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CONDUCTIVE PROBE AND FAST-FILMING TECHNIQUE FOR THE STUDY OF SLUG FLOW HYDRODYNAMICS

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Abstract. *Multiphase flow happens when two or more phases flow simultaneously. Its most common class is the gas-liquid combination, which is typical of many industrial applications and natural processes. The way the phases are distributed in the pipe geometry classifies what we call flow patterns. One of the most common flow pattern is the slug flow, which is characterized by a large gas bubble called Taylor bubble and a thin liquid film separating the bubble from the tube wall. The measured parameters related to its hydrodynamics have great relevance, given the complexity of this flow and the risks of operation and accident that it can cause. This study uses the conductive probe and fast technique to determinate the translation velocity of the gas phase in an ascending vertical slug flow. The conductive probe results are compared to the results given by the image technique and from empirical correlations. Both results measured by the two techniques, taking into account their relative errors, showed reasonable agreement when compared.*

Keywords: *slug flow, Taylor bubble, conductive probe, fast-filiming technique.*

1. INTRODUCTION

Two-phase flow happens when two phases flow simultaneously and the most common combination of phases is liquid-gas, often found in a large industrial applications, such as pumping systems in general, in which the presence of gas usually brings several complications to the operation. It also occurs in vaporization and condensation process in thermal systems, where the phase change is significant and forced convection is the main mechanism of heat transfer, like inside of boilers and condensers of energy generation systems, in heat exchangers of direct contact and in industrial refrigeration systems in general. This type of runoff is widely found in petroleum, nuclear, chemical and geothermal industries (De Oliveira *et al.*, 2015), and because of its intermittent nature, has been attracting the attention of researchers in recent decades; both because their specific characteristics are beneficial, as in the case of heat exchangers that use the recirculation caused in the wake of the bubble to increase its efficiency (Gupta *et al.*, 2010); and for more worrying causes such as the serious erosion-corrosion risks in pipelines in industries, often leading to catastrophic and large-scale failures (Thaker and

Banerjee, 2016).

The two phase flow has a complex nature, characterized by intense turbulence, due to the interface of the phases having a deformed appearance, by the continuous interaction with the permanent sliding between the phases and by the compressibility of the gas phase. This framework makes it difficult to obtain reliable flow models. These flows are classified into flow patterns which is what is called the phase distribution in the pipe geometry.

The most frequent patterns in the industrial applications mentioned above is the so-called continuous slug flow, which has an intermittent nature and exists in a wide range of phase velocities according to several authors, among which are the Taitel *et al.* (1980) and Kaichiro and Ishii (1984). This flow pattern will be the object of this study and it is characterized by the presence of an elongated gas bubble followed by a liquid piston that may or may not contain small bubbles of entrained gas.

The continuous slug flow along the tube is very dependent on the relative velocities between the bubbles. The short separation distance between elongated bubbles accelerates one toward the other causing coalescence. During the mixing process, both elongated bubbles and liquid pistons increase in size, this process is terminated when all elongated bubbles propagate at the same translational speed (Shemer, 2003).

Due to the need to evaluate the various conditions of occurrence of the multiphase flow, some instruments should be used. Herringe and Davis (1974) have shown that the conductive probe technique is the most suitable for detecting the local phase in the gas-liquid flow, the latter being the conductive phase. However, the literature dealing with the use of the conductive probe technique presents some considerations to the methods of analysis that deserve attention, such as those related to the calculation of the velocity of the bubble. In this analysis, the signals obtained by the probe when passing the front and back of the bubbles are used, and then all results must be treated statistically in order to minimize errors (Silva, 2007) and the adaptations in classical model are proposed.

