

STATISTICAL ANALYSIS OF DOWNWARD SLUG FLOW IN SLIGHTLY INCLINED PIPES

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Abstract: Understanding the hydrodynamics of the slug flow is essential for designing of off-shore production lines and equipments involved in oil and gas operations. Slug flow in downward inclined configuration is a matter of interest in petroleum industry since hilly terrain pipelines and risers pipes are present in the seabed. The main goal of this paper is to experimentally analyse and characterize the two-phase gas-liquid slug downward flow in pipes with inclination angles of -13° , -10° , -7° and -4° . The measurements were performed at different gas-liquid volumetric flow rates for which the slug flow regime was observed. An existing experimental loop in the NUEM/UTFPR labs was used to collect the data. A pair of wire-mesh sensors was employed to evaluate the flow structure so that void fraction temporal series could be obtained. From those series, statistical distributions for the characteristic parameters of such flows – namely the elongated bubble translational velocity, the slug frequency, the liquid slug and the elongated bubble lengths – were obtained.

Keywords: Two-phase flow, slug flow, experimental analysis

1. INTRODUCTION

Slug flow is a complex two-phase flow pattern. The unstable and stochastic nature of the slug flow is a challenge for researchers. Wallis (1969) described the slug flow by a structure known as the slug unit cell, composed by a region of liquid and another by an elongated bubble upon a liquid film. The occurrence of slug flow pattern in petroleum industry is largely observed. The pipelines in offshore fields are often connected to existing facilities. The downward flow may appear in hilly terrain pipelines and in risers pipes extending to offshore platforms (Roumazelles *et al.*, 1996). Sections of different orientation can undergo changes of slug flow parameters as the pipeline moves from horizontal position. The effects of inclined pipes on slug flow depends on several variables for example the operating flow rates, fluid properties, number of phases (Tzotzi *et al.*, 2010). Different techniques have been used to determine slug flow parameters (optical, gamma-ray, X-ray, conductive). A brief review of some works on reported literature is described as follows.

Jones and Zuber (1975) were one of the first to suggest a statistical approach to study two-phase vertical flow patterns. The authors employed a X-ray system to measure void fraction and identify differences between the flow patterns such as slug, bubbly and annular flows. It was possible to identify differences not only by visual observation but using a probability density function (PDF) of void fraction. The characteristics observed were: (i) single-peaked PDF at low void fraction for bubbly flows, (ii) single-peaked PDF at high void fraction for annular flows and (iii) twin-peaked PDF for slug flow. Heywood and Richardson (1979) made experimental tests with air-water in horizontal slug flow in a duct of 42 mm and total length of 4.57 m. Using a gamma-ray technique they generated PDFs and power spectral densities (PSD) of the void fraction. They compared the histograms of liquid holdup with a fitted curve for some liquid and gas superficial velocities. Kvernfold *et al.* (1984) experimentally studied slug flow in a horizontal pipe with internal diameter of 24 mm. The working fluids were a mixture of mineral oil and kerosene for liquid phase and nitrogen for gas phase. The measurement technique used was Laser Doppler Velocimetry (LDV) and it was possible to attain values for the mean of the slug length, slug frequency and translational speed of the liquid slugs. Also, they mapped the velocity distribution in the slug flow. The authors pointed out that problems arose in regions with high aeration. Such regions were the slug front and the slug core at the highest gas flow rates.

Bendiksen (1984) performed an experimental analysis of the bubble velocity in inclined ducts (-30° to 90°) using optical sensors. The author proposed a correlation between bubble movement and inclination angle based on a Froude mixture number with a critical value of 3.5. Matsui (1986) and Lin and Hanratty (1987) used pressure signals to identify statistical features for flow regimes. Nydal *et al.* (1992) used two conducting rings in horizontal slug flow in pipes of 52.9 mm i.d. (stainless steel) and 90 mm i.d. (acrylic) and 17-m long. They identified in their experiments with air-water flow two types of slugs: regular and developing slugs. They were distinguished by means of the statistical distributions of the slug holdup. Cumulative density functions (CDF) were used to investigate some features of slug parameters. The shape of the statistical distributions was fitted with normal and log-normal functions. Saether *et al.* (1990) and Franca *et al.* (1991) used fractal statistics technique to calculate slug length and identify two-phase flows regimes respectively.

