23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

EXPERIMENTAL CHARACTERIZATION OF VELOCITY IN DOWNWARD GAS-LIQUID SLUG FLOW IN SLIGHTLY INCLINED PIPES

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Abstract. *Downward gas-liquid slug flow occurs in hilly-terrain pipelines and is frequently observed in oil and gas transportation lines. The onset of this flow type is due instabilities generated by irregular pipe topography. Therefore, to understand the hydrodynamics of the slug flow is paramount in the design of crude oil production lines as well as in the project of equipment involved in oil and gas operations. The goal of this work is to experimentally analyze the translational and rear velocity in ducts with inclination angles from* $0°$ *down to* $-13°$*. The analysis was performed at different gas-liquid volumetric flow rates for which the slug flow regime was observed. An existing experimental rig in the NUEM/UTFPR labs was used to collect data. A pair of wire-mesh sensors to evaluate the flow structure, thus obtaining void fraction temporal series was employed. From those temporal series, the velocities were obtained and comparative analysis could be made.*

Keywords: *experimental characterization, two-phase flow, slug flow*

1. INTRODUCTION

Two-phase flow has emerged as an important topic over the last years, due its large applications in industry such as nuclear and chemical reactors, heat exchangers, and other types of process equipment. Besides the above industry applications, it's worth mentioning oil and gas transportation, which comprise two-phase gas liquid flows through horizontal and inclined pipelines at different orientations, connecting wells in seabed to production platforms (Milan *et al.* (2013)).

The most common flow pattern in oil and gas industry is slug flow which occurs in all range of pipe inclinations and at large range of gas-liquid flow rates (Al-Safran (2009); Shemer (2003)). Slug flow is a class of intermittent flows which can be described as a sequence of identical slug units called unit cell (Wallis (1969)).

There is extensive published data on two-phase slug flow in horizontal and upward flows (Nicklin *et al.* (1962); Gregory and Scott (1969); Greskovich and Shrier (1972); Bendiksen (1984); Nydal *et al.* (1992)), however few attention has been paid to downward slug flow. Milan *et al.* (2013) studied the influence of the mixer in flow patterns for vertical downward air-water flow. Tzotzi *et al.* (2010) investigate fluid properties such as gas density and surface tension in gas-liquid slug flow in downward inclination.

Significant amount of research has been done to determine bubble movement in theoretical and experimental slug flow (Davies and Taylor (1950); Benjamin (1968); Nicklin *et al.* (1962); Dukler *et al.* (1985); Bendiksen (1984); Alves *et al.* (1993). A relation obtained by Nicklin *et al.* (1962) for the translational velocity of elongated bubble V_{TB} in continuous slug flow has been proposed as follows

$$V_{TB} = C_0 J + C_\infty \sqrt{gD} \quad (1)$$

where V_{TB} is the translational velocity of elongated bubble, C_0 is the mean bubble motion coefficient, J is the mixture velocity, C_∞ is the drift velocity coefficient, g is the gravitational acceleration and D is the tube diameter.

The first term of the right side in Equation 1 represents the velocity of the liquid in front of the elongated bubble nose tip and the second term is the buoyancy-induced velocity, called drift velocity, which is related to bubble movement in quiescent liquid (Alves *et al.* (1993)).

The value of C_0 is based on the assumption that propagation velocity of elongated bubbles follow the maximum local velocity in front of the nose bubble (Van Hout *et al.* (2003)). Weber (1981) established a criterion for bubble movement in horizontal tubes as a function of contact angle and Eötvös number. Comparing with the experimental data of Zukoski (1966), he obtained a expression for C_∞:

$$C_\infty = 0.54 - 1.76Eo^{-0.56} \tag{2}$$

where Eo is the Eötvös number defined in Equation 3 as the relation between buoyancy and surface tension forces.

$$Eo = \frac{(\rho_L - \rho_G)gD^2}{\sigma} \tag{3}$$

The values of C_0 and C_∞ were determined by Bendiksen (1984) based in 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.

$$C_0 = \begin{cases} 1.05 + 0.15\; sen^2\theta & Fr_J < 3.5 \\ 1.2 & Fr_J \geq 3.5 \end{cases} \tag{4}$$

$$C_\infty = \begin{cases} 0.54\; cos\theta + 0.35\; sen\theta & Fr_J < 3.5 \\ 0.35\; sen\theta & Fr_J \geq 3.5 \end{cases} \tag{5}$$

where Fr_J is Froude mixture number which can be defined as

$$Fr_J = \frac{J}{\sqrt{gD}} \tag{6}$$

Theoretical and experimental analysis indicate in reported literature that C_0 is equal 1.2 for fully developed turbulent flow and 2.0 for fully developed laminar flow (Van Hout *et al.* (2003)).

