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EXPERIMENTAL ANALYSIS OF TWO-PHASE SLUG FLOW EVOLUTION WITH A SLIGHT UPWARD DIRECTION CHANGE

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Abstract. *The slug flow pattern has a liquid and gas intermittence characteristic and, this pattern is found especially in oil and gas production and transportation lines. The slug flow behavior is important for the correct industrials equipment design those operates in the lines. In deep-water oil operations, it is common to observe situations where the piping needs to adjust to the seabed relief, thus causing direction changes in the flow. In this context, the present work presents a liquid-gas two-phase slug flow pattern experimental study in ducts with slight direction changes, consisting of initial horizontal stretches followed by an upward inclined stretch with angles of + 3 °, + 5 ° and + 7 ° with respect to the horizontal in a 26 mm ID, 35,7 m long pipe. Resistive sensors were installed at four different locations to measure the slug flow characteristic parameters. Based on the obtained results, the slight direction change influence was evaluated in the characteristic parameters changes.*

Keywords: *two-phase flow, slug flow, flow with direction change*

1. INTRODUCTION

Multiphase flows are characterized by a simultaneous two or more phases flow, which can be liquid, gas or solid (Crowe, 2005). This kind of flow is widely observed in natural and industrial applications. Regarding the petroleum industry, multiphase flows are frequently compound by connate water, gas, oil and even solid particles, such as hydrates and sand. To simplify its comprehension, flow conditions are usually treated as an only two-phase gas-liquid flow, due to operating and geometry conditions, this two-phase mixture assumes different disposals in pipelines. Those disposals are known as flow patterns and, according to Shoham (2006), they are classified in: stratified (smooth and wavy flow), intermittent (elongated bubbles and slug flow), annular, and dispersed bubbles.

According to Shemer (2003), the slug flow is the most common pattern in oil and gas production, since it may be observed over a wide liquid and gas flow range. The slug flow pattern is mainly characterized by the alternating passage of a liquid slug and an elongated bubble. Some parameters characteristics used to understand its behavior are: elongated bubble velocity, unit cell frequency, liquid slug length, elongated bubble length and phases fractions.

In deep-water production, pipelines needs to adjust to the seabed relief, which may cause direction changes for long distances with a slight inclination. In this case, the slug flow tend to modify itself by transitioning the flow pattern or even changing its parameters. Therefore, recent studies (Henau and Raithby (1995); Taitel and Barnea (2000); Mandal et. al. (2008); Parra et. al. (2013); Ersoy et. al. (2017)) aimed at describing the flow behavior caused by direction change, since its evolution may be important both in equipment design and oil transportation.

The present paper introduces a liquid-gas two-phase slug flow pattern experimental study in long ducts with slight direction changes. The experimental layout consists of initial horizontal stretches, followed by an inclined stretch. Four different configurations were used: three upward with +3°, +5° and +7° angles and one completely horizontal. Based on the obtained results, the slight direction change influence was evaluated in the characteristic parameters changes.

2. EXPERIMENTAL METHODOLOGY

"Figure 1" illustrates the experimental facility. Air at ambient conditions (100kPa and 298K approximately) and water were used as the gaseous and liquid phases. The liquid phase was composed by tap water, stored in an open atmospheric liquid tank and pumped into the system by a centrifugal pump controls by a frequency inverter on the electric motor. A Coriolis-type flowmeter was used to measure the liquid flow rate. For the gaseous phase, air was compressed and stored in pressure vessels. The gas flow rate was also measured by Coriolis-type flowmeters, in addition to a manual valve placed between the flow meter and the mixer.

The experiments were performed in the test facility at NUEM labs (Multiphase Flow Research Center at Federal University of Technology – Paraná) and 4 different scenarios were proposed, all of them using a 26 mm ID transparent acrylic pipe. The first scenario was a 35.6 m(~1369D) long complete horizontal pipe (θ=0°). Furthermore, the 3 scenarios had 15 m(~577D) long horizontal section followed by 20.6 m(~792D) long upward inclined section, with inclinations (θ) of +3°, +5° and +7° in relation to the horizontal, as shown in "Fig. 1".