Considering the stochastic features of slug flow, in this work is presented an experimental investigation on main

statistical parameters of slug flow, such as translational velocity of elongated bubble (V_{TB}), slug frequency (f), bubble length (L_B) and slug length (L_S). A wire-mesh sensor and a high-speed camera were used in the test section to achieve the parameters. They are important in modeling and practical applications, in slug modeling since they serve as closure relations. In addition, these parameters can help to design facilities in petroleum industry, for example slug catchers, separator vessels, etc (Sausen *et al.* (2012)).

2. EXPERIMENTAL METHODOLOGY

This section focuses on describing the experimental setup and the process of measuring the parameters in gas-liquid slug flow. Further, a description on how to treat the time series extracted by the wire-mesh sensor is given.

2.1 Experimental setup

The scheme of experimental loop is shown in Fig. 1. Experiments were carried out in transparent acrylic pipes with internal diameter (D) of 25.8 mm, and the total length of 357 D . The experimental loop is mounted on a platform, which was oriented to the inclinations of -13° , -10° , -7° and -4° to perform the measurements. The working fluids used are water (liquid phase) and air (gas phase). The gas phase system consists of a gas reservoir, a compressor and three orifice plates to enable and control the gas flow rate. Also, the liquid system consists of a liquid reservoir, a centrifugal pump and a Coriolis mass flow meter. Liquid and gas reach the mixer which is the beginning of the two-phase pipeline section. The fluids return to the liquid reservoir and there is separation by gravity. The ranges of superficial velocities is up to 4.00 m/s for gas (J_G) and 0.5-2.5 m/s for liquid (J_L). Relative uncertainty for this measurements are $\pm 0.28\%$ and $\pm 2.02\%$ for liquid and gas superficial velocities respectively.

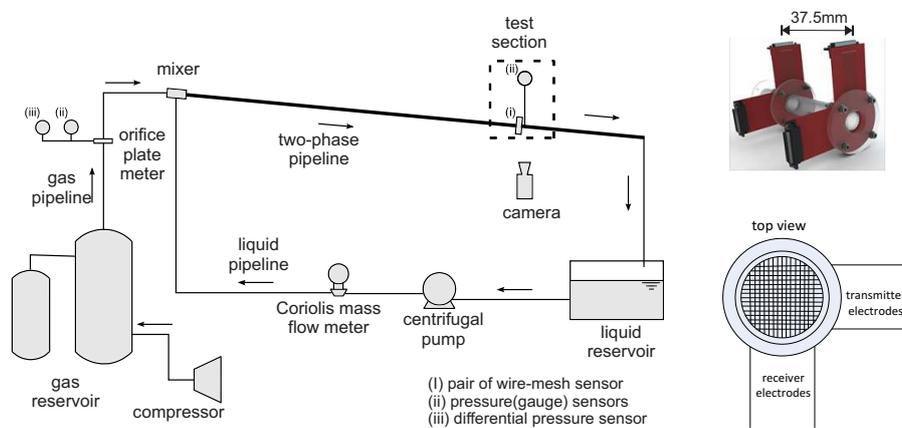


Figure 1: Experimental flow loop and a pair of wire-mesh sensor.

In the test section, a pair of wire-mesh sensor (WMS) and a high-speed camera are located at a distance of 291 D from the mixer. The WMS consists of 12x12 perpendicular wires (receiver and transmitter electrodes) which measures the electrical capacitance of the fluids as it flows through the nodes. Hence, using reference calibration measurements for dry and water-filled pipe, the instantaneous void fraction can be determined. The pair of WMS is 37.5 mm apart, in Fig. 1 there is a sketch of wire-mesh sensor type.

