EXPERIMENTAL STUDY OF TWO-PHASE GAS-LIQUID SLUG FLOW WITH A SLIGHT DIRECTION CHANGE

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Abstract. *Gas-liquid two-phase flow is very common in industrial applications, especially in the oil and gas, chemical, and nuclear industries. As operating conditions such as the flow rates of the phases, the pipe diameter and physical properties of the fluids change, different configurations called flow patterns take place. In the case of oil production, the most frequent pattern found is slug flow, in which continuous liquid plugs (liquid slugs) and gas-dominated regions (elongated bubbles) alternate. Due to its intermittent nature, slug flow is quite often a source of unwanted operational problems such as vibration, corrosion, erosion and high pressure drops. Offshore scenarios where the pipe lies onto the seabed with slight changes of direction are extremely common. With those scenarions and issues in mind, this work presents an experimental study of two-phase gas-liquid slug flows in a duct with a slight change of direction, represented by a horizontal section followed by a downward sloping pipe stretch. The experiments were carried out at NUEM (Núcleo de Escoamentos Multifásicos UTFPR). The flow initiated and developed under controlled conditions and their characteristic parameters were measured with resistive sensors installed at four pipe sections. A high-speed camera was also used. With the measured results the mean values of parameters such as bubble velocity and bubble length were evaluated in order to characterize the behaviour of the slug flow structures.*

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

1. INTRODUCTION

Multiphase flows are characterized by the simultaneous flow of two or more phases – be they liquid, solid or gaseous – through a pipe or channel. This type of flow is common in industrial applications, and is found in steam generators, refrigerators and other pieces of equipment in the chemical, nuclear and oil industries.

In the specific case of oil and gas production the presence of multiphase flow involving oil, water, gas and even solid particles such as sand is very common. The characterization of this type of flow has great importance in equipment sizing and, due to its complexity, simplified approaches are often used for design and project purposes. The liquid phase consists of oil and water, whereas the bulk of the gaseous phase may originate from several sources (out of the liquid by vaporisation, from gas injected into the reservoir rock, from gas lift operations and so on).

The gas-liquid interfaces can assume different configurations inside the pipeline during the flow from the oil well to the platform. Each configuration relates directly to and is determined by the flow rates of the phases, the physical properties of the fluids and the pipe geometry. Such configurations are called flow patterns (Shoham, 2006). Shoham (2006) classified the four most common flow patterns in horizontal two-phase flows: stratified, intermittent, annular and dispersed bubble. According to this classification the stratified flow pattern is divided into stratified smooth and stratified wavy, the intermittent flow into elongated bubble and slug, and the annular flow into wavy-annular and annular.

In oil production, fluids are usually transported over long distances through pipelines that present inclination changes due to irregular terrain profiles. Observations have shown that in such pipelines slug flow is the most commonly found pattern.

The slug flow pattern, represented in Fig. 1, is characterized by the intermittent occurrence of two structures: one composed by a continuous liquid plug that may or may not contain dispersed gas bubbles. This structure is called liquid slug. The other structure is formed by a gas pocket sliding over a liquid film. This structure is called elongated bubble and fills a large part of the pipe cross sectional area.

