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INFLUENCE ANALYSIS OF SLIGHT DIRECTION CHANGES ON THE TRANSITION FROM TWO-PHASE GAS-LIQUID SLUG FLOW TO STRATIFIED FLOW

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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. Different flow patterns take place along the flowlines, as long as the operating conditions such as the flow rates of the phases, the pipe diameter and physical properties of the fluids change. Slug flow is the most frequent pattern observed in oil and gas production operations. This flow is characterised by the continuous alternation of regions of liquid (liquid slugs) and regions where the gas phase dominates (elongated bubbles). Due to this intermittent behaviour, slug flow causes undesired operational issues on industrial facilities, such as vibration, corrosion, erosion and high pressure drops. Also, scenarios where the pipe stands slight changes of direction due to irregular seabed topographies are commonly found. In this context, this work presents an experimental study on two-phase gas-liquid slug flows in a pipe with a slight change of direction, represented by a horizontal section followed by a inclined downward section. The experiments were performed at NUEM (Multiphase Flow Research Center at UTFPR). The flow initiation and development took place under controlled conditions and its characteristic parameters were measured with resistive sensors installed at four sections of the pipe. Based on the experimental results, the influence of a slight change of direction on the transition between slug flow and stratified flow in the inclined downward section was evaluated.*

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

1. INTRODUCTION

Multiphase flows are characterised by the simultaneous flow of at least two phases, be those different liquids, gases or solids. Those flows are common in industrial applications such as boilers, refrigerators and many other equipment in chemical, nuclear and oil industries.

In the specific case of oil and gas production is very common the presence of multiphase flows containing oil, water, gas and occasionally solid particles as well. The characterisation of this type of flow has great importance in equipment design. Due to their complex nature, multiphase flows are usually modelled as two-phase gas-liquid flows. The liquid phase consists of oil and water, and the gas comes from either the reservoir, from the vaporisation of the oil's volatile components, or from the gas that is injected during artificial lift operations.

The gas-liquid interfaces may assume different configurations inside the pipeline along the flow from the well to the platform. Such configurations, according to Shoham (2006), are called flow patterns, and they are directly related to the flow rates of the phases, the physical properties of the fluids and the pipe geometry. Shoham (2006) classified the most common flow patterns in horizontal two-phase flows as four basic configurations: stratified, intermittent, annular and dispersed bubble. Based on this classification, the stratified flow pattern is divided into smooth and 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 characterised by the intermittent occurrence of two structures: one composed by a continuous liquid plug, the liquid slug, that may or may not contain dispersed gas bubbles; the other structure is formed by a gas pocket, called elongated bubble, sliding over a liquid film.

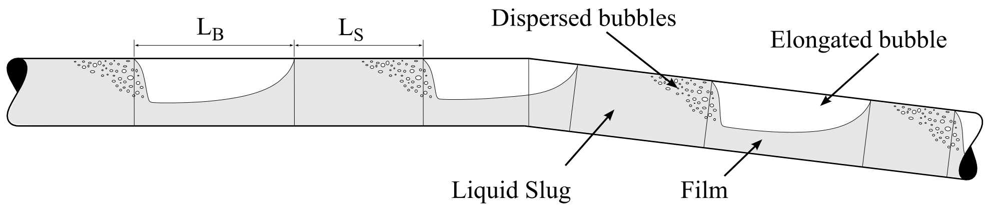

Figure 1. Representation of the slug flow.

Several authors have sought to describe the behaviour of the slug flow with direction changes 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 pipe with a slight direction change. The test rig is composed by a horizontal section followed by a slightly inclined downward section, as shown in Fig. 1. The influence of this direction change on the transition between slug and stratified flow in the inclined downward section is then evaluated. Resistive sensors are used to characterize the flow, obtaining the following characteristic parameters from slug flow: elongated bubble velocity (V_B), frequency (f), bubble (L_B) and slug (L_S) lengths, gas fraction in the bubble (R_{GB}) and in the slug (R_{GS}).

