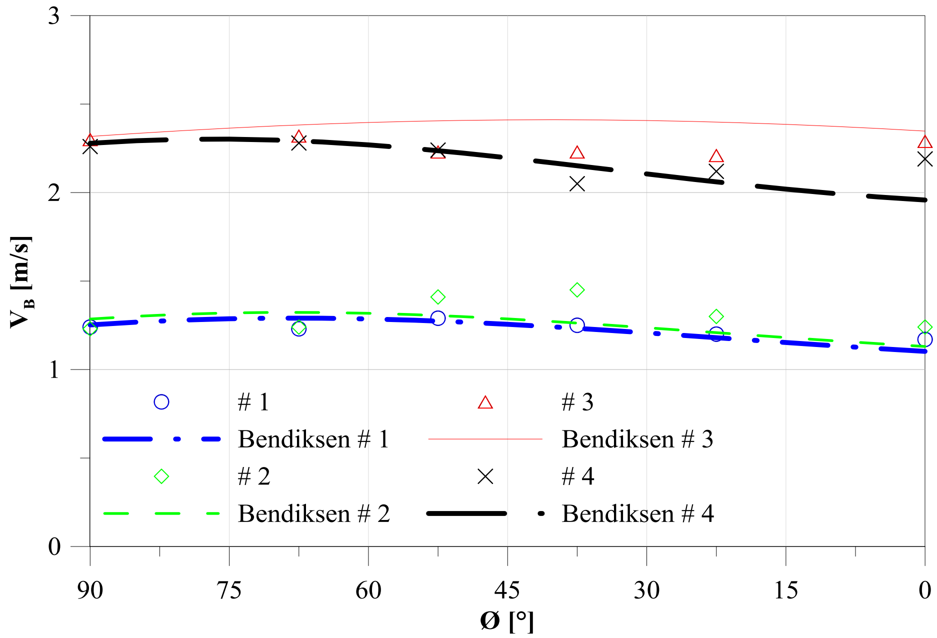

Figure 3. Comparison between experimental and calculated bubble velocity

3.2 C_0 and C_∞ parameter

The C_0 and C_∞ parameter can be obtained with the dimensionless form of the translational bubble's velocity defined as:

$$\frac{V_B}{\sqrt{gD}} = C_0 Fr_J + C_\infty , \tag{2}$$

where $Fr_J = J/\sqrt{gD}$ is the Froude number. C_0 and C_∞ parameter values were obtained using a minimum square fits in the experimental bubble´s velocity.

However, when the bubble´s velocity is plotted against the mixture velocity, an extrapolation to zero to obtain the C_∞ was not satisfactory due to large scatter values for its values (Alvez *et al.*, 1993). For a proper determination of C_∞ a single bubble should be released into the pipe with an accurate low liquid flow rate. This is very difficult to be done in this setup and a more enforceable procedure should be used. In this work, the C_0 parameter was established with a minimum square fit with the linear coefficient determined by Bendiksen´s C_∞ parameter. To assure a more reliable C_0 value, extra tests were performed with different Fr regimens. It was not possible to distinguish the Fr influence on C_0 parameter using the proposed procedure. Figure 4 shows the adjustments in the bubble velocity according to the process described above. The C_0 values varied from 1.11 to 1.16 with a maximum deviation of 8% as proposed by Bendiksen, (Tab. 3).

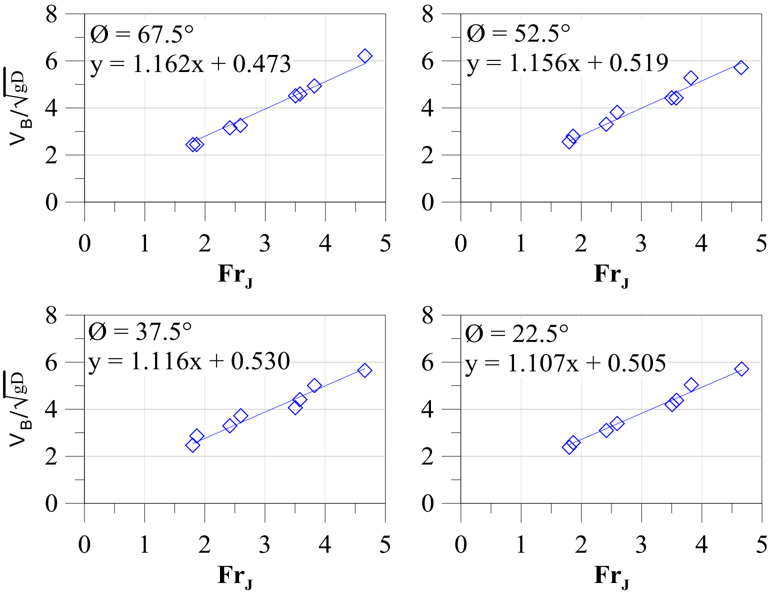

Figure 4. Determination of experimental values of C_0

Table 3. C_0 values when the linear regression is forced to pass through the theoretical C_∞ values