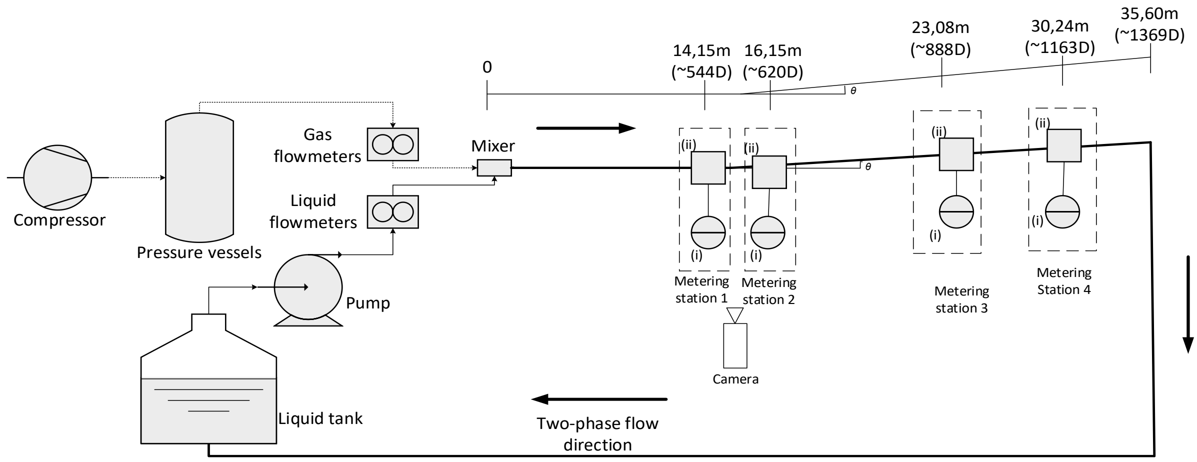

Figure 1. Schematic representation of the test facility

The two-phase flow was formed at the parallel plate mixer and developed along the pipe. The mixture flowed through the inclined section until reach the test section outlet, where the phase separation was conducted using gravity in a 35.60 m(~1369D) long pipe. The metering stations were disposed 14.15 m(~544D), 16.15 m(~620D), 23.08 m(~888D) and 30.24 m(~1163D) distant from the mixer. A pair of resistive sensors and a pressure gauge composed each metering station. The resistive sensor was used for the slug flow main characteristic parameters extraction. Meanwhile, the pressure gauge monitored the pressure along the flow and provided the gas surface velocity corrections. A high-speed camera was placed between metering stations 2 and 3, in order to observe the phenomenon in the inferior elbow.

The resistive sensor acquired voltage values and related them to the liquid and gas fractions along the pipe. The sensors were developed by Machado *et. al.* (2013) at NUEM and its signals were processed according to Vicencio's (2013) algorithm That processing provided slug flow characteristic parameters, such as elongated bubble velocity (V_B), unit cell frequency (f), elongated bubble (L_B) and liquid slug lengths (L_S).

3. RESULTS

In this section, experimental results of slug flow parameters (elongated bubble velocity (V_B), unit cell frequency (f), elongated bubble (L_B) and liquid slug lengths (L_S)) will be presented, discussed and compared, with literature correlations. The experimental points were defined to their superficial velocities pairs, varying from 0.3 to 2.5m/s for gas and 0.3 to 3m/s for liquid phases, being 18 points in total as "Tab. 1" shows. This was done in order to ensure the slug flow pattern along the horizontal test section occur.

Table 1. Test grid

Pair	**J_G (m/s)**	**J_L (m/s)**	**Pair**	**J_G (m/s)**	**J_L (m/s)**
P01	0.3	0.7	**P10**	1.3	0.7
P02	0.5	0.5	**P11**	1.5	0.5
P03	0.7	0.3	**P12**	1.0	2.0
P04	0.5	1.0	**P13**	1.5	1.5
P05	1.0	0.5	**P14**	2.0	1.0
P06	0.5	1.5	**P15**	1.0	3.0
P07	0.75	0.75	**P16**	1.5	2.5
P08	1.0	1.0	**P17**	2.0	2.0
P09	0.7	1.3	**P18**	2.5	1.5

"Figure 2" shows, for each inclination, the elongated bubble velocities (V_B) obtained with the resistive sensor for all points and stations in compare to Bendiksen's (1984) correlation. The comparative errors observed are around ± 10% and this indicates a good experimental data agreement with the literature. Moreover, there are no observed significant variations in the V_B relative to Bendiksen (1984) when the inclinations change to 0° until 7°, as shows in "Fig. 2.a" to "Fig. 2.d".