2. EXPERIMENTAL METHODOLOGY

The experiments were performed in the test facility at NUEM labs (Multiphase Flow Research Center at UTFPR) in a 26-mm ID transparent acrylic pipe, which was composed of a 5.76-m long horizontal section followed by a 3.38-m long inclined downward section with inclinations (θ) of -3º, -5º or -7º in relation to the horizontal. The pipe outlet was subjected to the atmospheric pressure and a mixture of water and air at ambient conditions made the test fluid.

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.

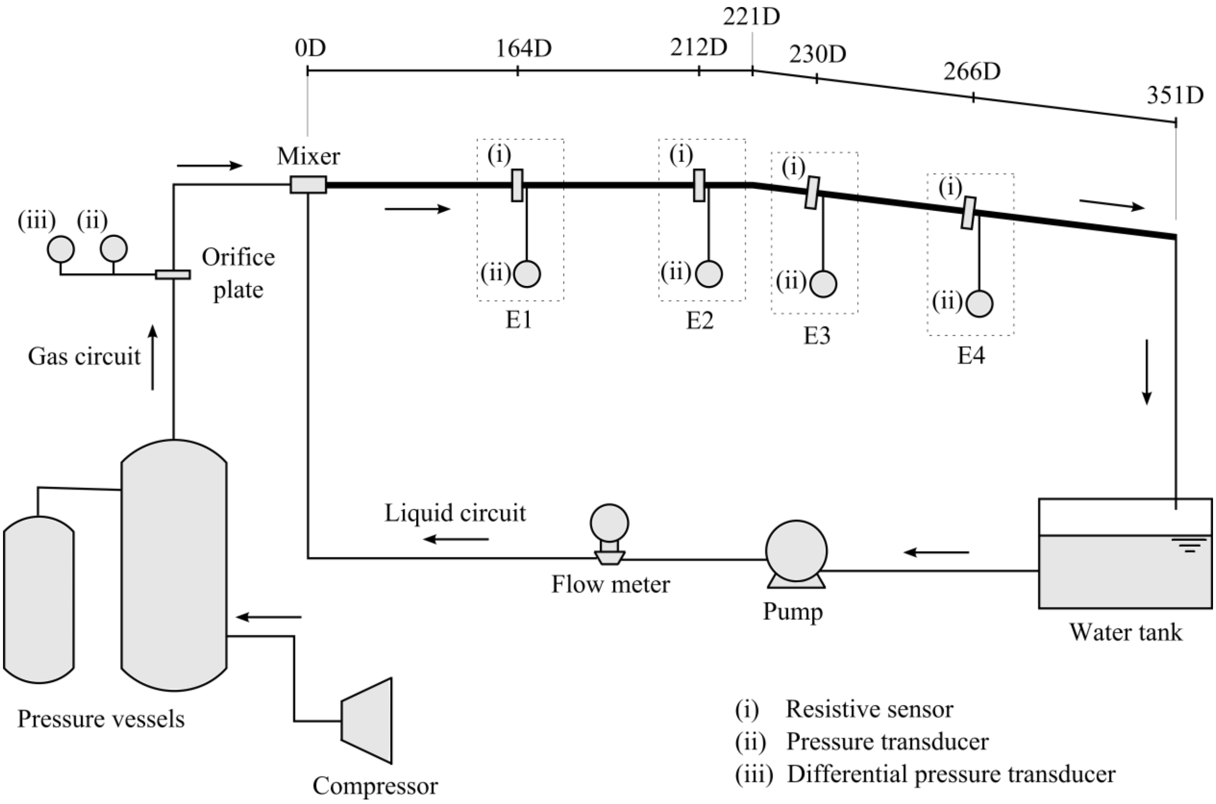

Figure 2. Schematic representation of the test facility.

Four measuring stations were positioned at 164D, 212D, 230D and 266D from the mixer, represented in Fig. 2 by E1, E2, E3 and E4. One pair of resistive sensors measured the flow parameters at each measuring station.

The resistive sensors built at the NUEM were based on the technique developed by Machado *et al*. (2013). The sensors operate by measuring voltage values and correlating it to the liquid level (h_L) at each specific station. Those sensors consist of two stainless steel filaments with 0.1-mm diameter. The first filament works as the excitation electrode and the second one as the receiving electrode. These filaments were assembled on a 2-mm thick printed circuit board made of fiberglass and positioned 3 mm apart, as shown in Fig. 3 (a).