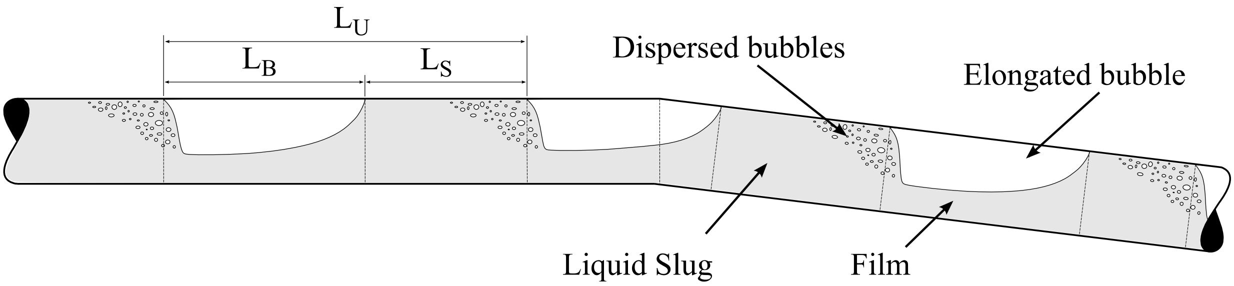


Figure 1. Schematic representation of the slug flow

Several authors have sought to describe the behaviour of the slug flow with direction change through numerical (Zheng *et al.*, 1994; Taitel and Barnea, 2000; Al-Safran *et al.*, 2004) and experimental studies (Al-Safran *et al.*, 2000; Al-Safran *et al.*, 2005; Mandal *et al.*, 2008). The present work introduces an experimental study of the two-phase gas-liquid slug flow in a pipeline with a slight direction change, composed by a horizontal section followed by a slightly inclined downward section, as shown in Fig. 1. To evaluate the influence of the change of direction in the flow, the following parameters are analyzed: the elongated bubble velocity (V_{TB}) and the bubble length (L_B).

The elongated bubble velocity is an important parameter in the development of flow prediction models. The velocity is related to the pipe diameter and inclination, to the phase velocities and to the fluid properties (Bendiksen, 1984).

As the bubble and the piston carry, respectively, the majority of the gas and of the liquid in the flow, determining the length of both the elongated bubble and the liquid slug (L_S) becomes very important. The combination of those two structures is known as a *unit cell*, a term coined by Wallis (1969). The unit cell length, L_U, is shown in Fig. 1.

2. EXPERIMENTAL METHODOLOGY

The experiments were performed at the test facility in the NUEM (Núcleo de Escoamentos Multifásico UTFPR) labs, a 26-mm ID transparent acrylic pipeline composed of a 5.76-m long horizontal section followed by a 3.38-m long inclined downward section with an inclination (θ) of –7º in relation to the horizontal. The pipe outlet was subjected to the atmospheric pressure and the tested fluid was a mixture of tap water and air at room conditions.

The test facility shown in Fig. 2 includes: a water tank (350 l); a centrifugal pump (Fabo BCIE602/7822); a coriolis flow meter (Micromotion F050S11); a compressor (PEG, with maximum pressure of 8 bar); two pressure vessels (Engetank, with maximum pressure of 14 bar and capacities of 100 and 500 l); an orifice plate to measure the gas flow rate; a parallel plate mixer; a differential pressure transducer (Rosemount 2051CD) and five relative pressure transducers (Rosemount 3051TG).

The instrumentation was connected to a communication network using the Foundation Fieldbus protocol, linked to software developed in LabVIEW for monitoring the flow conditions.