The grid of J_L versus J_G shown in Fig. 2 served as a basis for selecting slug flow conditions to enable studying the effect of pipe inclination angle. Experimental conditions are chosen so far that for all inclinations slug flow is observed for each combination of superficial liquid and gas velocities.

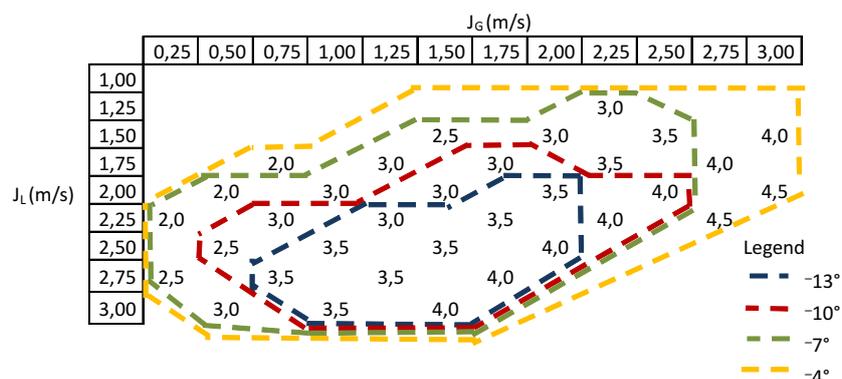


Figure 2: Range of superficial gas and liquid velocities.

2.2 Signal processing

The WMS provides the void fraction time series of the flow. In Fig. 3 shows examples of the time series for some flow conditions obtained. A threshold is necessary to attain a binary function $u(\alpha, t)$ as suggested by Bertola (2003). This threshold is adjusted for each flow condition and takes into account the amount of aeration in the slug flow.

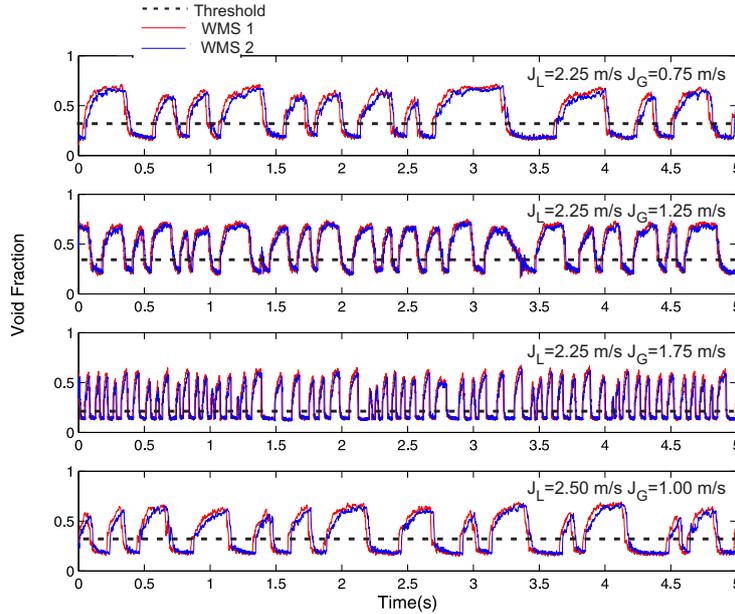


Figure 3: Time series associated with threshold.

The Equation 1 illustrates the procedure of binarization. If some value of the void fraction is above the threshold then there is a bubble, otherwise there is a slug.

$$u(\alpha, t) = \begin{cases} 0 & \text{if } \alpha < \text{threshold} \\ 1 & \text{if } \alpha > \text{threshold} \end{cases} \quad (1)$$

In Fig. 4 an example of the binarized signal from processed time series is shown, where B_i is the bubble and P_i is the slug. There is a discrepancy in the identification signals of a bubble and a slug which is measured by a time difference in the front of the bubble (Δt_B) and in the front of the slug (Δt_S).