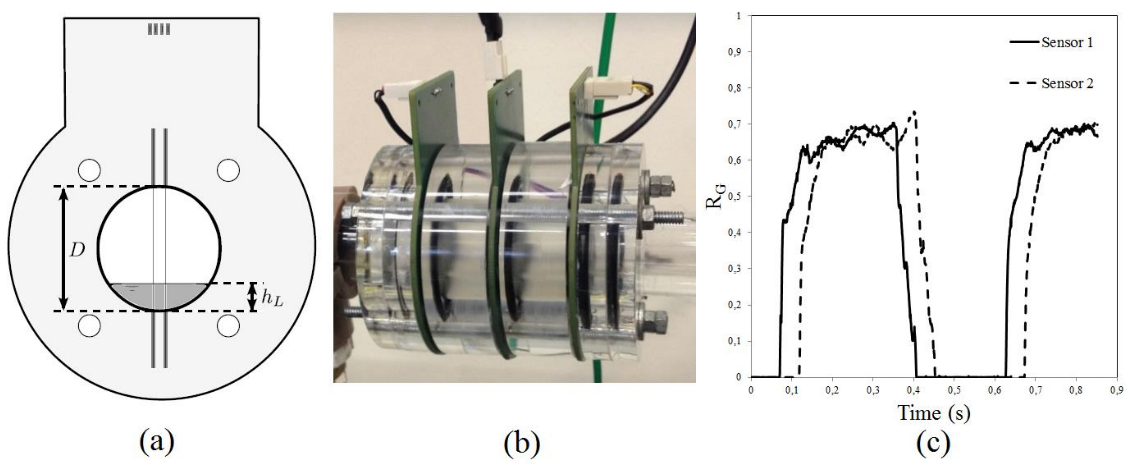

Figure 3. (a) Resistive sensor (b) Arrangement to accommodate a pair of resistive sensors (c) A sample of the signal obtained from the pair of resistive sensors.

The excitation electrode sends a square-wave signal with a 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 electrical conductivities, it was found out that the measured voltage at the receiving electrode varies linearly with the amount of liquid in the section, reaching its maximum value when the pipe is completely 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, shown in Fig. 3 (b), was conceived 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 were located on the plates at the assembly ends, 53 mm apart. Thus, velocities were obtained by measuring the time taken by the structures to travel the distance between the two sensors.

The gas fraction (R_G) was 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 those signals are processed and how V_B, f, L_B, L_S, R_{GB} and R_{GS} values are obtained for each unit cell. This work follows the methodology developed by Vicencio (2013).

3. RESULTS

The experimental grid was defined according to the superficial velocities. All data in the grid presented slug flow in the horizontal section, whereas in inclined downward section some cases presented stratified flow whilst others presented slug flow.

Forty-five different pairs of superficial gas (J_G) and liquid (J_L) velocities were chosen, as shown in Tab. 1. Each pair was measured in a completely horizontal pipe, as a blank test, and in three pipes with direction change (-3º, -5º and -7º), totalling 180 runs.

Table 1. Test grid.

Case	J_G (m/s)	J_L (m/s)	Case	J_G (m/s)	J_L (m/s)	Case	J_G (m/s)	J_L (m/s)
P01	0,25	0,75	**P16**	1	2	**P31**	2	0,5
P02	0,25	1,25	**P17**	1	2,5	**P32**	2	1
P03	0,25	1,75	**P18**	1,25	0,75	**P33**	2	1,5
P04	0,25	2,25	**P19**	1,25	1,25	**P34**	2	2
P05	0,5	0,5	**P20**	1,25	1,75	**P35**	2,25	0,75
P06	0,5	1	**P21**	1,25	2,25	**P36**	2,25	1,25
P07	0,5	1,5	**P22**	1,5	0,5	**P37**	2,25	1,75
P08	0,5	2	**P23**	1,5	1	**P38**	2,5	0,5
P09	0,75	0,75	**P24**	1,5	1,5	**P39**	2,5	1
P10	0,75	1,25	**P25**	1,5	2	**P40**	2,5	1,5
P11	0,75	1,75	**P26**	1,5	2,5	**P41**	2,75	0,75
P12	0,75	2,25	**P27**	1,75	0,75	**P42**	2,75	1,25
P13	1	0,5	**P28**	1,75	1,25	**P43**	3	0,5
P14	1	1	**P29**	1,75	1,75	**P44**	3	1
P15	1	1,5	**P30**	1,75	2,25	**P45**	3,25	0,75

3.1 Analysis of the conditions in which the flow becomes stratified

The signal obtained by the resistive sensor at measuring station E4 was analyzed, showing that under the superficial velocities and inclination conditions presented in Tab. 2 the transition from slug to stratified flow has occurred.