θ	C_0 experimental	R^2	C_0 Bendiksen (1984)		Deviation
67.5	1.162	0.982	$Fr_J > 3.5$	1.171	0.75 %
			$Fr_J < 3.5$	1.200	3.27 %
52.5	1.156	0.963	$Fr_J > 3.5$	1.126	2.61 %
			$Fr_J < 3.5$	1.200	3.81 %
37.5	1.116	0.955	$Fr_J > 3.5$	1.074	3.75 %
			$Fr_J < 3.5$	1.200	7.53 %
22.5	1.107	0.984	$Fr_J > 3.5$	1.029	7.02 %
			$Fr_J < 3.5$	1.200	8.40 %

3.3 Average slug flow parameters

The bubble and liquid slug length at vertical, horizontal and along the elbow, the frequency before and after the elbow and the coalescence rate at elbow are shown in Fig. 5. The open and closed symbols represents the experimental data obtained with this study and by Bueno (2010), respectively. The values represents average values of all units passing through the sensors. As showed in Fig. 5(a) the bubble length increases through the vertical to horizontal transition, mainly in the last part of it. The dimensionless bubble´s length increase is near 50% in the transition. The most data show a bubble 5 to 10D long, but in the horizontal section in test #3 the average bubble length is 15D. The exception is test #2, where the bubble´s length increased at the beginning of the transition. There is a maximum length near 45º and after that the bubble length decreases. In this test the bubble length increased by nearly 30% in the vertical to horizontal transition. The average bubble´s length found in this study was in the same order of magnitude of Bueno (2010) at the same gas and liquid flows rates, except for the horizontal station. In this station, the bubble was shorter than Buenos´s, but this can be associated with the short distance between the station and the transition. Therefore, the curvature doesn't seem to have any significant influence in the bubble´s length.

The dimensionless liquid slug length through the transition was shown in Fig. 5(b), and the curvature effect is more intense than in the bubble´s length. The liquid slug length changes all around the transition, and the behavior was the same for all tested cases. The liquid slug length increased at transition entrance, reaching its maximum value nearby 45º and decreasing to the horizontal values. The maximum liquid slug length it is 20% bigger than the minimum and at horizontal the liquid slug length it is 10% bigger than the vertical one. The liquid slug lengths for all the tested cases span from 8 to 10D. There are only two points outside these values. All the measured liquid slug lengths are shorter than the Bueno´s (2010), but compatible with van Hout *et al*., (2003) for developing slugs flows. Figure 5(c) shows that there is no changes in the frequency through the transition. The frequency is 2, 3, 4 and 6 Hz for the tested cases #1 to #4, respectively. Thus, there is a frequency increase with the mixture velocity and with the J_L/J_G ratio. The measured frequency in this study is higher than Bueno´s. Figure 5(d) shows the coalescence rate into the vertical to horizontal transition. The coalescence rate as determined by the frequency measured at vertical and horizontal station by:

$$R(\%) = \frac{100}{L/D} Ln\left(\frac{f_h}{f_v}\right), \tag{3}$$

where L is the distance between the two measure station; D is the pipe diameter and f_h e f_v is the frequency at horizontal and vertical station, respectively.

The high values for the coalescence ratio in the vertical to horizontal transition indicates a strong interaction. As presented by Fig. 5(c) and (d), there is a tendency to achieve shorter liquid slugs and there is a higher interaction when the curve is present. However, it is not possible to distinguish if this behavior is due to the presence of the transition or if it could still be induced by the formation process or even if the high coalescence rate is due to the thickening of the liquid film during the transition. A carefully study regarding the influence of these matters should be done in order to answer these questions.