The main objective of the present work is to investigate some features of velocity in continuous slug flow. Experimental results are compared to correlations found in specialized literature, and from experimental fit, correlations to translational velocity can be proposed.

2. EXPERIMENTAL METHODOLOGY

This section focuses on describing the experimental setup and the process of measuring the velocity in gas-liquid slug flow. Further, the time series extracted from wire-mesh sensor measures was processed to attain rear and translational velocity.

The experimental loop is mounted on a platform, which was oriented to the inclinations of $-13°$, $-10°$, $-7°$ and $0°$ to perform the measurements. The pipeline consists of a transparent acrylic pipe with an internal diameter (D) of 25.8 mm, and the total length (L) 357 D. A wire-mesh sensor (WMS) and a high-speed camera is located at a distance of 291 D from the mixer.

A schematic layout of the flow loop is shown in Figure 1. Air and water is used as working fluids in this study. The air from gas reservoir flows through an orifice plate meter and reaches the mixer. In addition, water from liquid reservoir is pumped through a Coriolis mass flowmeter into the mixer. Fluids return to the liquid reservoir where they are separated by gravity.

Gas flow rate was measured using three orifice plates, for ranges of J_G measurements up to 4.00 m/s. A centrifugal pump and a Coriolis mass flowmeter controls the superficial liquid velocity J_L measurements in the water pipeline. The range of superficial liquid velocity is 0.5-2.5 m/s. Relative uncertainty are $\pm 0.28\%$ and $\pm 2.02\%$ for liquid and gas superficial velocity respectively.

Wire-mesh sensor have been largely applied in two-phase flow characterization (Prasser *et al.* (1998); Reinecke *et al.* (1998); Da Silva (2008)). The wire-mesh sensor used consists of 12x12 perpendicular wires, the receiver and transmitter electrodes, which enables measuring of electrical capacitance (permittivity) of the fluids at each node. Hence, the instantaneous value of void fraction for each node can be determined using reference calibration measurements for dry and water-filled pipe. Figure 1 shows a wire-mesh sensor type and in the present study, a pair of WMS is used to perform velocity measures, which is 37.5 mm apart.

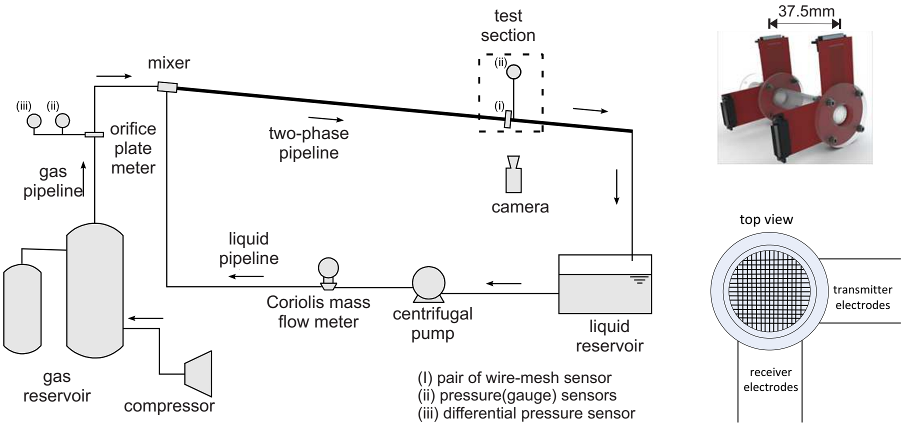

Figure 1: Experimental flow loop and a pair of wire-mesh sensor.

