

ENCIT-2018-0647 EXPERIMENTAL ANALYSIS OF SLUG FLOW EVOLUTION IN HORIZONTAL PIPES

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Abstract. *The slug flow pattern occurs in many industrial applications, especially in the oil industry, where it is the most commonly found pattern in oil and gas production lines. Slug flow is characterized by the intermittent repetition of two structures: a continuous region of liquid, called liquid slug; and a region where the gas fills much of the pipe's cross sectional area as an elongated bubble. As the slug flow develops along the pipe, those structures have their lengths, velocities and phases fractions modified. The correct description of those structures is important in the design of oil & gas production equipment, and thus essential to understanding how they are affected by the flow development. In this context, this work describes an experimental study of liquid-gas slug flow in a 26-mm ID, 34.77-m long horizontal pipe. The evolution of the slug flow along the pipe is evaluated based on characteristic parameters, such as: elongated bubble velocity, unit cell frequency and elongated bubble and liquid slug lengths. Those parameters are measured by resistivity sensors located on five measuring stations positioned along the pipe. Based on the obtained results, the effects of gas expansion and bubble coalescence were correlated with the main variations observed with the slug flow development along the pipe.*

Keywords: *two-phase flow, slug flow, slug flow development, horizontal pipes*

1. INTRODUCTION

Multiphase flows occur in many natural and industrial applications, particularly in the oil and gas industry. During the production and transportation two-phase phase flows consisting of oil and water mixtures along with a gas phase and, possibly, solid particles such as sand and hydrates (Thomas, 2001) are commonly found. This flow condition is usually approximated as a two-phase gas-liquid flow. As operating conditions vary, this two-phase mixture may assume different configurations in the pipe, known as flow patterns (Shoham, 2006). Shoham (2006) classifies those flow patterns into the following denominations: stratified, smooth and wavy; intermittent, elongated bubbles and slug flow; annular; and dispersed bubbles.

The most commonly found pattern in the oil production is the slug flow, which is characterized by the intermittent repetition of two structures: a continuous region of liquid, called liquid slug, which may contain a small amount of gas in the format of dispersed bubbles; and a region with large amount of gas, called elongated bubble, where the gas fills much of the pipe's cross sectional area and flows atop a liquid film (Shoham, 2006). Together, the elongated bubble and the liquid slug were defined by Wallis (1969) as being a *unit cell*. Several studies have been developed with the aim of correctly describing the mechanisms involved in the slug flow (Dukler and Hubbard, 1975; Fernandes *et al.*, 1983; Taitel and Barnea, 1990), being the focus of several works the description of the behavior of the slug flow structures, such as the elongated bubble velocity (Nicklin *et al.*, 1962; Bendiksen, 1984), the unit cell frequency (Gregory and Scott, 1969; Heywood and Richardson, 1979), the length of the structures (Barnea and Taitel, 1993) and the phases fractions (Barnea and Brauner, 1985).

As the flow develops along the pipe, the slug flow structures tend to modify, changing their lengths, velocities and phase fractions. In order to characterize slug flow correctly, it is paramount to know beforehand how those structures change depending on their positions along the pipe. Studies aimed at describing the phenomena involved in the flow evolution may be important both in equipment design and as input data for numerical models seeking to describe the slug flow behavior.

In this work, experimental study of the two-phase gas-liquid slug flow evolution along a 26-mm ID, 34.77-m long horizontal pipe is presented. Measurements using resistivity sensors located on five measuring stations along the pipe were made, and the following characteristic parameters of the slug flow were measured: elongated bubble velocity, unit

cell frequency and elongated bubble and liquid slug lengths. With the variation of these parameters, the phenomena occurring with the flow development will be discussed.

2. EXPERIMENTAL METHODOLOGY

The experimental flow loop shown in Figure 1 was assembled so as to obtain information about the two-phase gas-liquid slug flow. Water and air at ambient conditions were used as the liquid and the gas phases respectively.