Table 2. Cases for which the flow becomes stratified along the inclined downward section.

Case	J_G (m/s)	J_L (m/s)	-3º	-5º	-7º
P01	0,25	0,75	X	X	X
P05	0,5	0,5	X	X	X
P06	0,5	1			X
P09	0,75	0,75			X

3.1.1 Stratification mechanism

A common behaviour in the signal was observed at measuring station E3 for all cases where the flow became stratified. This behaviour is highlighted in Fig. 4, which also presents examples of the signal at measuring stations E2 (horizontal section) and E4 (stratified flow).

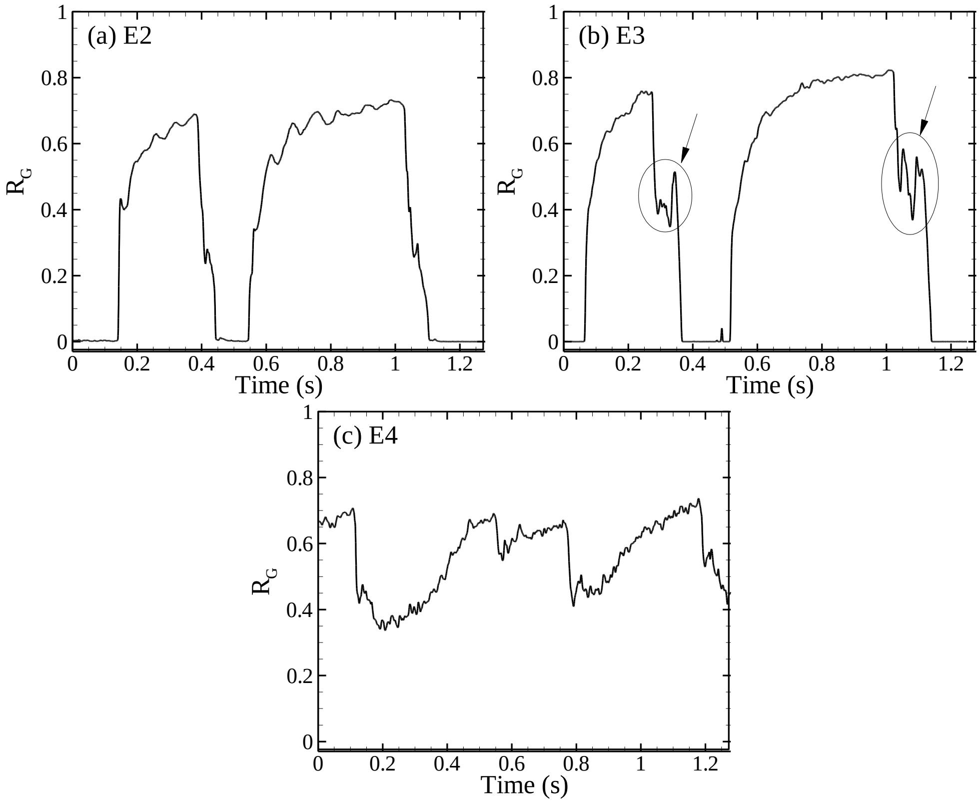

Figure 4. Signals of R_G obtained in case P05 to -5º.

The Fig. 4 (a) shows a sample of the gas fraction signal in horizontal slug flow, while the Fig. 4 (c) shows a signal sampling of the wavy stratified flow measured at station E4.

The Fig. 4 (b) represents the signal at measuring station E3, where it can be observed that the slug flow persists, showing however the tail in the elongated bubble in its onset. This phenomenon is highlighted in Fig. 4 (b). It must be emphasised that this behaviour was observed in all cases where the flow becomes stratified at measuring station E4.