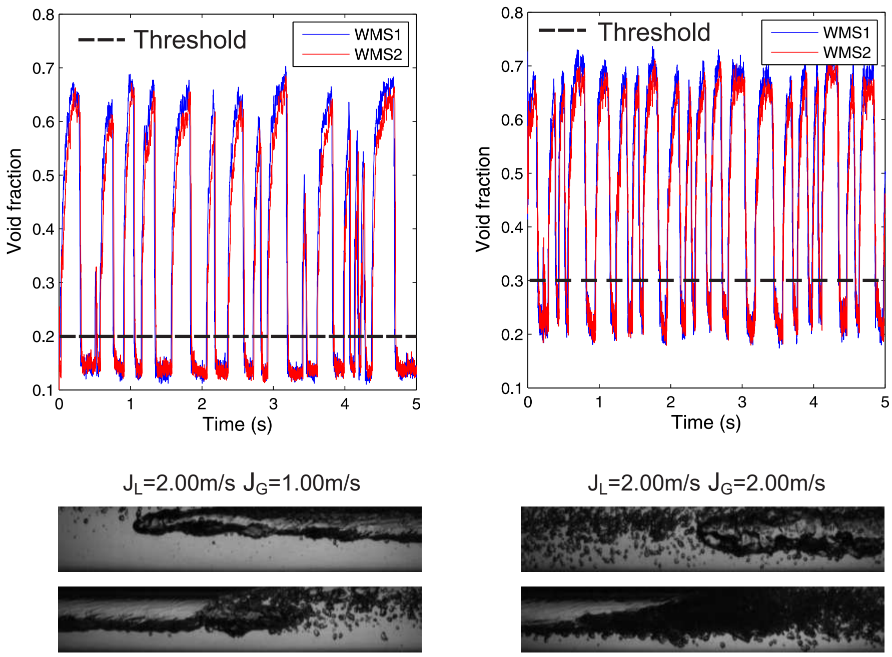

Figure 2: Time series associated with elongated bubble images.

Even a slightly increase of gas superficial velocity (1.00 m/s to 2.00 m/s) can promote a high aeration in the slug as one can see in Figure 2, the front and rear of an elongated bubble snapshot image. Thus, to process the WMS signal its necessary take into account this amount of aeration that is settled by a threshold (dashed line).

In order to attain the translational and rear velocity for gas-liquid slug flow, the signal processed from the void fraction time series can be converted to a binary function ($u(\alpha, t)$) as suggested by Bertola (2003).

$$u(\alpha, t) = \begin{cases} 0 & if\ \alpha < threshold \\ 1 & if\ \alpha > threshold \end{cases} \tag{7}$$

In Figure 3 an example of the binarized signal from 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 front of bubble (Δt_B) and in front of slug (Δt_S). Therefore, to calculate the translational velocity (V_{TB}) and the rear velocity (V_R), can be made as follows:

$$V_{TB} = \frac{d_{WMS}}{\Delta t_B} \tag{8}$$

$$V_R = \frac{d_{WMS}}{\Delta t_S} \tag{9}$$

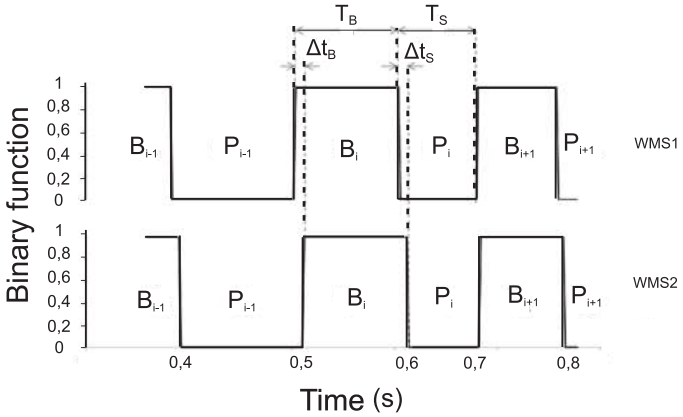

Figure 3: Binary function for the slug flow analysis.

3. RESULTS

3.1 Translational velocity

The translational velocity of the elongated bubble is a key parameter to understand slug flow hydrodynamics since the gas is carried by these long bubbles. Comparison of experimental results for translational velocity is shown in Figure 4.