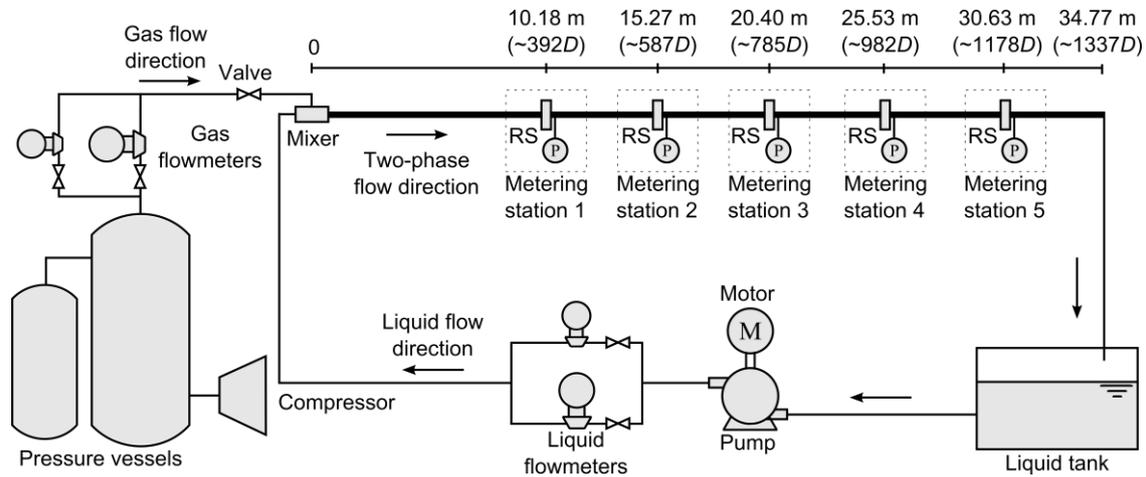


Figure 1. Experimental flow loop

The liquid is stored in a tank, from where is transported by a centrifugal pump driven by an electric motor to the mixer. The flow rate is measured by Coriolis-type flowmeters and controlled by a variable frequency drive actuating on the electric motor.

The compressed gas is stored in the pressure vessels. The gas flow rate from the pressure vessels to the two-phase circuit is measured by Coriolis-type flowmeters and controlled by a manual valve positioned just before the mixer.

In the experiments, the flow rates of both phases are controlled in terms of liquid (J_L) and gas (J_G) superficial velocities, which presented a relative standard uncertainty, estimated by the propagation of uncertainties from the flowmeters, of $\pm 0.54\%$ and $\pm 0.84\%$, respectively.

The two-phase flow is created at the parallel plate mixer, develops through a horizontal pipe made of transparent Plexiglas with internal diameter (D) of 26 mm and 34.77 m ($\sim 1337D$) of length, flows through five metering stations and is discharged into the liquid tank. The separation of the phases occurs in the tank by gravity.

The metering stations are positioned 10.18 m ($\sim 392D$), 15.27 m ($\sim 587D$), 20.40 m ($\sim 785D$), 25.53 m ($\sim 982D$) and 30.63 m ($\sim 1178D$) apart from the mixer. At each metering station a pressure gauge was installed so that the gas superficial velocity could be corrected. A pair of resistivity sensors to extract the characteristic parameters of the slug flow was also installed.

The resistivity sensors used were developed at NUEM by Machado *et al.* (2013). The sensors work by acquiring voltage values and relating them to the fractions of liquid and gas in the pipe. The signals of the sensors are processed by an algorithm developed by Vicencio (2013) in order to provide the characteristic parameters of slug flow. The parameters measured and evaluated in this study are: elongated bubble velocity (V_B), unit cell frequency (f), and elongated bubble (L_B) and liquid slug lengths (L_S).

Table 1 shows a summary of the configurations used during the experimental tests.

Table 1. Experimental flow loop characteristics.

Fluids	Air and water
Pressure and Temperature	Ambient
Relative standard uncertainty of J_L	$\pm 0.54\%$
Relative standard uncertainty of J_G	$\pm 0.84\%$
Pipe ID	26 mm
Pipe length	34.77 m ($\sim 1337D$)
Metering stations (position from the mixer)	10.18 m ($\sim 392D$)/ 15.27 m ($\sim 587D$)/ 20.40 m ($\sim 785D$)/ 25.53 m ($\sim 982D$)/ 30.63 m ($\sim 1178D$)

3. RESULTS AND DISCUSSION

Eleven liquid and gas superficial velocity pairs, varying from 0.3 to 1.5 m/s, were investigated. They are represented in a flow map proposed by Taitel and Dukler (1976) in Figure 2. The experimental cases were defined in order to ensure the slug flow pattern along the entire pipeline.