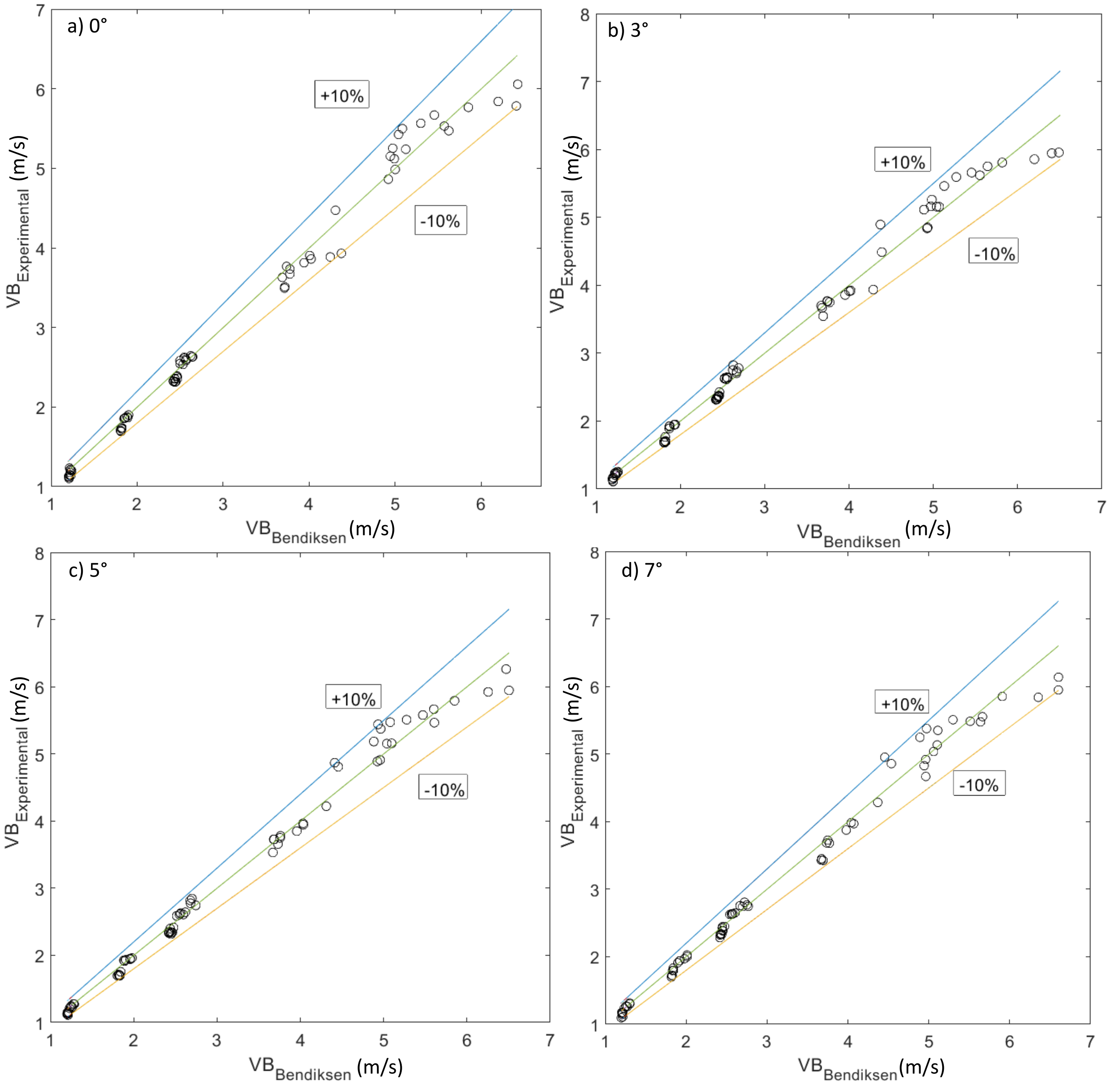

Figure 2. Elongated bubble velocity compared with Bendiksen (1984) correlation.

In "Figure 3.a", it can be observed the dimensionless bubble length (L_B/D) behavior in compare to superficial velocity ratio for θ=3° and 7°. The dimensionless bubble length tends to increase with the superficial gas velocity increase, what was expected because with more gas, the bubble tends to grow up. Furthermore, when the superficial gas velocity increases, the bubble coalescence increase to and the length of it grows. Otherwise, the dimensionless unit cell frequency, represented by the Strouhal number (St), tends to decrease with de superficial gas velocity increases, as "Fig. 3.b" shows. The frequency is related with the bubble length, because when the bubble length grows, less unit cell pass and, with that, the frequency decrease. Observing "Figure 3.a" and "Figure 3.b", the inclination angle (θ) of 3° and 7° do not affect the bubble length neither the frequency behaviors in compare to superficial velocity ratio.

In addition to the bubble length and the unit cell frequency, two other parameters are important to understand how the slug flow behaves, despite its stochastic form; those are the slug length (L_S) and the intermittence factor (β). The slug length is related to bubble coalescence because when the slug length is not long enough to be stable, the wake region from the front bubble accelerate the back bubble and the coalescence occurs. When that phenomenon happens, the liquid in the slug that has disappeared migrates to the other slugs growing and stabilizing them. The second one is defined as being the ratio between bubble lengths with the unit cell length (Taitel and Barnea, 1990). The intermittence factor is use to ponder, in mean terms, the slug and bubble structures occurrence.