2. HYDRODYNAMICS OF RISING VERTICAL SLUG FLOW

The full description of the hydrodynamics of the slug flow includes the average flow parameters, such as the characteristic velocities of propagation of the gas-liquid interfaces, the length and shape of the elongate bubbles and the liquid pistons. The hydrodynamics of this pattern is characterized by an almost periodic alteration of liquid pistons and elongated bubbles of gas occurring over a wide range of flow conditions in vertical and horizontal pipelines. In vertical pipelines these bubbles have a spherical shell-shaped front (top, nose), while the rear (base, tail) is generally assumed to be flattened, depending on the flow conditions.

In the vertical slug flow a large part of the gas is found in the elongated bubbles (Taylor bubbles) whose length, L_{TB}, take up almost the entire cross section of the tube, and whose void fraction is α_{TB}. The liquid piston has the length L_{LS}, which separates the bubbles, and may or may not be aerated (depending on the flow conditions) with small gas bubbles (sparse bubbles), whose void fraction is α_{LS}. The unit cell is completed with the length of the unitary liquid piston L_{SU}. The liquid confined between the elongate bubbles and the tube wall flows around the bubble like a thin film of falling liquid. Each piston shed liquid from its end into the subsequent liquid film, which is cast into the bubble wake as a jet through the circular wall, producing a mixing zone on the wake whose shape resembles that of a toroidal vortex, so small bubbles are entrained in the region of the piston as can be seen in Fig. (1). In general the vertical slug flow maintains axial symmetry and the liquid phase flow regime is often turbulent.

The elongated bubbles with their characteristic shape move upwardly in the liquid with a mean velocity U_N and the length L_{TB} remaining unchanged because the expansion effects are small in the axial direction of the flow for ducts with short distances or in high pressure systems, because the gas density does not change significantly, which does not compromise the size of the bubbles. In most cases, the density and viscosity of the gas are much lower than those of the liquid, so the pressure inside the Taylor bubbles remains practically constant. As a result, the internal region remains constant, the interfacial frictional forces are negligible and the liquid film descends around the U_{LTB} velocity elongated bubble as if in free fall (Fernandes *et al.*, 1983).

In the region of the liquid piston are dispersed small bubbles that move with velocity U_{GLS}. The distribution of the void fraction in the liquid piston is practically constant, however as a function of the liquid film that descends into the liquid piston, it causes the entrainment and storage of small bubbles in the region near the tail of the bubble, the fraction of void in this region is much larger than the void fraction α_{LS}. As a result, the void fraction of a slug flow can vary from 25% to 90%, but when counting the air distributed on the wake, the liquid piston and the region containing the elongate bubbles, the void fraction in the pipe is α_{MED}.

The slug flow is complex and intermittent, mainly due to the presence of elongated bubbles. The principal models then seek to somehow describe the movement of these bubbles. The velocity of the elongated bubbles depends on the acceleration of gravity, the diameter and slope of the duct, the volumetric flow of both phases and the properties of the fluids, including their viscosity, specific mass and surface tension. The sizes of the elongated bubble and the liquid piston generally follow this same dependence.

It is the one that refers to the velocity of the gas-liquid interfaces and this concept applies both to the Taylor bubble and to the bubbles dispersed inside the liquid piston in a vertical pipeline. A simple criterion for distinguishing between

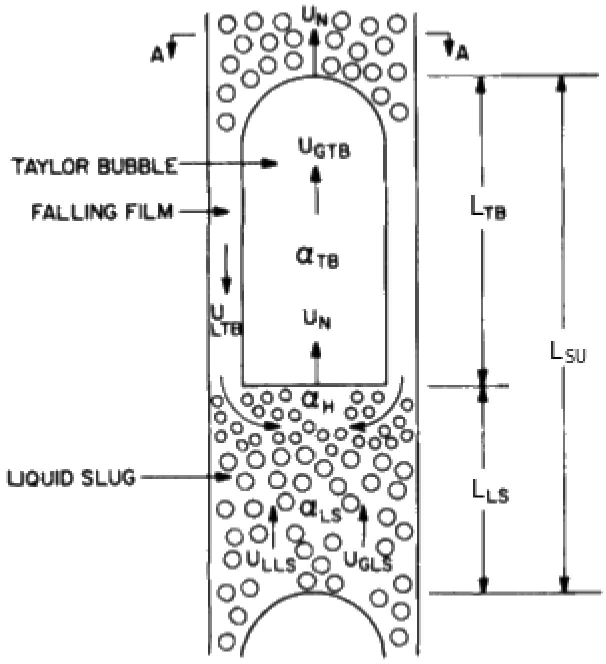

Figura 1. Standard cell of a vertical slug flow adapted from (Fernandes *et al.*, 1983).