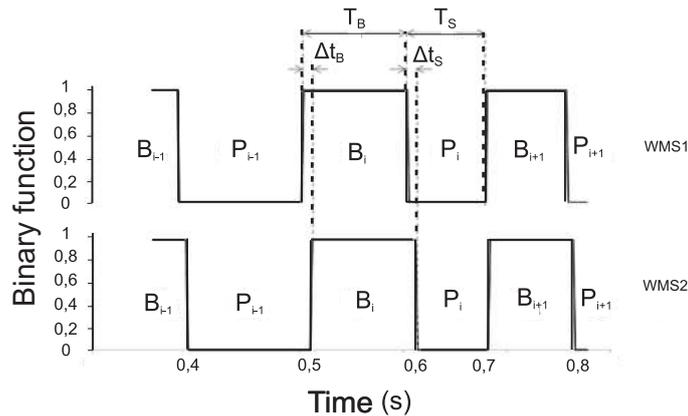


Figure 4: Binary function for the slug flow analysis.

Therefore, the determination of slug parameters (V_{TB} , f , L_B and L_S) can be made as follows. The translational velocity of the elongated bubble V_{TB} is determined by dividing the distance between the pair of WMS (37.5mm) by the time difference in front of bubble.

$$V_{TB} = \frac{d_{WMS}}{\Delta t_B} \quad (2)$$

The bubble and slug length is determined by multiplying the translational velocity by the period of passage of bubble T_B and slug T_S .

$$L_B = V_{TB}T_B \quad (3)$$

$$L_S = V_{TB}T_S \quad (4)$$

And finally, the slug frequency is the inverse of period of residence of the slug unit:

$$f = \frac{1}{T_B + T_S} \quad (5)$$

where T_B and T_S are the period of passage of bubble and slug respectively.

3. RESULTS

As the flow characteristics changes in the downward flow, the shape and type of the distribution was investigated as well. The quantile-quantile or qqplot is a graphical method used to validate an assumption of the distribution type. The main idea is to compute the theoretically expected value for each data point based on the standard distribution. If the data match with the selected distribution, then the points on the qqplot will fall approximately on a straight line. The qqplots of the slug parameters are showed in the Fig. 5. The liquid and gas superficial velocity for this case is $J_L=1.50$ m/s and $J_G=2.00$ m/s respectively. The normal distribution is used as a preliminary assumption. It can be seen that the translational velocity (V_{TB}) and bubble length (L_B) appear to follow the normal distribution for all inclinations in this study. However for the slug frequency and slug length parameters there is some discrepancy from the normal distribution.