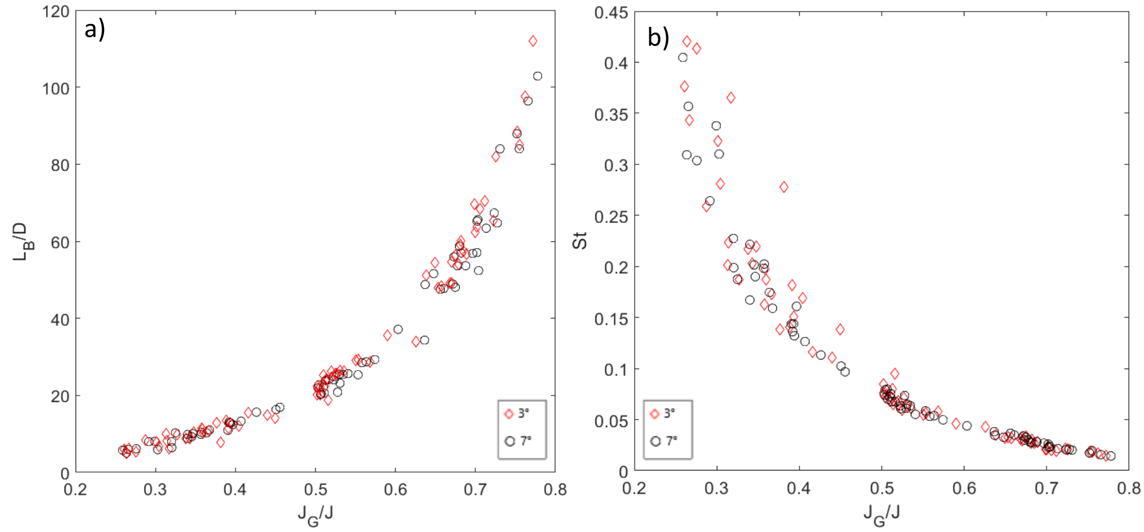

Figure 3. (a) Dimensionless bubble length (L_B/D) and (b) dimensionless unit cell frequency (St) compared with superficial gas velocity ratio (J_G/J) for 3° and 7°, respectively.

The "Figure 4.a" shows the dimensionless slug length in compare to superficial gas and liquid velocities ratio. In firstly place, Dukler *et. al*. (1985) says that for horizontal pipes the L_S tends to be between 12 and 24D for stables slug. In this work, for inclined upward pipes, the slug length is observed with values below 30D, and has values below 12D that is may be those slugs are unstable.

In the "Figure 4.a", the dimensionless slug length tends to increase with the superficial gas and liquid velocity ratio increases. That should occur because, when the superficial velocity ratio increase, the bubble interactions and their coalescences increases and, with that, the liquid migrates for slug to other and grow, how was explained in the last paragraph.

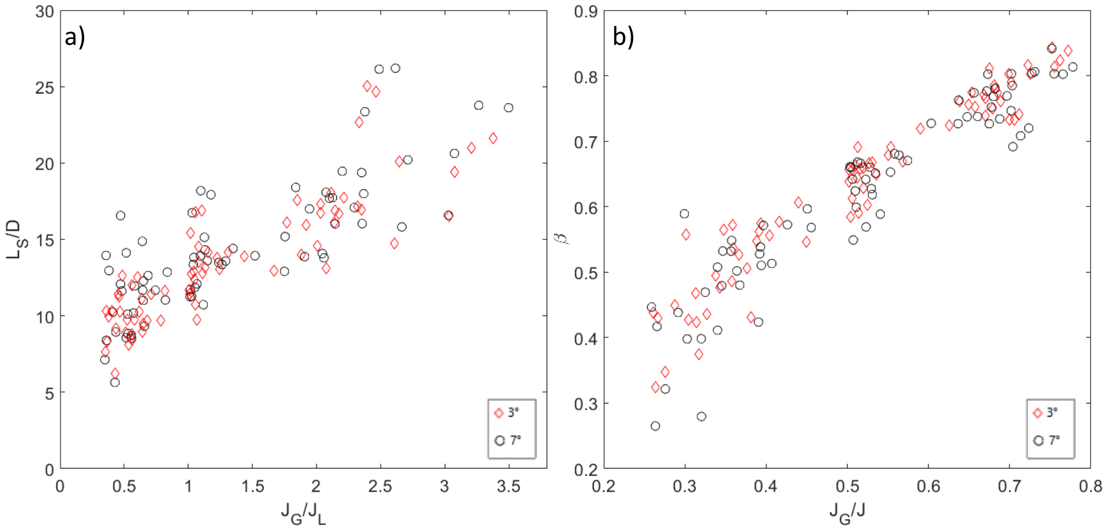

Figure 4. (a) Dimensionless slug length (L_S/D) and (b) Intermittence factor (β) compared with superficial velocity ratio (J_G/J_L) for 3° and 7°, respectively.