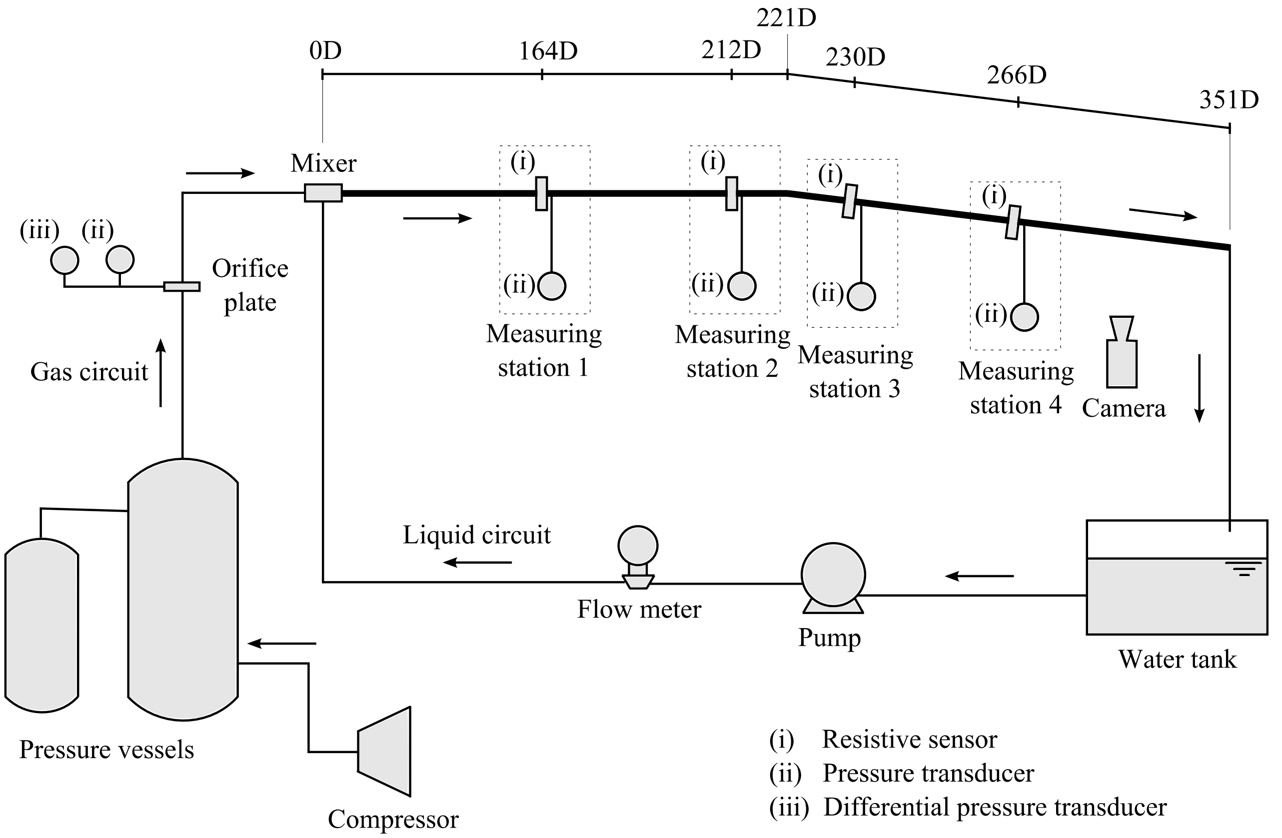


Figure 2. Schematic representation of the test facility

Four measuring stations were positioned at 164D, 212D, 230D and 266D from the mixer, as shown in Fig. 2. A pair of resistive sensors measured the flow parameters at each measuring station.

The sensors were developed at the NUEM labs by Machado *et al.* (2013) and they work by measuring voltage values and relating them to the liquid level (h_L) at each specific station. Those sensors consist of two 0.1-mm OD stainless steel filaments, the first working as the excitation electrode and the second one as the receiving electrode. Those filaments were assembled on a 2-mm thick printed circuit board made of fiberglass. The filaments were positioned 3 mm apart, in parallel, as shown in Fig. 3(a).

The excitation electrode sends a square-wave signal with frequency of 1.75 kHz to the receiving electrode through the mixture flowing through the measured section. Due to the difference between the liquid and gas conductivities, it was found that the voltage measured at the receiving electrode varies linearly with the amount of liquid in the section, reaching its maximum value when the pipe is filled with liquid. Thus, the liquid level in the measured section is determined in accordance with the intensity of the received signal.

The arrangement with two resistive sensors as shown in Fig. 3 (b) was conceived so as to facilitate the assemblage of the sensors in the pipe, and to enable velocity measurements as well. It consists of three plates (two for the sensors and one for the ground), acrylic flanges and O-rings. The sensors are located in the plates at the assembly ends, 53 mm apart. Thus, velocities are obtained by measuring the time the structures takes to cover the distance between two consecutive sensors.