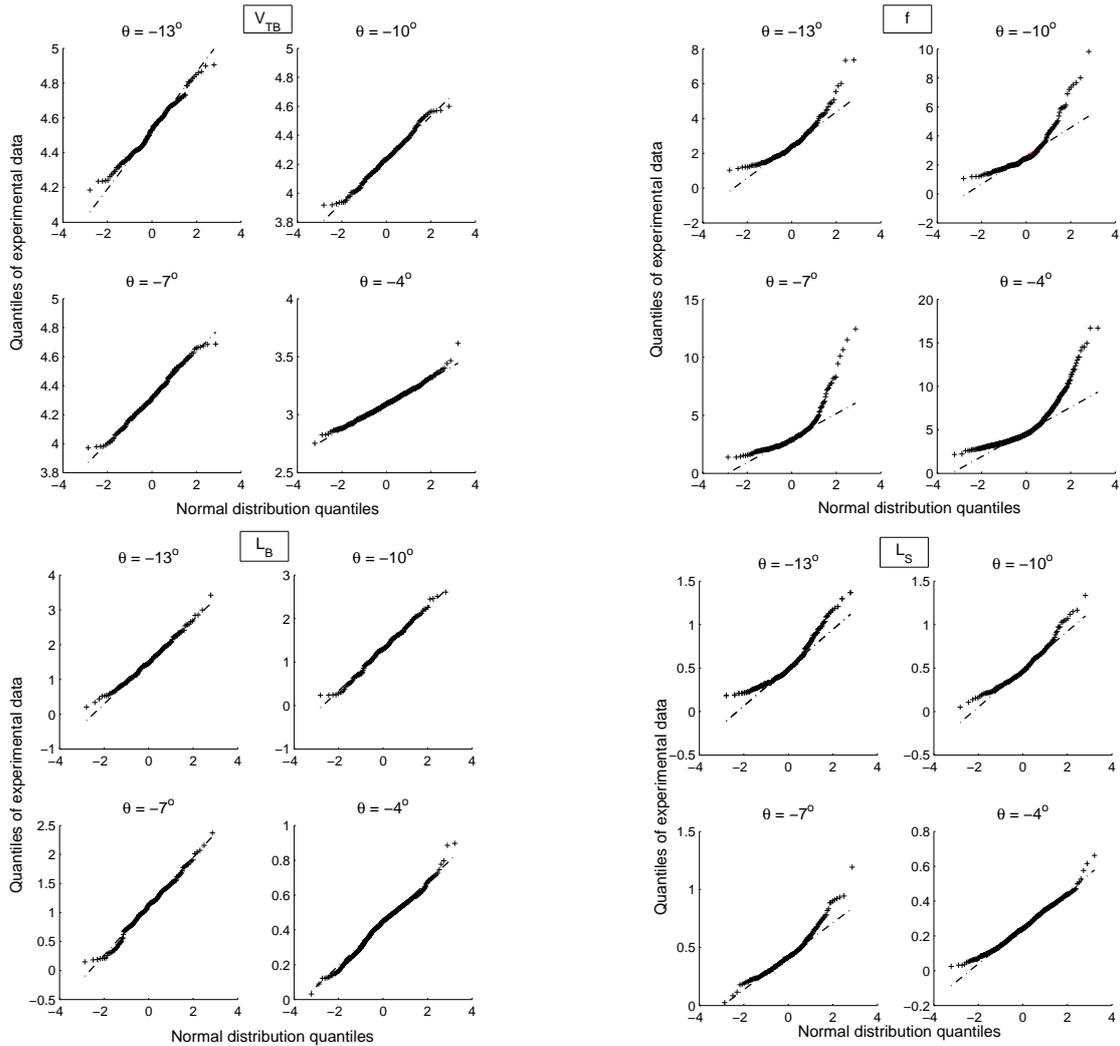


Figure 5: Normal quantile-quantile plots of V_{TB} , f , L_B and L_S for inclinations of -13° , -10° , -7° and -4° .

In order to better predict the distribution type, as suggested by Saether *et al.* (1990), Nydal *et al.* (1992), the log-normal distribution is tested. In Fig. 6 the qqplot of the slug frequency and slug length data are compared to a log-normal