The intermittence factor (β), observed in "Fig. 4.b", tends to increase with the superficial gas velocity ratio (J_G/J), this was expected because when the gas flow rate increases more coalescence happens, the slug lengths increases, causing more intermittence in the flow. How the β are defined in slug and bubble lengths, the values it can assume varies between 0 and 1, but β =0 configures L_B=0 (dispersed bubble) and β=1 to L_S=0 (annular or stratified flow), so for slug flow, these cases do not apply. In this way, for slug flow the intermittence factor should have values 0<β<1. In the "Figure 4.b", it can be observed the values are correct.

Analyzing the inclination degree change, it was observe the dimensionless slug length (L_S/D) do not vary so much with the superficial velocity ratio (J_G/J_L), but for the intermittence factor (β) has a slight difference between 3° and 7° for low superficial gas velocities. That difference can be created because for 7° and for the points with low mixture velocity (J) the elbow influence bubble breaks and slug generation.

The "Figure 5" shows the mean values obtained experimentally for the elongated bubble velocity (V_B), for each metering station and inclination, as function dimensionless position along the pipe (L/D). The points represented in "Fig. 5.a" and "Fig. 5.b" corresponded to P01 and P03, respectively. In both graphics, the elongated bubble velocity tends to increase in all the scenarios.

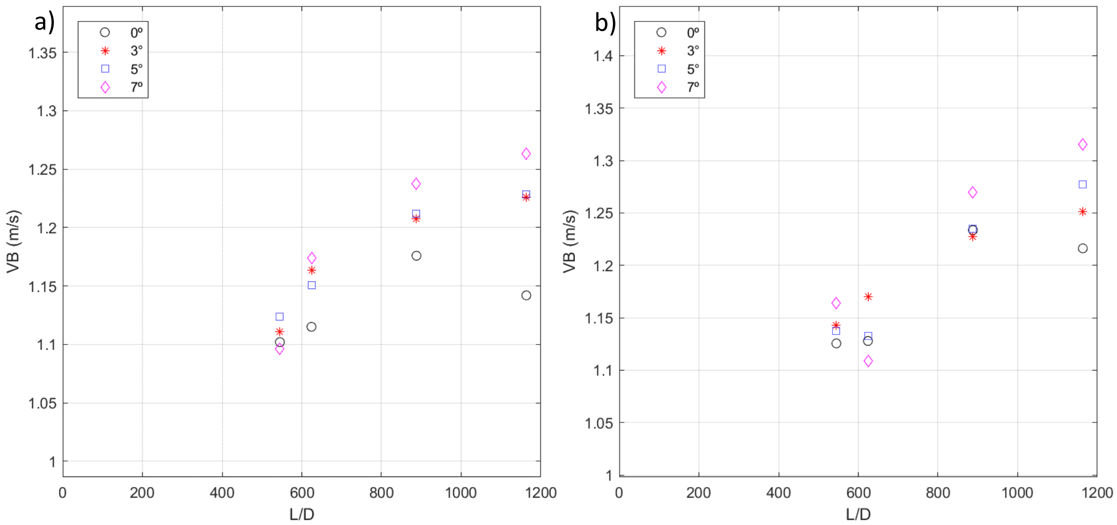

Figure 5. (a) The mean elongated velocity for P01 (J_L=0.7 m/s; J_G=0.3 m/s) and (b) for P03 (J_L=0.3 m/s; J_G=0.7 m/s) for all scenarios.

In the 0° scenario, the V_B increases until arrives a plateau and does not vary so much in the last stations, that is, the flow is fully developed. Otherwise, for +3°, +5º and +7º, the velocity continues to increase until the last station. That effect can be explained because, for those inclinations, the liquid film above the elongated bubble flows downward due to gravity, meanwhile the buoyancy assists the bubble in the flow direction causing the velocity increase along the flow.

In "Figure 5.b", another effect can be observed, that is after the +5º and +7º there is a slight velocity decrease for the point P03. This can be caused by the turbulence generated by the liquid film flowing both downwardly after and that which goes toward the flow before the elbow. This phenomenon accumulates fluid in the elbow and may causes it to break the elongated bubble in two, slowing the mean velocity promptly, as seen in "Fig. 6.b". For the point P01, that is not observed the velocity decrease after de elbow, because for that velocity pair, the bubble breaks do not happen, as "Fig. 6.a" shows. However, it was noted small bubbles detachment in the rear region due the turbulence generated by the liquid accumulation in the elbow, and that effect decrease the bubble tail.