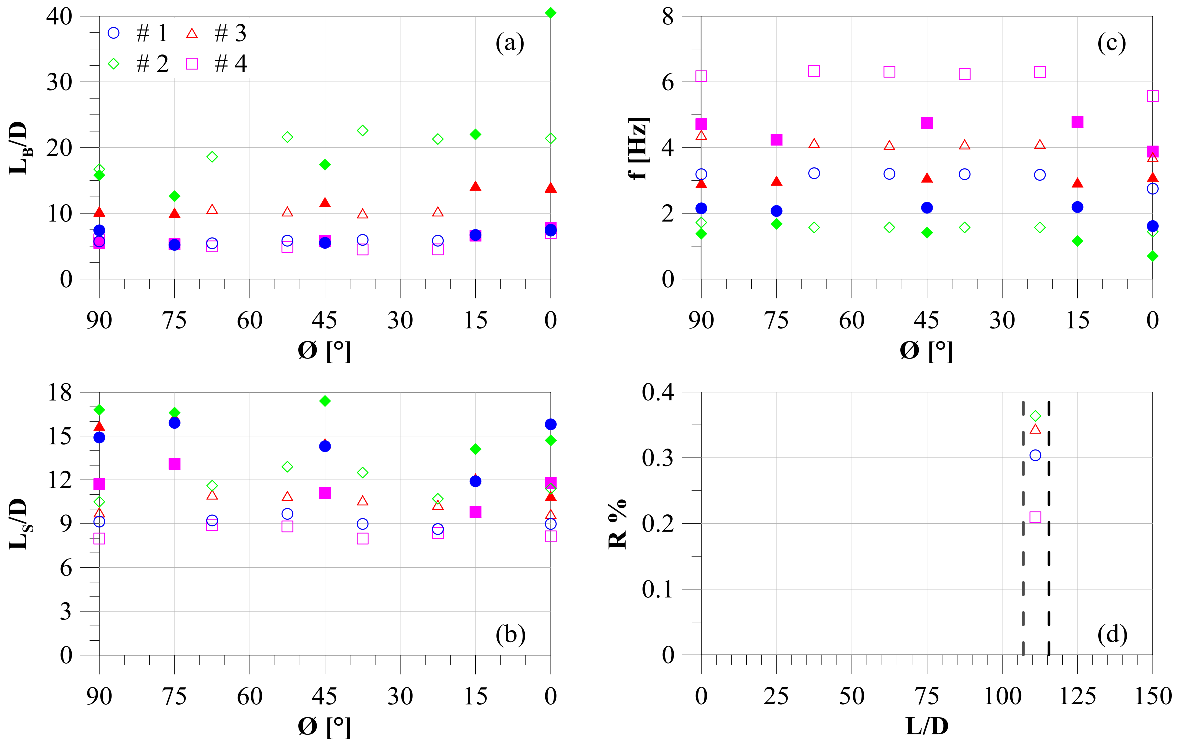

Figure 5. Mean parameters of (a) bubble length; (b) liquid slug length; (c) frequency; (d) coalescence rate
Dashed lines represents the beginning and the end of the elbow and closed symbol data from Bueno (2010)

3.4 Slug flow parameters distributions

Figure 6 shows the probability density functions for the bubble´s velocity, bubble and liquid slug lengths and frequency into the vertical, horizontal and along the transition for the all tested cases. All the measured parameters had a normal PDF distribution as expected for a developed slug flow. The PDF for the bubble velocity is shown in Fig. 6(a). The curvature didn´t affect the velocity dispersion for test case #1, but with the increase of the J_G/J_L ratio (case #2) the dispersion increased from vertical to horizontal. The dispersion increased by increasing the mixture velocity, as shown in the bubble velocity PDF for the case #3 and #4. This phenomenon can be related with the liquid profile change due to the curvature. The curvature induced a secondary flow which shifted the maximum liquid's velocity of the pipe's line symmetry.