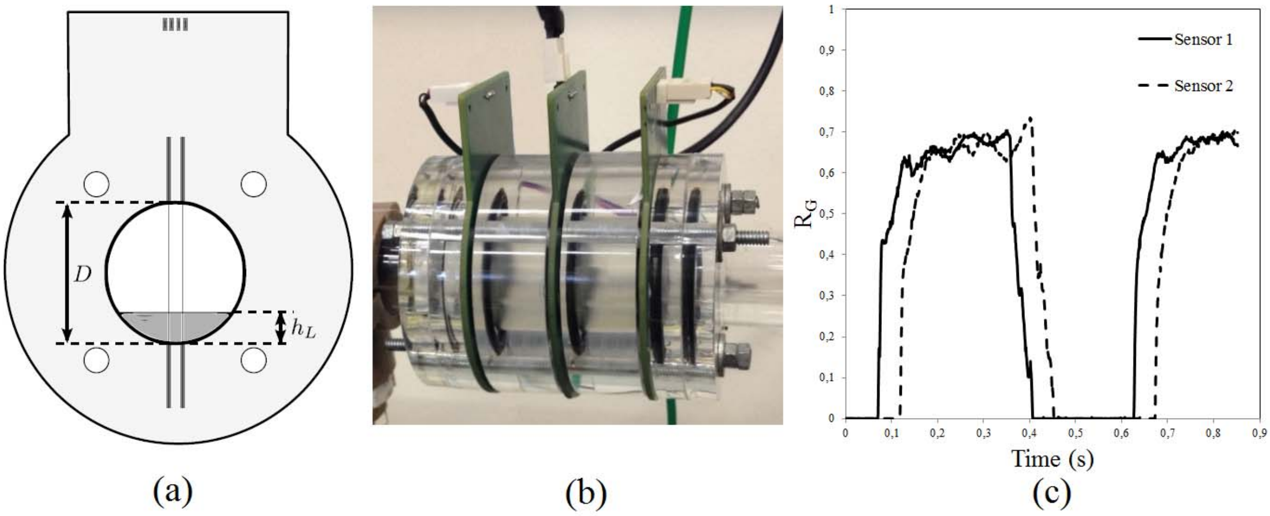


Figure 3. (a) Board used to mount the resistive sensor (b) Arrangement to accommodates a pair of resistive sensors (c) A sample of the signal obtained from the pair of resistive sensors

The gas fraction (R_G) is computed from the liquid level values obtained by the sensors and geometrical relationships, providing a signal as shown in Fig. 3 (c). Vicencio (2013) describes how this signal is processed and how V_{TB} and L_B values for each unit cell are obtained.

Footages with a high-speed camera (La Vision 500K-M3, up to 3600 frames/s at maximum resolution of 1024 x 1024 pixels) were taken so that the method used to obtain the parameters with resistive sensor could be validated. This camera was positioned close to the fourth measuring station. The footages were processed in accordance to the technique described by Amaral *et al.* (2013), providing V_{TB} values for each bubble in the flow. These values were directly compared with those obtained by the resistive sensor installed at the fourth measuring station.

3. RESULTS

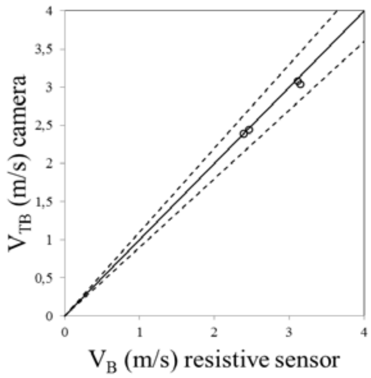
Four experiments were carried out, with the superficial liquid (J_L) and gas (J_G) velocity pairs shown in Tab. 1. The cases were picked because they correspond to horizontal slug flow, according to theoretical grounds laid by Taitel and Dukler (1976). It should also be observed that those pairs correspond to two different mixture velocity (J) values.

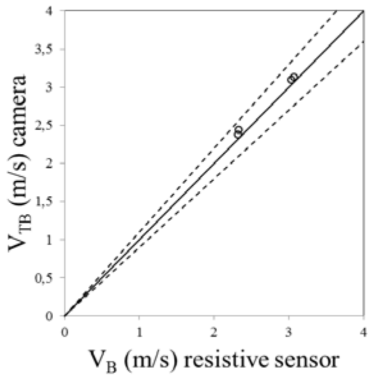
Table 1. Test grid.

Case	J_G (m/s)	J_L (m/s)	J (m/s)
P01	0.75	1.25	2.00
P02	1.00	1.00	
P03	1.00	1.50	2.50
P04	1.25	1.25	

The experiments were carried out with two pipe configurations: the first one using a single horizontal pipe, which served as the base case for all the analyses; and a second configuration with a horizontal section followed by a downward section with a -7-degree inclination, as shown in Fig. 2. In both cases the values of the elongated bubble velocity and length were obtained by the resistive sensors at each of the four measuring stations.