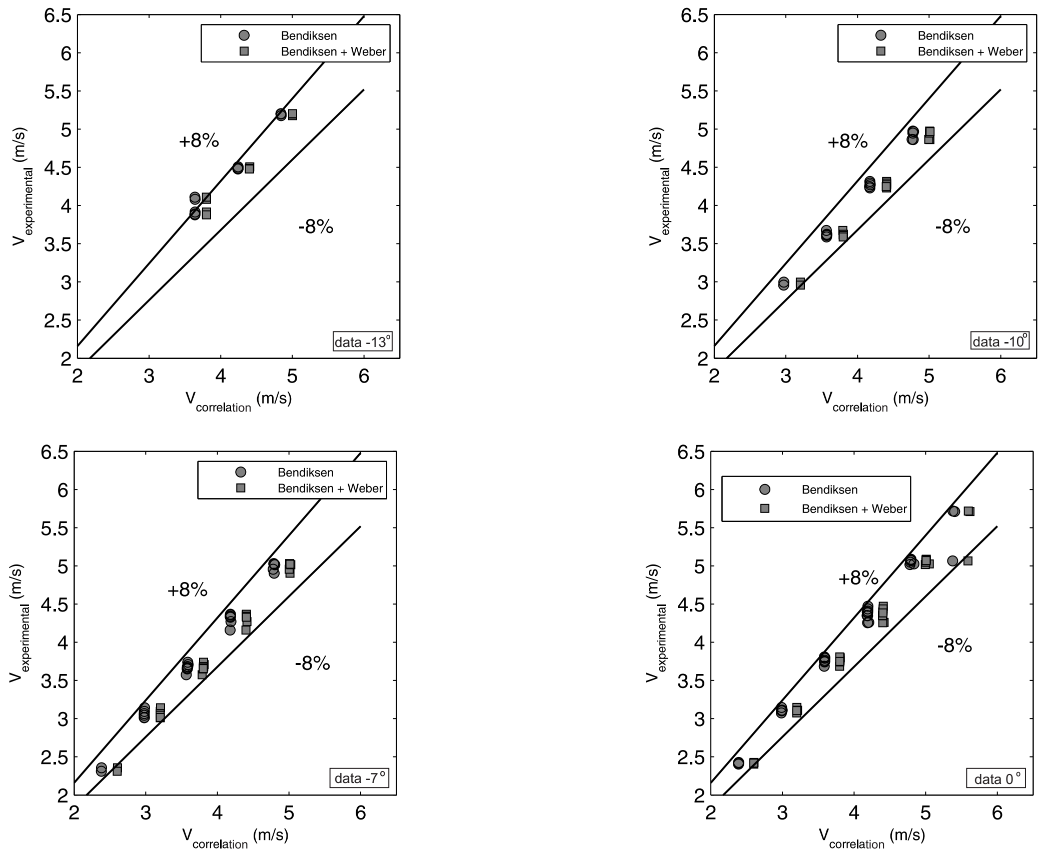

Figure 4: Comparison between experimental data and correlations of Bendiksen (1984) and Weber (1981) for air-water slug flow.

Two correlations are evaluated, the first one is the Bendiksen correlation (1984) and the second is a modification of the drift velocity suggested by Weber(1981).

$$V_{TB} = 1.2J + 0.35\sqrt{gD}sin\theta \quad (10)$$

$$V_{TB} = 1.2J + (0.54 - 1.76Eo^{-0.56})\sqrt{gD} \quad (11)$$

Continuous line in Figure 4 indicate limits of 8% comparing experimental data and the correlations which indicate good agreement in the prediction of translational velocity. A proper way to analyze the experimental translational velocity is to normalize Equation 1 through Froude mixture number:

$$V^* = C_0 Fr_J + C_\infty \tag{12}$$

where V^* is

$$V^* = \frac{V_{TB}}{\sqrt{gD}} \tag{13}$$

Figure 5 shows the experimental results to the normalization procedure and a linear feature for the normalized velocity occurs. In reported literature several authors claim the same behavior (Nicklin *et al.* (1962); Bendiksen (1984); Nydal *et al.* (1992); Fossa *et al.* (2003); Vicencio (2013)). An explanation to this behavior is due mass conservation in front of bubble nose tip (Weber (1981)).