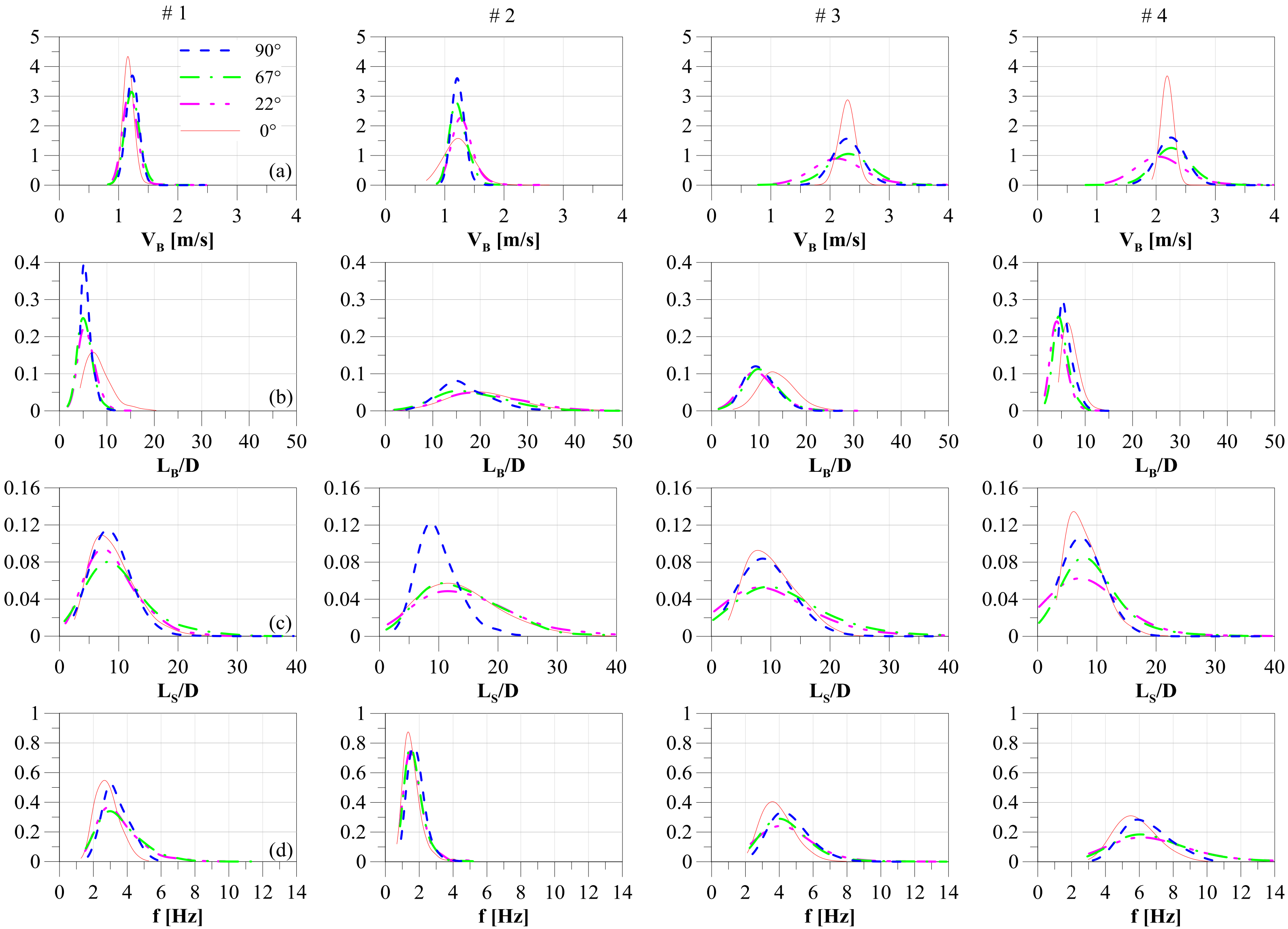

Figure 6. Parameters distributions of (a) bubble velocity; (b) bubble length; (c) liquid slug length; (d) frequency

The bubble's length PDF is shown on Fig. 6(b) and the length spans from 2 to 20D for all tested cases, except for case #2 where the bubble´s length spans from 5 to 50D. This is the highest J_G/J_L ratio case, i.e, it is the highest proportional amount of gas being transported and the slug flow was not developed yet. The coalescence ratio is the highest too, which support this hypothesis. The liquid slug length PDF was shown in Fig. 6(c). Test cases #2 and #3 presented higher dispersion on the horizontal station than the vertical. In this cases, there are liquid slugs with 30D length. In case #1 the maximum length is 20D and in #4 there is a small amount of liquid slug length larger than 20D, but only for measuring stations at 22º and at horizontal. The Fig. 6(d) shows the frequency's PDF for all test cases. The frequency spans from 2 to 6 Hz in case #1 and from 1 to 4 Hz in case #2. In cases #3 and #4 the frequency spans from 2 to 8 Hz. The maximum frequency in case #4 is at the horizontal station and it is 12 Hz.

4. CONCLUSIONS

The presence of the vertical to horizontal elbow as proposed in this study doesn't have a major influence on the translational bubble's noise velocity. The measured bubble's velocity results through the transition was in accordance to the values presented by Bendiksen (1984). The values of C_0 parameter spans from 1.11 to 1.16 and are in accordance with data for inclined pipes. However, a better process for the determination of C_0 and C_∞ should be tested to confirm the results presented. The transition doesn´t affect the dimensionless bubble's length, but the liquid slug length was affected. It was not possible to determine if the high frequency and the high coalescence ratio through the transition was due to a developing slug flow condition or to the transition. The PDF´s showed a major bubble velocity dispersion trend due to the mixture velocity increase. The bubble's length dispersion increased with the J_G/J_L ratio.

The majority of measured parameters through the transition are compatible with the ones for inclined ducts. Consequently the curvature in the vertical to horizontal transition tested doesn´t have a significant effect on them. The distance between the injector and the vertical station in the experimental setup was short and this could have affected the results. Therefore further studies must be performed to verify and eliminate, if necessary, the influence of the injection process in data gathering.

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6. RESPONSIBILITY NOTICE

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