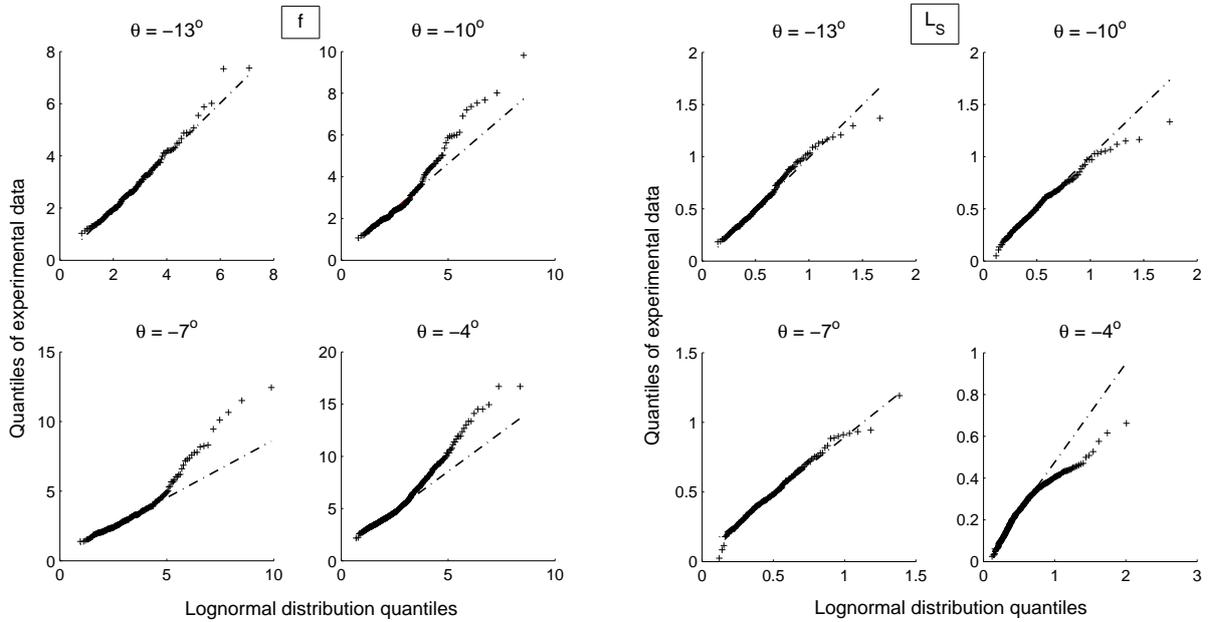


Figure 6: Log-normal quantile-quantile plots of f and L_S for inclinations of -13° , -10° , -7° and -4° .

distribution. As can be observed, there was an improvement of the predictions for these parameters (f and L_S) by using a log-normal distribution.

Verified the distribution type assumption for the slug parameters, the next step is to investigate the statistical data and perform a histogram of number of slugs for the experimental data with the fitted distribution. As can be observed in Fig. 7, the distributions appear to be well-fitted with the experimental data for all inclinations in the present study.