The appearance of this tail indicates that the liquid film accelerates and begins to flow faster than the liquid slug in the inclined downward section. Thus, the slug begins to provide liquid to the forward film, causing the bubble rear to penetrate the slug region (initially forming a tail) until the flow becomes stratified.

3.1.1 Method for predicting the conditions under which the flow becomes stratified

Figure 5 shows a remarkable disagreement between the number of cases that become stratified during the inclined downward flow experiments (shown in Tab. 2) and the patterns predicted by the flow map proposed by Taitel and Dukler (1976). This is explained on the grounds of the phenomenon considered by the authors to predict the slug-stratified transition, which assumes stratified flow at the inlet, to subsequently apply the Kelvin-Helmholtz stability criterion in order to determine if the wave growth will cause the transition to slug flow. Whereas in the experiments a horizontal section precedes the downward one, the flow at the inlet of the inclined downward section is slug flow. Therefore, given the conditions evaluated in this work, the approach used by Taitel and Dukler (1976) to predict the slug-stratified transition is not the most appropriate.

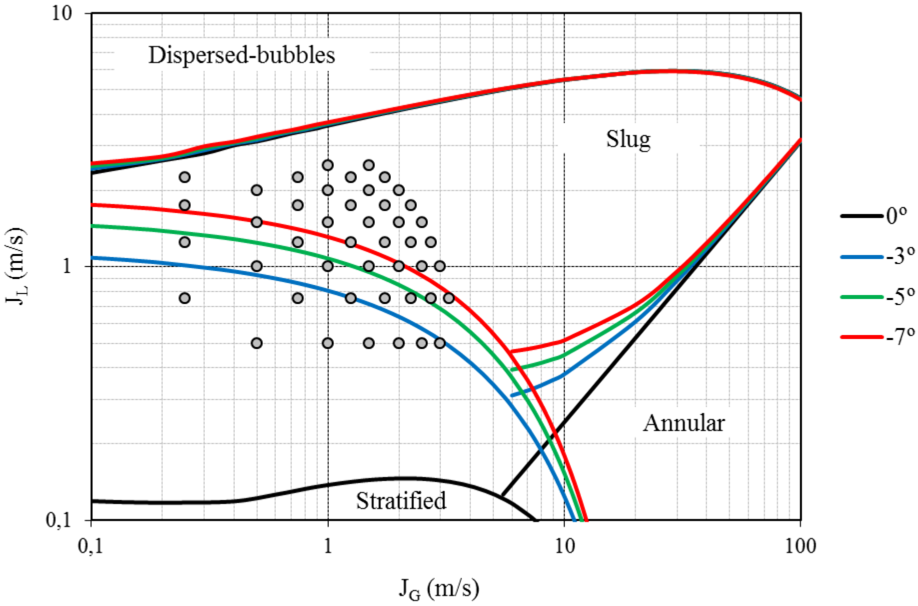

Figure 5. Test grid represented at flow map proposed by Taitel and Dukler (1976).

The study presented by Taitel *et al.* (2000) on stability in downward slug flows is evaluated with the objective of more accurately predicting the conditions where the transition between slug and stratified flow in the inclined downward section occurs.

Taitel *et al.* (2000) evaluated whether the momentum and continuity equations would apply to the slug flow, resulting in a model that works well for horizontal and upward configurations. However, in downward configurations there are flow conditions for which a solution for the equation system does not exist. The authors highlight two main cases where physically consistent solutions were not found (named case 1 and case 2), and suggest that in these situations slug flow would dissipate and the transition to another flow pattern would occur.

In case 1, the solution for the system of momentum and continuity equations does not exist, a fact that the authors correlated to a faster liquid film flow relative to the liquid slug. In case 2, the solution to the equation system exists, however the calculation of the film length provides a negative value that can be associated to two subcases: the flow pattern is dispersed bubble or the slug flow dissipates in the inclined downward section due its passage through a top elbow.

The authors presented the results in a graph, in terms of liquid and gas superficial velocities, where a similarity between the stratified-slug and slug-dispersed bubble transitions provided by the proposed method (the criterion of non-existence of solution to slug flow model) and the provided by a flow map can be observed.