An image processing technique was used to validate the signal acquisition and processing methods. The velocities obtained by this image processing technique were compared to the values yielded by the resistive sensor located at the fourth measuring station (the one located nearest to the filmed region). The values obtained from the experiments executed with the fully horizontal pipe are presented in Fig. 4 (a) and the ones for the pipe with direction change are shown in Fig. 4 (b).



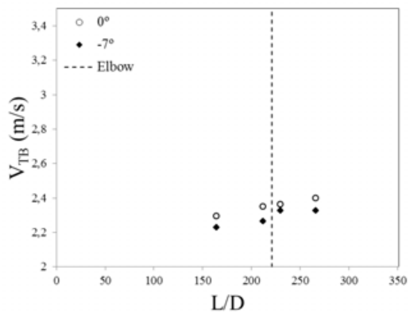


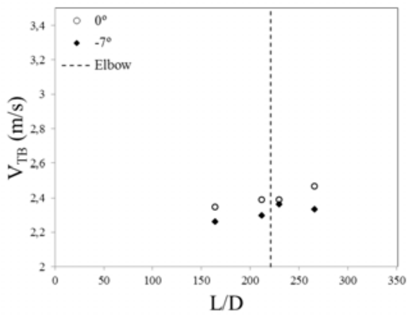
(a) (b)

Figure 4. Comparison between the velocities obtained from resistive sensor measurements and by the high-speed camera (a) 0º (b) -7º

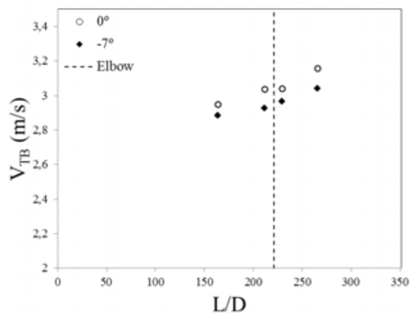
The comparison between the two techniques showed a maximum error of 4.0% for the fully horizontal pipe and 4.5% for the pipe with direction change, with average errors of 1.7% and 2.5%, respectively. These results show that the results obtained by the two methods are quite similar, hence validating the technique used to obtain the variables with resistive sensors.

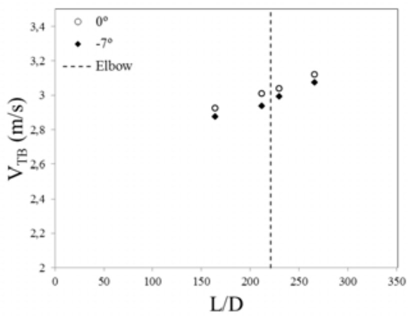
The mean bubble velocity values obtained by the resistive sensors for all experiments and at each measuring station for the two pipeline configurations used are presented in Fig. 5.





(a) (b)





(c) (d)

Figure 5. Evolution of the bubble velocity in the pipe (a) P01 (b) P02 (c) P03 (d) P04

A slight rise of the bubble velocity during the flow was observed during the horizontal pipe experiments. This rise is caused by the pressure drop inside the pipe and the consequent gas expansion. The same behaviour is observed in the horizontal section of the configuration with direction change.

Two distinct behaviours are observed when the mixture flows through the elbow: the cases P03 and P04 follow the same trend observed in the horizontal pipeline, and no significant influence due to the direction change is verified. By their turn, the cases P01 and P02 present an increase in bubble velocity after the elbow, showing an increase in the bubble velocity at measuring station 3, followed by a decrease in the same velocity at measuring station 4.

In order to evaluate the different behaviours observed during the experiments a theoretical study to verify to what flow patterns the measured flow rates in a purely downward flow would correspond. To achieve this objective, the flow map presented in Taitel and Dukler (1976) for a -7º downward flow was used. The four experimental cases plotted onto such flow map are shown in Fig. 6.