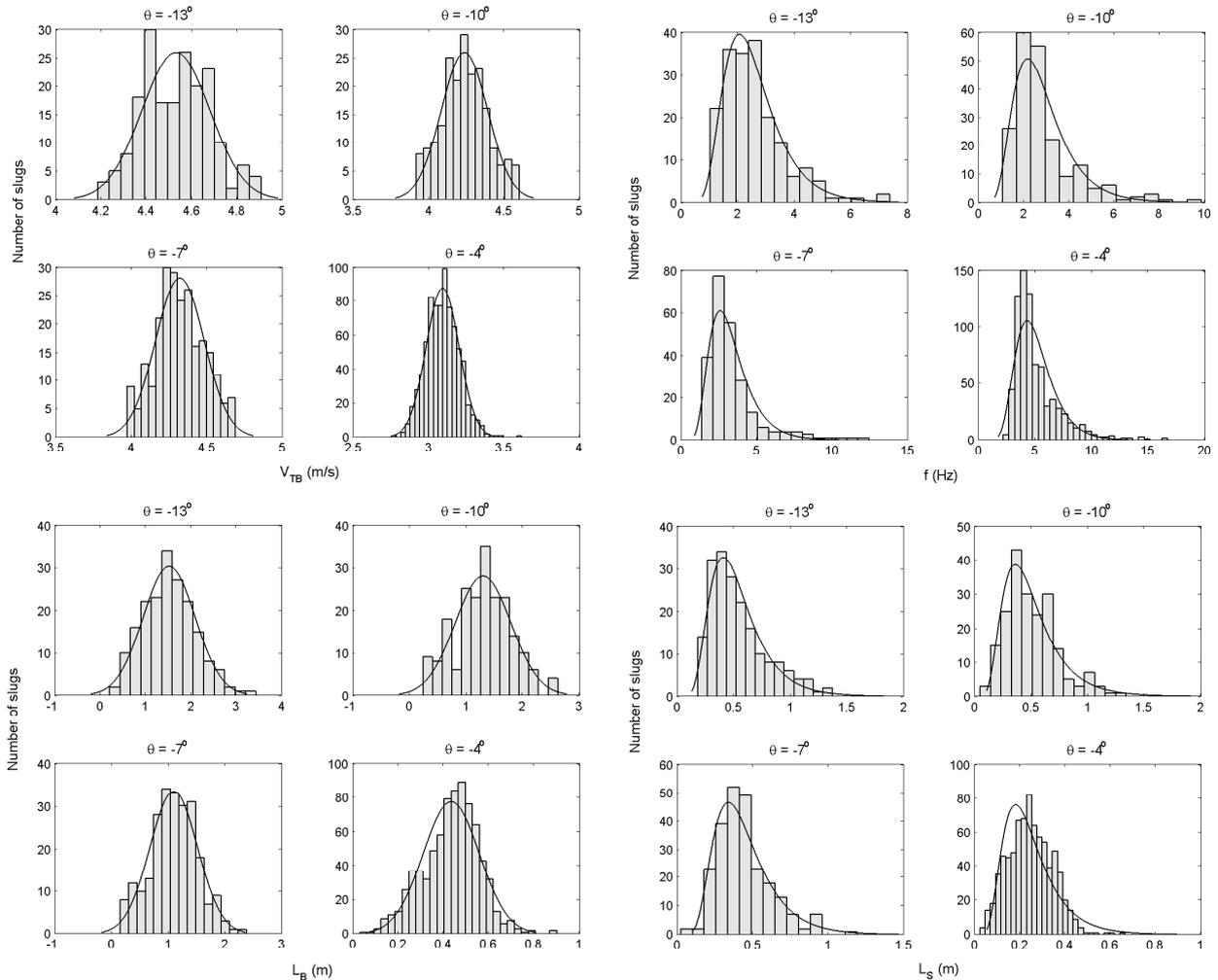


Figure 7: Histograms of experimental data with the fitted distribution.

The influence of the inclination angle on slug parameters also was investigated. A cumulative density function (CDF) was performed with the kernel density estimation for three flow conditions with constant superficial liquid velocity ($J_L=2.00$ m/s) and varying the superficial gas velocity ($J_G=1.00-2.00$ m/s). Figure 8 showed the CDFs of the translational bubble velocity. However, a clear tendency of the inclination angle was not observed in this study. In addition, it can be observed that the increase of the superficial gas velocity promoted an increase in the translational velocity not only for the mean value, but for the whole distribution as well.

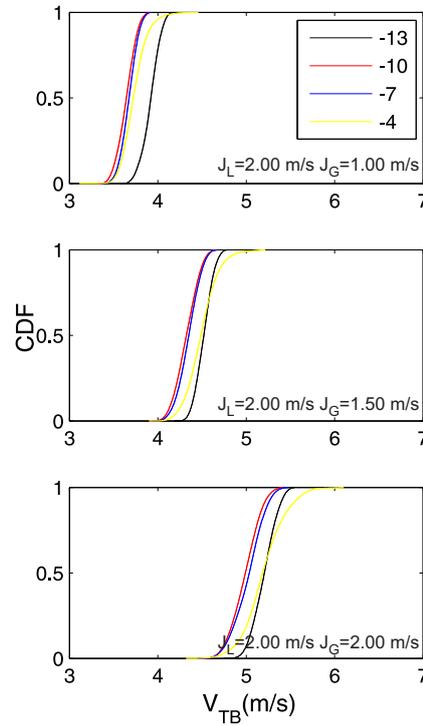


Figure 8: CDFs of the translational bubble velocity for downward flow.

4. CONCLUSIONS

In this paper, statistical measurements of translational velocity (V_{TB}), frequency (f), bubble (L_B) and slug (L_S) length in gas-liquid downward slug flow were presented. The inclination angles in this experiments were -13° , -10° , -7° and -4° . Experiments were carried out by wire-mesh sensors, which enables a time series signal of void fraction to attain the slug parameters. Quantile-quantile plots (qqplot) were performed to investigate distribution type for each parameter. In sequence, a histogram of number of slugs with the fitted distribution was shown to corroborate the distribution type assumption. A resume the distributions types found were presented as can be seen in Table 1.

Tabela 1: Distributions types for downward slug parameters

Slug parameter	Distribution type
V_{TB}	Normal
f	Log-normal
L_B	Normal
L_S	Log-normal

It was not observed in this study a major influence of the inclination angle on the slug parameters with the CDF plots.

5. ACKNOWLEDGEMENTS

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