The possibility of using the dissipation model in slug flow to predict the stratified-slug transition has already been discussed in some previous studies (Bendiksen and Espedal, 1992; Bendiksen *et al.*, 1996). Bendiksen *et al.* (1996) suggested that in downward sections the flow pattern depends on inlet conditions: when stratified flow is found at the inlet, the transition to slug flow follows the Kelvin-Helmholtz stability criterion; otherwise, when slug flow exists at the inlet, the transition to stratified flow occurs as result of a slug flow dissipation process.

The subject of the present work, however, deals with situations where slug flow had been found at the inlet of the inclined downward section. Therefore, the slug flow dissipation model proposed by Taitel *et al.* (2000) will be used herein. As discussed before, the transition in this model is obtained by considering two different situations (case 1 and case 2). Case 2 is nevertheless inconsistent with the experimental data, as the transition to dispersed bubble is not part of the present work, and a top elbow to cause the slug flow dissipation does not exist. The experimental data has shown that the transition to stratified flow is caused by a liquid film flowing faster than the liquid slug, corresponding to the case 1.

Thus, the prediction of the transition between slug and stratified flow in the experimental data is made only by the case 1 presented by Taitel *et al.* (2000). Figure 6 shows the predicted transition for the three pipe inclinations, along with the cases where the transition to stratified had been predicted.

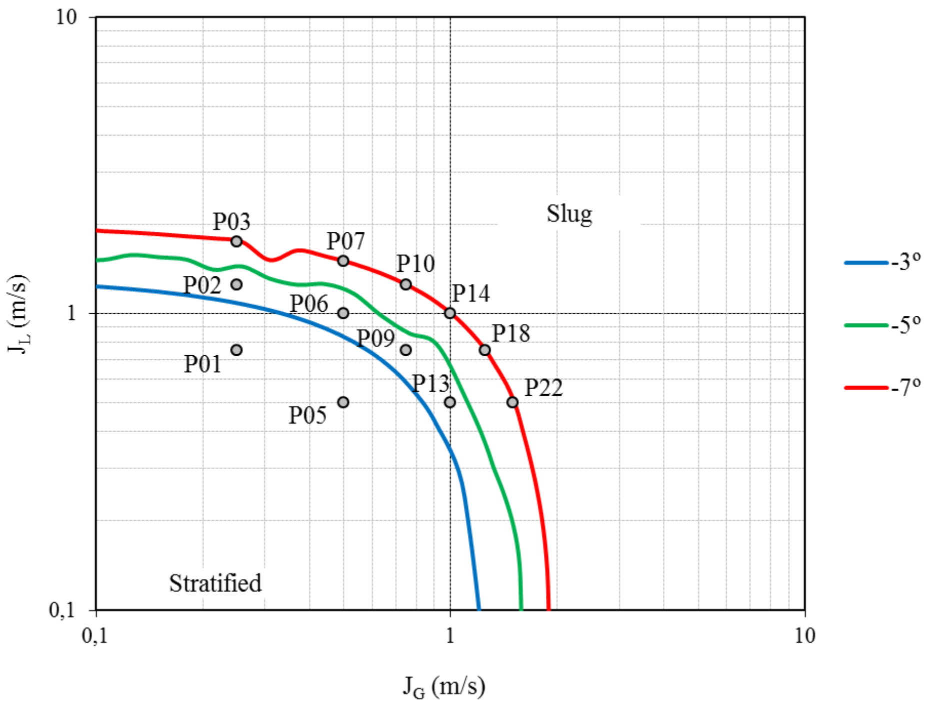

Figure 6. Transitions between slug and stratified flow predicted by the model presented by Taitel *et al*. (2000).

It can be seen in Fig. 6 that all cases in which the transition to stratified occurs (P01 and P05 to -3º, -5º and -7º; P06 and P09 to -7º) are indeed within the region where stratified flow is predicted. However there are some cases within this region that presented slug flow at measuring station E4 (P02, P06, P09 and P13 to -5º; P02 and P13 to -7º); those cases are analyzed below. Being in a transition region where the phenomena are not very pronounced, the cases in the transition curve to -7º (P03, P07, P10, P14, P18 and P22) will not be considered herein.