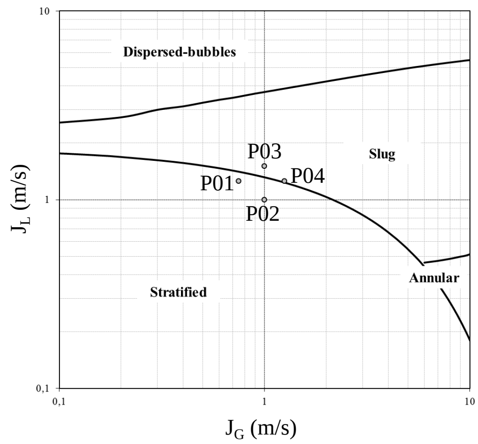


Figure 6. Experimental cases on the flow map proposed by Taitel and Dukler (1976) for -7º

Figure 6 indicates that the cases P03 and P04 would present slug flow in a downward flow with -7º inclination, whereas the cases P01 and P02 would be in the stratified flow region.

This indicates that the cases P01 and P02 destabilize and tend to stratified flow after passing through the elbow, thus affecting the flow parameters as the decrease of the bubble velocity at measuring station 4 seems to demonstrate. The cases P03 and P04 tend to remain within the slug flow pattern region after the elbow, hence not suffering great influence from the direction change and the parameters follow the same trend observed in the horizontal pipeline.

In Fig. 5 can be observed that in the pipes with direction change in the section right before the elbow, albeit the velocities present the same trend they are systematically smaller than those observed in the horizontal pipe, showing the influence of the direction change upstream from the flow. The gauge pressures in each of the measuring stations were analyzed for all the tests, as shown in Fig. 7. That was done in the hopes that this influence could be understood.

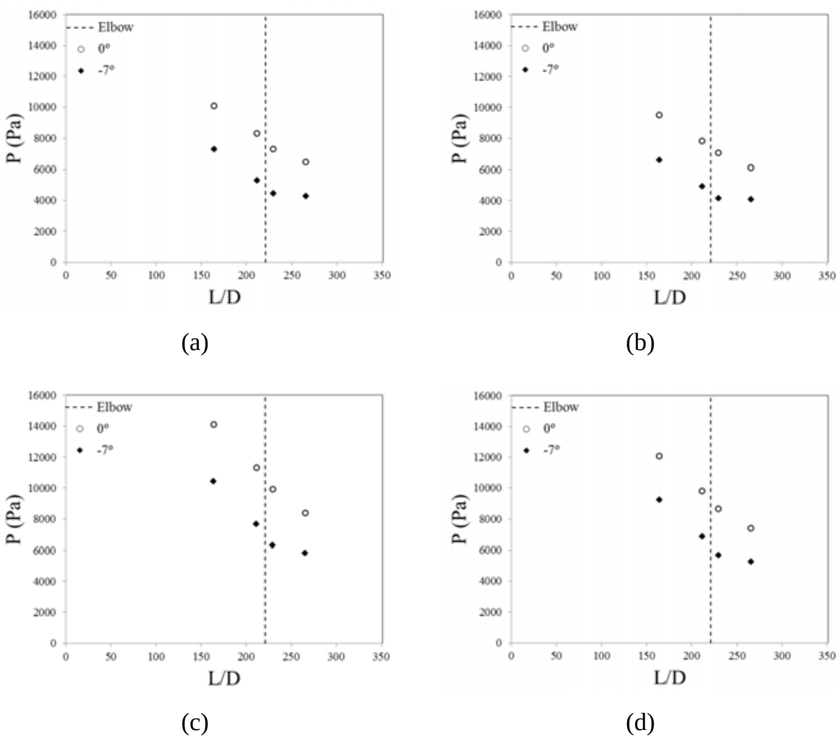


Figure 7. Evolution of the gauge pressure in pipeline (a) P01 (b) P02 (c) P03 (d) P04

Fig. 7 shows that the pressures upstream from the elbow in the configuration with direction change are always smaller than the pressures measured in fully horizontal configuration.

It can be seen in Fig. 7 that the pipeline with change of direction affect the pressure profile upstream the elbow, in its horizontal section, making the pressures always lower than that measured on the pipeline completely horizontal. However, it was not possible to correlate the variations observed in the bubble velocity to the changes observed in the pressure profile.

In Fig. 8 the mean values of the bubble length measured by the resistive sensors at the four measuring stations are presented.