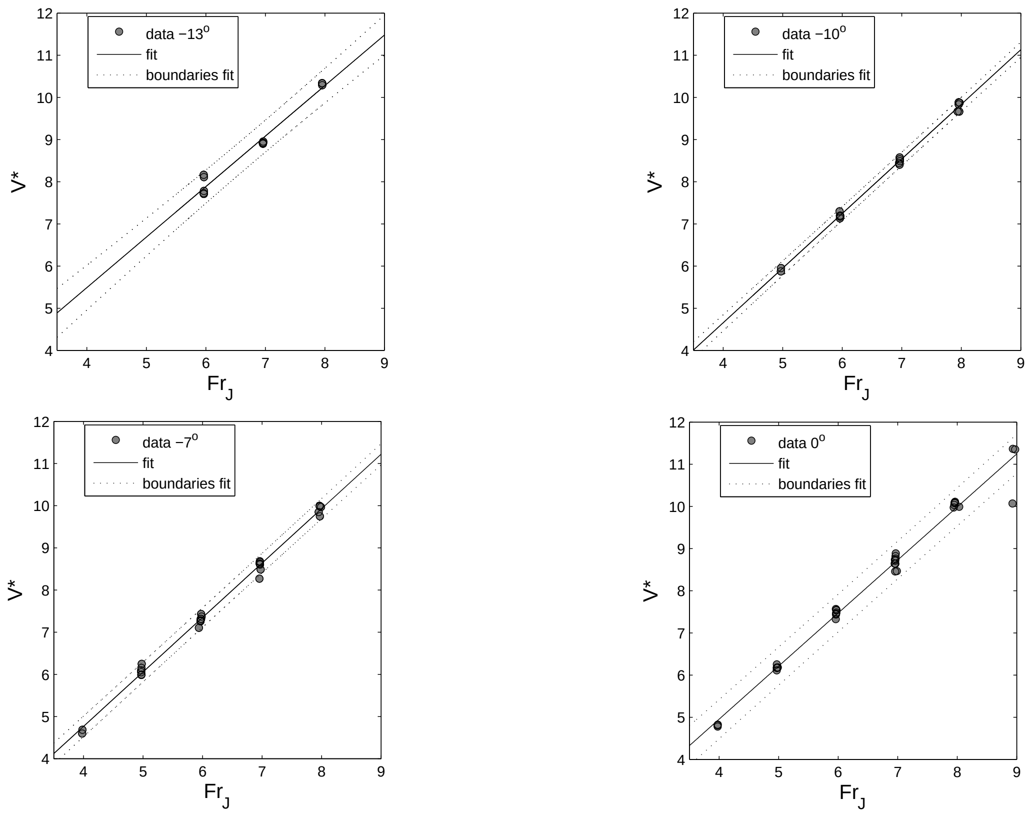

Figure 5: Normalized velocity versus Froude number for air-water slug flow.

The results are summarized in Table 1 with confidence interval of 95%. In the last column is the correlation coefficient (R^2) and the values close to 1 indicate the agreement between the experimental data and the linear approximation. The coefficients values C_0 and C_∞ are in accordance to values found in the literature. For the horizontal case, the drift velocity is zero. This result according to analysis of Bendiksen (1984) is due high velocities ($Fr_J > 3.5$) which leads elongated bubble moving to center position of the tube and neglecting surface tension effects, there are no causes for the drift velocity, therefore $V_D = 0$. For the inclination angles of $-10°$ and $-7°$ the drift velocity is negative which can be explained by the arise of the buoyancy effect. For the last inclination ($-13°$) a shift behavior is observed and need further investigation, for instance it is possible that occurred a Froude mixture number transition due to higher liquid velocities to accomplish the slug flow in this orientation.

Table 1: Translational velocity coefficients

Inclination angle (∘)	C_0	C_∞	R^2
-13	1.20	0.70	0.97
-10	1.30	-0.52	0.99
-7	1.29	-0.40	0.99
0	1.25	0	0.99

3.2 Rear velocity

Theoretical models in two-phase slug flow consider the translational velocity(V_{TB}) as the major in the unit cell (Fabre and Line (1992); Shoham (2006)). This feature indeed is valid for horizontal and upward flow, however in downward flow it can not occur in some cases. A schematic description of the behavior discussed is shown in Figure 6 where V_S is the slug velocity, V_f is the film velocity which varies along the gas pocket, as the height of the gas pocket is not constant due to changes in the bubble shape.

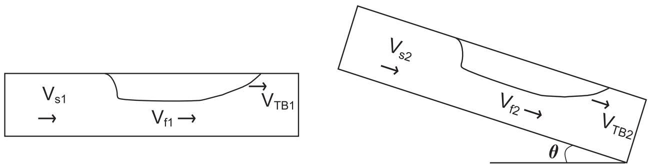

Figure 6: Schematic velocities in horizontal and downward slug flow.

When in horizontal case the subscript used is 1 and in downward case the subscript is 2. Therefore:

$$V_{S2} > V_{S1} \tag{14}$$

$$V_{f2} > V_{f1} \tag{15}$$

When the inclination angle changes in downward direction, the liquid velocity moves faster than horizontal case. The gravity effects in downward inclination arise the buoyancy effect which increase the liquid velocities in slug flow. It is expected that this behavior will promote recirculation and turbulence in the bubble tail (wake zone) and this disturbance will affect the velocity profile which can lead to different velocities in the slug unit cell.