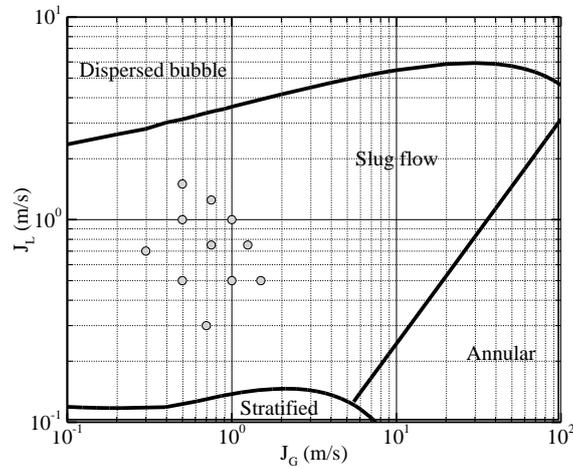


Figure 2. Test grid presented in a flow map proposed by Taitel and Dukler (1976)

The Figure 3 show the mean values obtained for the elongated bubble velocity (V_B), unit cell frequency (f), and elongated bubble (L_B) and liquid slug (L_S) lengths, at each metering station, as functions of the dimensionless position along the pipe (L/D). The experimental case represented in Figure 3 corresponds to liquid and gas superficial velocities equal to 1 m/s.

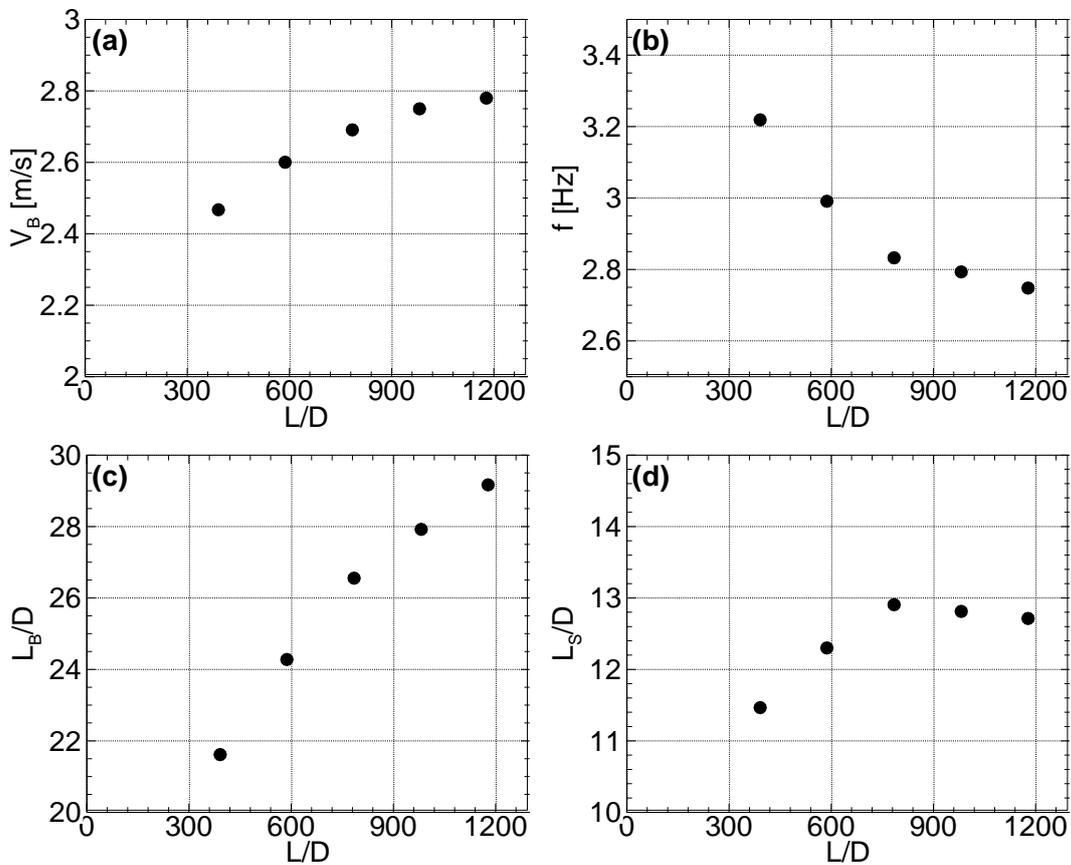


Figure 3. Mean values of the characteristic parameters along the flow

Figure 3 shows how the slug flow structures vary along the pipe. It may be noted that the elongated bubble velocity and length have a tendency to increase, while the unit cell frequency has a tendency to decrease with the flow development. The liquid slug initially increases, followed by a slight decrease.