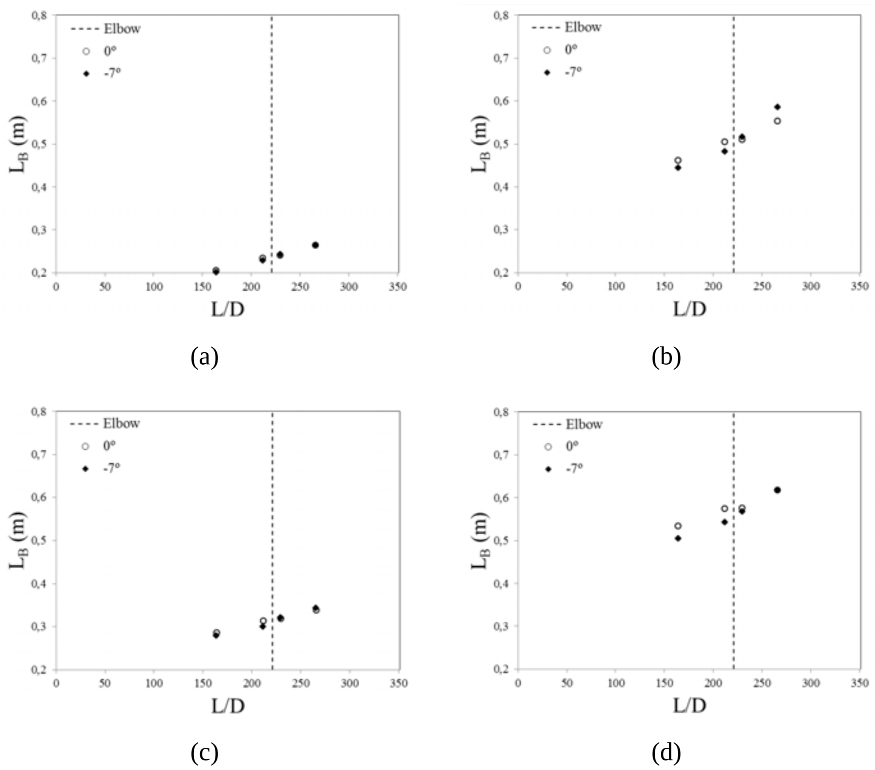


Figure 8. Evolution of the bubble length in pipeline (a) P01 (b) P02 (c) P03 (d) P04

It is possible to observe, in both configurations, a gradual growth of the bubble length with the development of the flow. This is caused by the gas expansion and probable coalescence between bubbles. However, it was not possible to perceive considerable variations caused by the direction change.

In the cases P03 and P04, due to the trend of the slug flow in remaining stable, it was expected that the bubble length would not suffer influence from the direction change as it was observed. In cases P01 and P02 a growth in the bubble length to a point where the flow would become stratified was expected. This phenomenon, however, could not be observed during the course of the experiments.

It is believed that the growth trend was not observed due to the short distance between the elbow and the station where the measurements were taken, as considerable variations would demand flow development so that they could be detected.

The case that requires a smaller distance to present bubble length variations is the one that has a greater stratification trend. This is the case P02 that, as Fig. 6 shows, is the farthest one from the slug-to-stratified flow transition. Therefore, it is possible to observe in this case a small increase in the bubble length at the measuring station 4.

4. CONCLUSIONS

An experimental study on the two-phase gas-liquid slug flow in a pipeline with a slight direction change was performed. A pipe section composed of a horizontal section followed by a -7° downward section was used. Elongated bubble velocities and lengths were obtained for four water-air velocity pairs. To validate the measurements made with the resistive sensors flow footages were obtained with a high-speed camera and processed.

The values of elongated bubble velocity presented two different behaviours past the direction change: they either decreased or did not change noticeably. In order to determine the occurrence of each case a flow map for a -7° downward flow was used. It was shown that the cases influenced by the change of direction are the ones that tend to stratify in the downward flow. The results have also shown the influence of the change of direction in the bubble velocity upstream from the elbow.

The elongated bubble lengths were not significantly affected after passing through the elbow. The cases where a stratification trend was not observed were not distant enough for the flow to develop, thus not showing a significant increase in the bubble length.

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