In order to visualize the behavior described above, a plot of the relation between the translational bubble velocity (V_{TB}) and the rear bubble velocity (V_R) is made. In Figure 7 the continuous line (horizontal) indicate that the points above the translational velocity is greater than rear velocity ($V_{TB} > V_R$) whereas the points below indicates the opposite ($V_{TB} < V_R$). The differences between rear and translational bubble velocity can be explained by the gas expansion in the bubble. For the inclination angle of $-13°$, $-10°$ and $-7°$ the behavior $V_{TB} < V_R$ is more pronounced because of gravity effects. In the case of $0°$ can be observed that $V_{TB} > V_R$ in great amount of points which indicate the gravity effect decreased.

4. CONCLUSIONS

In this paper, measurements of velocity in gas-liquid slug flow were presented. Experiments were carried out by wire-mesh sensors, which enables a time series signal of void fraction to attain the translational and rear velocity of the elongated bubble. The linear relationship between normalized translational velocity and Froude mixture number was observed, and the values of C_0 and C_∞ could be determined from linear fit of experimental data. A schematic description of the velocities in downward direction is also presented and to observe this behavior a plot of the relation between rear and translational velocity is also made. It could be observed that rear velocity exceeds translational velocity as the inclination angle changed to downward direction.Finally, correlations for experimental translational velocity in each orientation angle is shown in Table 1 with a confidence interval of 95%.

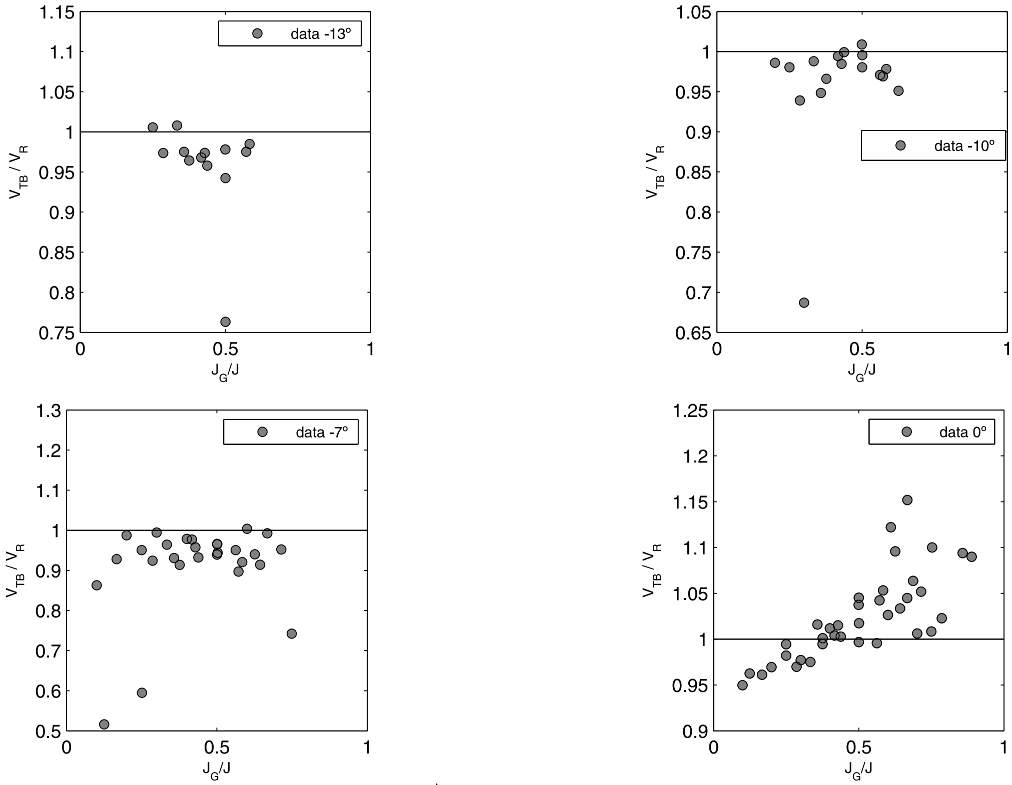

Figure 7: Measured values of V^* versus Froude number for air-water slug flow.

5. ACKNOWLEDGEMENTS

The authors acknowledge the financial support from CAPES, ANP and FINEP through the Human Resources Program to Oil and Gas Segment PRH-ANP (PRH 10 - UTFPR) and from TE / CENPES / PETROBRAS.

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