The main phenomena involved in these parameter changes caused by the flow development are the gas expansion and the coalescence between neighbor elongated bubbles. The gas expansion occurs due to the decrease in pressure to which the flow is subjected on its way towards the outlet. The coalescence occurs due to the interaction between two consecutive flow structures, where elongated bubbles with low velocities relative to other elongated bubbles preceding them tend to be reached and captured by the said preceding bubble, thence creating a single structure.

The mean velocity of an elongated bubble increases mainly due to the gas expansion along the pipe as pressures drop. This expansion induces an increase in the volumetric flow rate of the gas phase, thus increasing the elongated bubble velocity.

The increase on the mean elongated bubble length comes from the combined effects of the gas expansion and the bubble coalescence. With the gas expansion, the bubble increases its length to accommodate the new volume that the gas now occupies. At the same time, when two bubbles coalesce, the gas initially contained in both bubbles is rearranged in a single bubble with a consequently greater length.

The considerable increase that occurs in the structures lengths, in contrast with the less pronounced increase in the elongated bubble velocity, leads to a decrease in the mean values of unit cell frequency.

The liquid slug length undergoes the competitive effect of gas expansion and bubble coalescence. Gas expansion decreases its length, whereas coalescence increases it. The gas expansion increases the length of the regions corresponding to the liquid film. Thus, an amount of liquid which initially composes the liquid slug is scooped by the film region, thereby decreasing the amount of liquid in the liquid slug and, consequently, its length. The coalescence of two bubbles makes the liquid slug between them to disappear; thus, its mass of liquid is redistributed amongst other liquid slugs in the flow, thereby increasing their lengths.

Figure 3(d) shows the regions of the pipe where each of the effects has greater influence on the liquid slug length. From the pipe inlet to approximately the location of the metering station #3, which is located at 20.40 m (~785D) from the mixer, a growth in the liquid slug lengths is observed, suggesting that a considerable coalescence rate is associated to this region, which is commonly seen in sections near to the flow inlet. From the metering station #3 to the outlet one can observe a slight decrease in the liquid slug lengths, indicating that the coalescence rate decreased and that the gas expansion became the predominant effect.

Figure 3(c) also shows the decrease in the coalescence rate after the metering station #3. This can be noticed by the decrease in the growth rate of the bubble length after the 3rd metering station, that is, when the number of coalescence decreases, the bubble length growth decreases too, because it is caused mainly by the gas expansion. Similarly, the effects of the decrease in the coalescence rate can be seen in Figure 3(b), where a decrease in the unit cell frequency decay rate after the metering station #3 can be observed.

The behaviors observed in the evolution of the mean values of the slug flow parameter can be confirmed by evaluating the experimental data PDFs. Figure 4 shows the characteristic parameters PDFs at each metering station.

From the PDFs shown in Figure 4 one can observe that the flow evolution does not cause considerable variations in the curves' format and in the data dispersion, being the displacements of the curves the main variations observed indicating a smooth variation in the flow characteristic parameter of all unit cells.

A similar behavior of the flow characteristic parameters' evolution observed in Figures 3 and 4 to the experimental case with liquid and gas superficial velocities equaling 1 m/s (increase in the bubble velocity and length, decrease in the unit cell frequency, and an increase followed by a slight decrease in the liquid slug length) was verified in the other experimental cases.

Based on the presented analysis it was possible to get a better understanding on how the slug flow develops along the pipe, verifying how the phenomena of gas expansion and bubble coalescence influence the main characteristic parameters of this flow pattern.