The bubble length (LB) influences the bubble break effect. The "Figure 7.a" and "Figure 7.b" shows, for the points P01 and P03, respectively, the mean values obtained experimentally and for the dimensionless bubble length (L_B/D), for each metering station and inclination, as function dimensionless position along the pipe (L/D). The bigger difference between the points P01 and P03 is the mean value range. The P01 has a dimensionless bubble length 10 times smaller than P03. That was because the superficial gas velocity for the P03 is proportionately higher than P01. When the P01 bubble pass through the elbow there is not enough length to the accumulated liquid breaks the bubble. However, the P03 for having enough bubble length, the bubble break in two other bubbles.

In the "Figure 7", for 0°, the bubble length tends to grow up for the both points. For the P01 show in "Fig. 7.a", the L_B increase until the pipe end. These was because, for smaller bubbles is higher the interaction between those, and that support the coalescence effect besides the gas expansion caused by the pressure drop. However, for the P03 show in "Fig. 7.b", the L_B increase until arriving a plateau in the last station and that was explained because, the P03 has a big bubble length which has a little interaction between bubbles decreasing the coalescence rate.

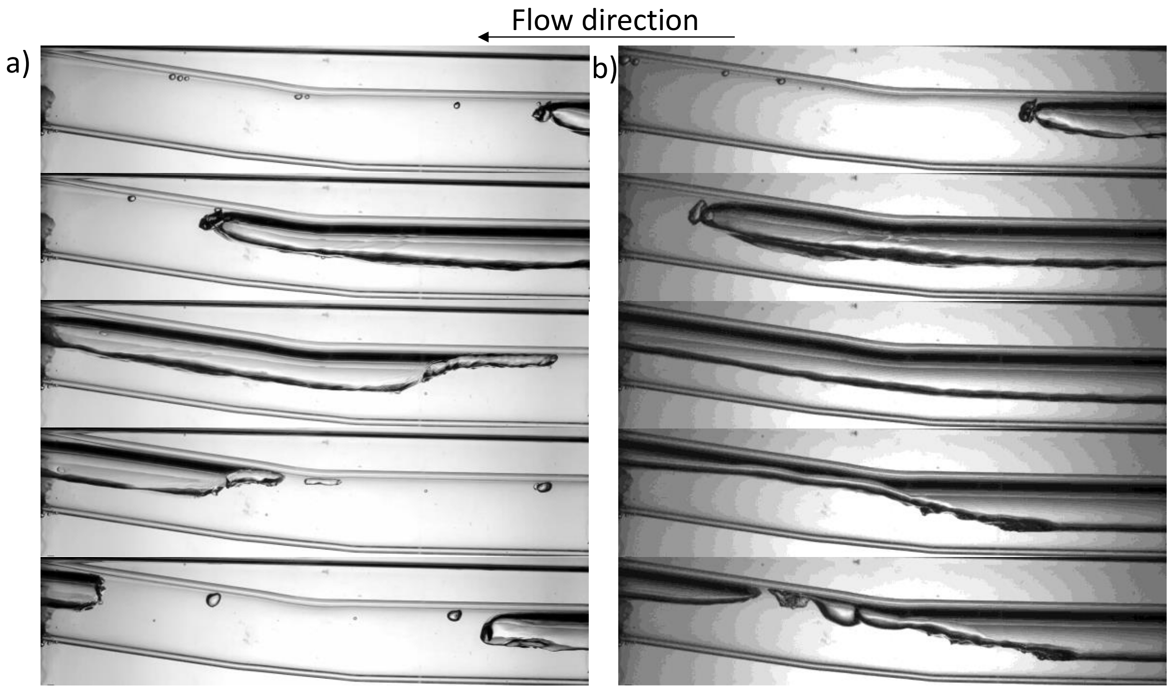

Figure 6. (a) P01 and (b) P03 elongated bubble passing through a 7° elbow.

Analyzing the upward inclination in compare to horizontal pipe in the “Fig. 7”, it was observed the bubble length decrease after the elbow for the three scenarios, but along the upward region increase again until the end. That L_B decreases is more intense when the inclination grows, what is expected because, the turbulence grows with higher inclinations. For the P01, the L_B decrease after the elbow because of the tail bubble length decreases and bubble detachment, as can be seen in “Fig. 6.a”, however the buoyance assist the bubbles in the flow direction and promotes the coalescence and with that grow the bubble length until the las station. In the P03 case in “Fig. 7.b”, the L_B decreases after the elbow because the bubble breaks and along the upward region the L_B increases because some broken bubbles coalesce again.