Initially, the behaviour of the slug flow characteristic parameters along the pipe is evaluated for case P13 to -7º. Figure 7 shows the PDFs at each measuring station for the following parameters: elongated bubble velocity (V_B), frequency (f), bubble (L_B) and slug (L_S) lengths, gas fraction in the bubble (R_{GB}) and in the slug (R_{GS}).

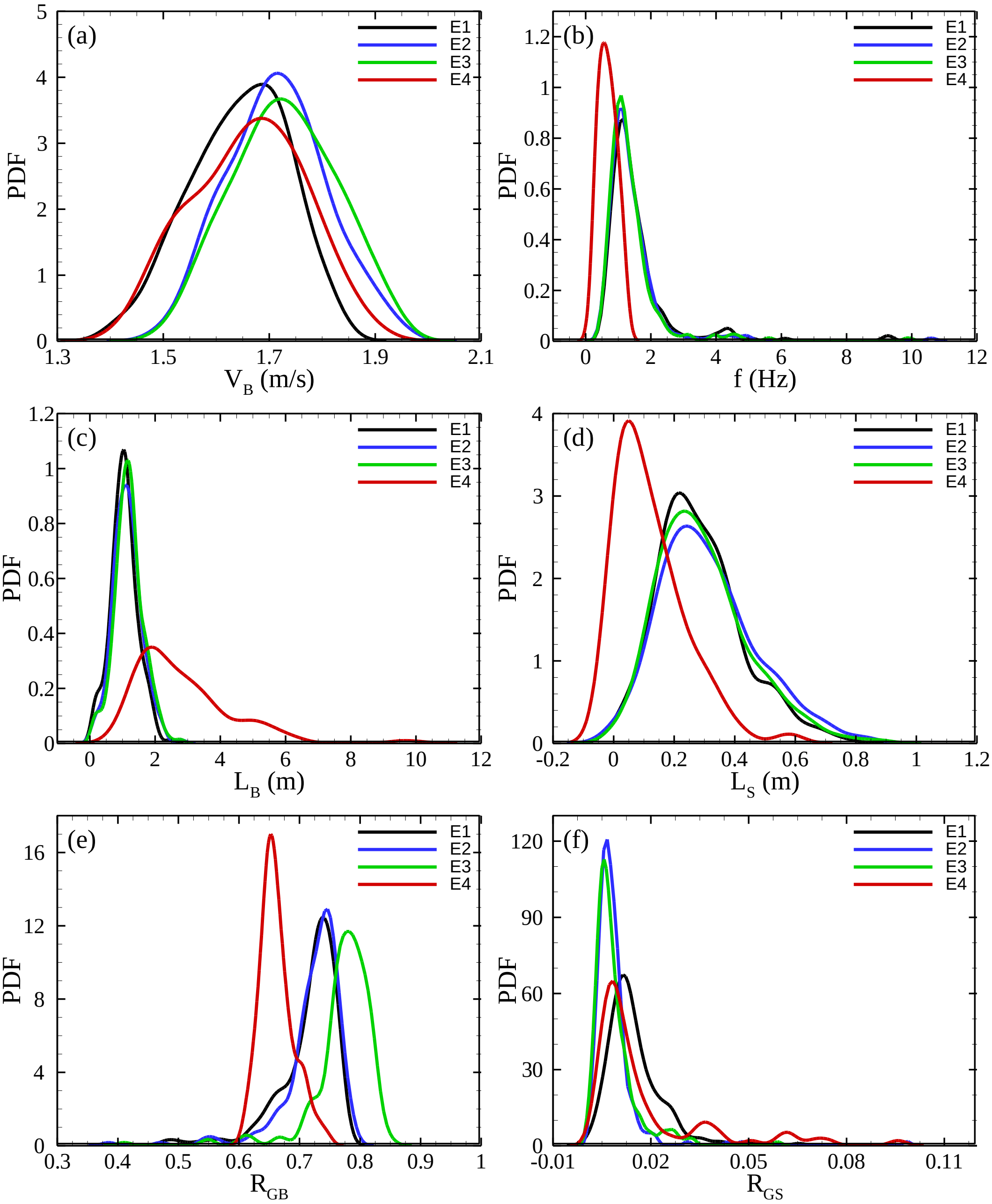

Figure 7. Flow parameters PDFs measured in case P13 to -7º.