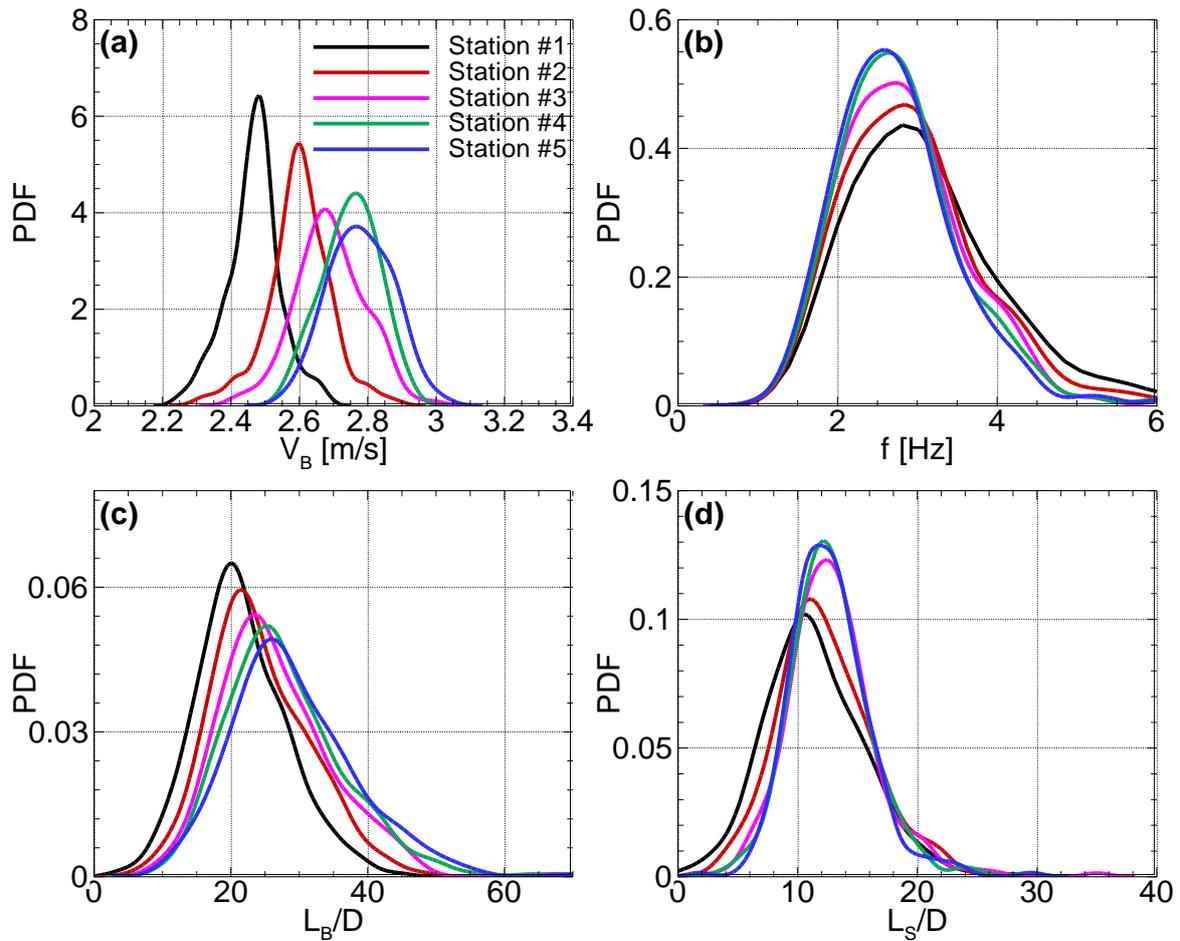


Figure 4. PDFs of the characteristic parameters in each metering station

4. CONCLUSIONS

In this work an experimental study of the two-phase gas-liquid slug flow evolution in a horizontal pipe was presented. The experiments were performed in a pipe with 26 mm of internal diameter and 34.77 m of length. Five metering stations were positioned along the pipe, and at each of those stations a pair of resistivity sensors was installed. Those sensors were used to extract some parameters characteristic of slug flow.

The slug flow evolution along the pipe was evaluated based on the elongated bubble velocities, unit cell frequencies, and liquid slug and elongated bubble lengths. On evaluating the mean values and PDFs, it was verified that the bubble velocities and lengths had an increasing trend. A decrease in the unit cell frequencies and an increase followed by a slight decrease in the liquid slug lengths were also observed.

The variations observed in the flow parameters were mainly related with the phenomena of gas expansion and bubble coalescence. The gas expansion it was directly related with the increase in the bubble velocity and length, and with the decrease in the unit cell frequency and liquid slug length. The bubble coalescence was related with the increase in the bubble and liquid lengths, and with the decrease in the unit cell frequency.

A competitive effect of the phenomena of gas expansion and bubble coalescence in the variations of liquid slug length was observed. In the region near to the pipe inlet the high coalescence rate plays a predominant role in the liquid slug length variation, making it to increase, whereas in the regions farther away from the inlet (where the coalescence rates are lower) the gas expansion predominates, thus decreasing the liquid slug length.

5. ACKNOWLEDGEMENTS

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