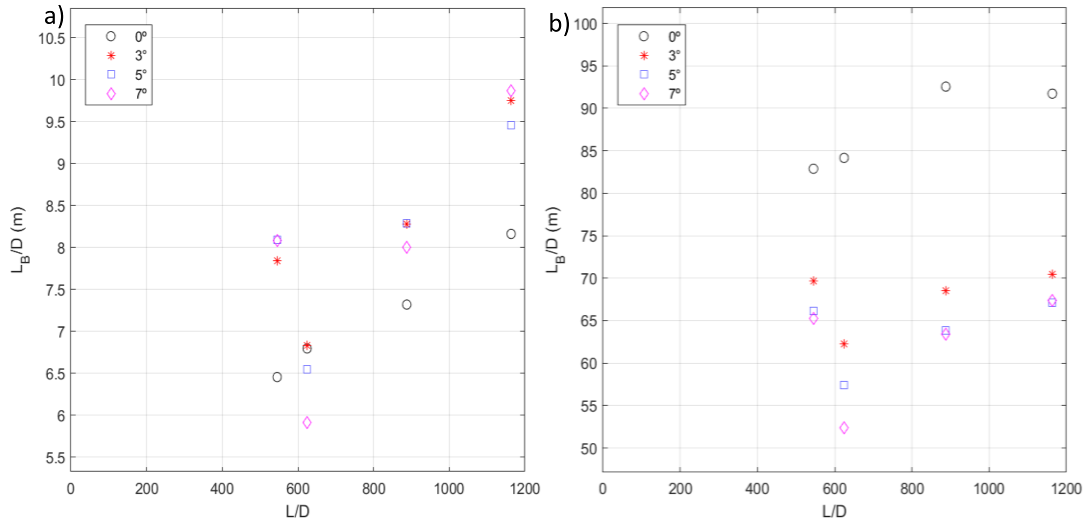

Figure 7. (a) The mean bubble length for P01 (J_L=0.7 m/s; J_G=0.3 m/s) and (b) for P03 (J_L=0.3 m/s; J_G=0.7 m/s) for all scenarios.

Besides the elongated bubble velocity (V_B) and the bubble length (L_B), the liquid accumulate in the elbow influences to the slug length (L_S). The “Figure 8.a” and “Figure 8.b” shows the mean values obtained experimentally for the dimensionless slug length (L_S/D), for the points P01 and P03, respectively, for each inclination and metering station. The L_S tends to increase for all inclinations in both points, only for the last station for the P03 decreases or arrives a plateau in the four scenarios. The L_S increases are influenced by the bubble coalescences, because when that happen the liquid between the bubbles migrates to the other slugs growing them. In the P03 last station, the L_S decrease happens because in that station almost has no coalescence. Instead of that, it occur the gas expansion, that expansion grows the bubble length, which was discussed before, and grows the liquid film above the bubble removing liquid from the slug and decreasing them. In both graphics in "Figure 8", it can be observed an accelerated growth after the elbow in compare to the horizontal pipe, this is caused by the accumulated liquid in that region.

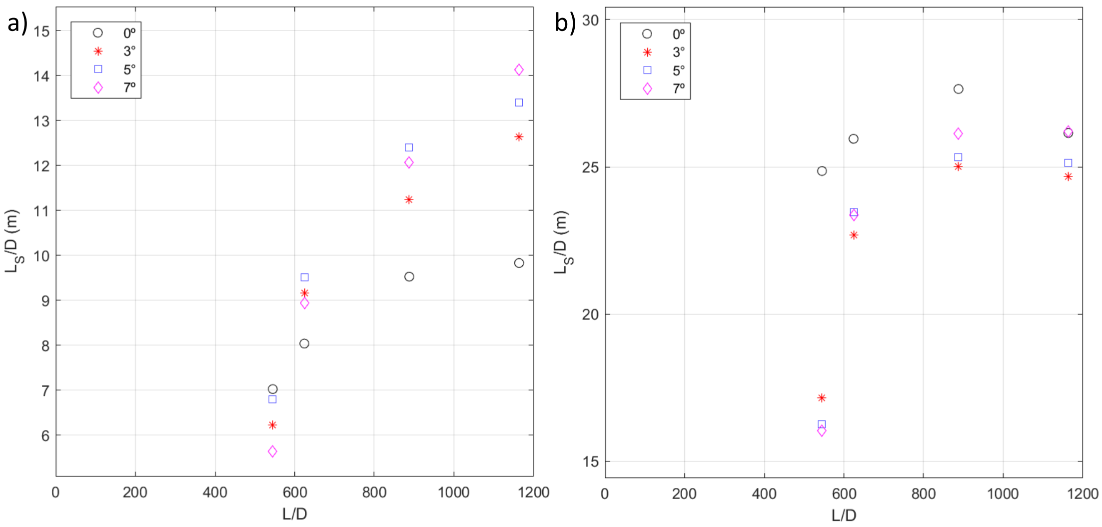

Figure 8. (a) The mean slug length for P01 (J_L=0.7 m/s; J_G=0.3 m/s) and (b) for P03 (J_L=0.3 m/s; J_G=0.7 m/s) for all scenarios.