The considerable variation of the parameters in case P13 to -7º, shown in Fig. 7, occurs at measuring station E4, where the flow is fairly developed in the inclined downward section. Thus, the behaviour of the flow parameters on this measuring station will be described next.

Yet the variations in elongated bubble velocity are not noteworthy, a lesser symmetrical distribution can be observed in the PDF, with the appearance of bubbles with smaller velocities, thus increasing the data dispersion.

The frequency decreases, indicating that coalescence occurs more often. Furthermore, very high frequencies (compared to the average) vanished, showing that the smaller unit cells completely disappeared at this flow stage.

The bubble length values present a considerable increase, confirming that, as verified by frequency analysis, indicating a high coalescence rate. Additionally, an increase in the data dispersion and the appearing of very high values, indicating that the flow is near to the transition to stratified flow.

A decreasing in slug length can also be observed, showing that the remaining liquid slugs in the flow are dissipating, thus confirming the tendency of the flow to become stratified.

The bubble gas fraction decreases, indicating that in the absence of considerable variations of slug gas fractions, the gas in the flow is distributed so as to occupy a smaller portion of the cross section of the pipe and, consequently, a longer length in the pipe (as considerable pressure variations are not present). This behaviour agrees with the observations of bubble length increase and slug length decrease.

Considering the behaviour observed in case P13 to -7º, it is possible to realize that in measuring station E4 the slug flow persists, notwithstanding a strong trend of the flow to become stratified, indicating that with a longer development length in the inclined downward section would cause the transition to stratified flow.

Analyzing the slug flow characteristic parameters in the other cases within the region where stratified flow is predicted (P02, P06, P09 and P13 to -5º; P02 to -7º) the same behaviour was observed. Then, in those cases, such as P13 to -7º, it might be claimed that the transition between slug and stratified flow shall occur as long as the development lengths in the inclined downward section increase.

It was concluded that all cases within the region where the transition to stratified flow is predicted became stratified before crossing measuring station E4, or exhibit a behaviour indicating that it will become stratified with a longer development length in the inclined downward section.

When the characteristic parameters of the cases within the region where stable slug flow is predicted are analyzed, the trend of the flow to become stratified could not be observed.

Thus, it was shown that the method employed to predict the transition between slug and stratified flow is valid for experimental conditions similar to those used in this study.

4. CONCLUSIONS

An experimental study of two-phase gas-liquid slug flow through a pipe under a slight change of direction was presented in this work. The test rig was composed by a horizontal pipe section followed by an inclined downward section. The aim of this study was to verify the influence of this direction change on the transition from slug to stratified flow in the inclined downward region. The working fluids were water and air and the inclination angles used in the inclined downward section were -3º, -5º and -7º. Resistive sensors were installed in four sections of the pipe in order to obtain characteristic parameters of the slug flow.

It was observed that in some cases the flow became stratified at the last measuring station of the inclined downward section. The appearance of an elongated bubble tail before flow becomes stratified was also noticed. This phenomenon may be associated to the mechanism that leads to the transition to stratified flow, when the liquid film flows faster than the liquid slug.

A significant difference between the number of experiments that became stratified and the theory proposed by Taitel and Dukler (1976) for downward flow was also observed, indicating that the use of this model is not recommended for the cases herein analyzed.

Therefore, the slug flow dissipation model proposed by Taitel *et al.* (2000) was used for predicting the transition from slug to stratified flow in the inclined downward section, taking only situations consistent with the phenomena experimentally observed into account. The proposed method presented good results, showing to be valid for the conditions comprehended by this work.

Finally, some cases where the slug flow persisted at the measuring station E4 were observed. However, with a longer development length in the inclined downward section the flow will become stratified. Those points were identified by a specific behaviour in their characteristic parameters observed at measuring station E4: an increase in the bubble length and a decrease of the frequency, the slug length, the bubble gas fraction and the bubble velocity.

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