The "Figure 9.a" and "Figure 9.b" presents the unit cell slug frequency (*f*) similar to the previously figures. The P01 frequency tends to decrease along the pipe for all inclination, as "Fig. 9.a" shows, and that is because the unit cell length (L_U) increase, decreasing the unit cell passage in the same time. The frequency decreases are bigger in the upward scenarios in compare to the horizontal. That difference was because in the upward scenarios the L_U was higher at each station them the horizontal case as discussed before. For the P03, in "Fig. 9.b", the frequency decrease for the horizontal scenario for the same frequency of P01 reason. However, for the upward scenarios, the frequency increase after the elbow, which was expected because in this region the number of bubble increases in function of the bubble breaks. The local unit cell number increase decreasing the frequency. Far from the elbow, the bubble coalesces and the frequency tends to decrease similar to the horizontal. In the other hand, for the last station how the L_S tends to decrease, as "Fig. 8.b" shows and discussed in the last paragraph, the L_U has slight decrease and, because of that, the frequency has a slight increases.

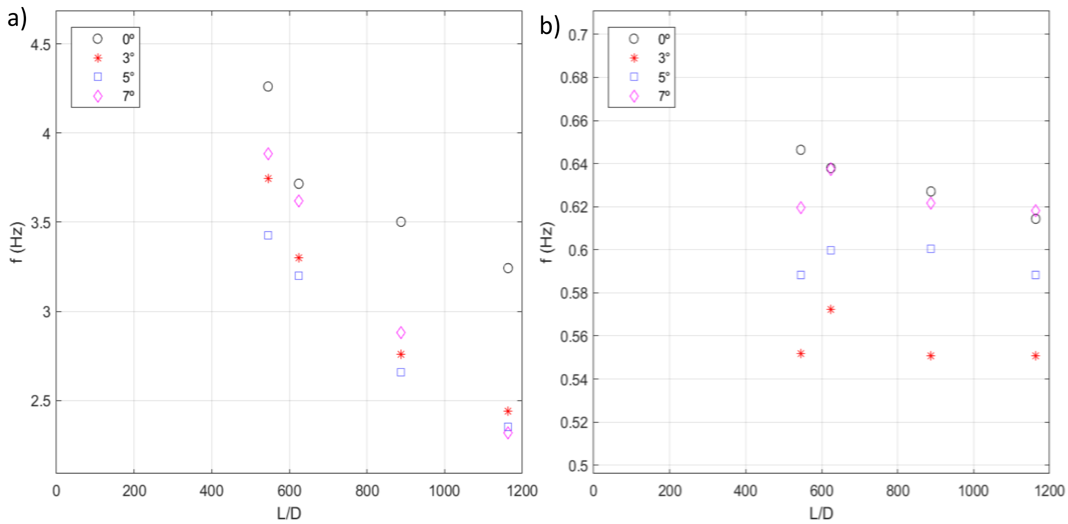

Figure 9. (a) The mean unit cell slug frequency for P01 (J_L=0.7 m/s; J_G=0.3 m/s) and (b) for P03 (J_L=0.3 m/s; J_G=0.7 m/s) for all scenarios.

4. CONCLUSIONS

In this work, a two-phase gas-liquid slug flow with slight change direction experimental study was presented. Four different configurations were used: three upward with +3°, +5° and +7° angles and one completely horizontal. It was used four metering station disposed 14.15 m (~544D), 16.15 m (~620D), 23.08 m (~888D) and 30.24 m (~1163D) distant from the mixer. A pair of resistive sensor and a pressure gauge composed those metering station. In addition, a high-speed camera was used to observe the flow.

The results are slug flow characteristic parameters mean values and observe how they change when there is a slight direction change. The elongated bubble velocity (V_B) evolution tends to increase for all points and scenarios, what is expected due the gas expansion induce to the pressure drop along the pipe. In the 0º scenario, the V_B arrives a plateau and assume a fully developed flow in the last station, for some points. However, that is not observed for the upward inclinations, because the buoyancy assists the bubbles in the flow direction accelerating them until the end.

In the elbow region, it can be observed some effects, for example, the liquid accumulate and the bubble breaks. Those effects influence the slug flow parameters promptly or, sometimes, propagated along the pipe. After the elbow, the V_B tends to decrease because of the bubble breaks. The new formed bubbles are not so fast them the original bubbles. However, the V_B increases again when moves away from the elbow.

The bubble breaks influence the slug unit cell frequency and the bubble length to. In the 0º scenarios, the bubble length increases for all points because of gas expansion and bubble coalescences. However, when the bubbles break happen the bubble length decrease and, with that, a new unit cell is created. Because of that, the frequency, which tends generally to decrease because of coalescences, in this case increases. The liquid accumulation in the elbow besides assists the bubble breaks also increases the slug length more fast in compare to the normal increases for 0º scenario.

5. ACKNOWLEDGEMENTS

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