elongated bubbles and bubbles dispersed within the liquid piston is the characteristic value of the pipe diameter. Bubbles having a length greater than or equal to the internal diameter of tubing D are considered elongated, while smaller bubbles are called dispersed (Barnea and Taitel, 1993).

The velocity of ascension of an elongated bubble U_N is affected by two factors: the velocity of the liquid ahead of the nose of the bubble U_l, and the velocity induced by the buoyancy of the bubble, i.e. the drift velocity of the bubble U_d in a stagnant liquid. Nicklin (1962) have suggested that for a Taylor bubble rising in a liquid moving upwards, its translational speed is given by a superposition of these two velocities, which can be expressed by:

$$U_N = C_1 U_l + U_d \tag{1}$$

In the case where the bubble is in a continuous slug flow condition, the velocity of the liquid is replaced by the mixture velocity U_m.

$$U_N = C_1 U_m + U_d \tag{2}$$

The mixture velocity is defined as

$$U_m = U_{SL} + U_{SG} \tag{3}$$

where U_{SL} and U_{SG} are the superficial velocity of the liquid and gas phase, respectively.

The drift velocity is determined by the three-dimensional flow at the front of the bubble and is defined by:

$$U_d = C_2 \sqrt{gD} \tag{4}$$

For the case of only inertial flow, and disregarding the interfacial and viscous effects, several authors reached a consensus that the constant C_2 is in the range of 0.33 to 0.36, being 0.35, widely used. The magnitudes g and D are respectively the acceleration of gravity and the internal diameter of the pipe.

The drift velocity also depends on the kinematic viscosity of the liquid or the Reynolds Re number, but Zukoski (1966) showed that for $Re > 300$ based on the deviation velocity U_d, the influence of viscosity on this same velocity is negligible.

In fully developed flow, it is assumed that the translational velocity of the elongated bubble is generally associated with the velocity value in the center line of the liquid piston, where this velocity reaches its maximum value. Therefore, the translational velocity of the elongated bubble is equal to the maximum local velocity of the liquid in front of the nose of the bubble. Thus the value of the constant C_1 in the first portion of Eq. (1) and Eq. (2) depends on the velocity profile of the liquid piston in front of the bubble, and is defined as the ratio between the maximum and average velocities of the velocity profile U_{max}/U_m. Thus, the values of $C_1 \approx 1.2$ for turbulent flow and $C_1 \approx 2.0$ for laminar flow are widely used, and although these are approximate values, they have been validated by analytical and experimental models.

Bendiksen (1984) suggested that the coefficients C_1 and C_2 depend on a larger scale of the Froude number and the Reynolds number; and to a lesser extent on the surface tension and inclination angle of the pipe.

The effect of surface tension is calculated in terms of the parameter of surface tension Σ, given by Eq. (5). Zukoski (1966) showed that this effect is particularly greater for smaller diameters and becomes influential over the deviation speed such that it decreases considerably with an increase in surface tension, and may eventually reach zero when Σ is of the order of unit.

$$\Sigma = \frac{4\sigma}{g(\rho_L - \rho_g)D^2} \tag{5}$$

Mazza *et al.* (2010) analyzed the different conditions for the estimation of C_1 and C_2 values and proposed correlations that take into account the influence of all the parameters related by Bendiksen (1984), which should be used in the equation proposed by Nicklin (1962).

If $Re_m \geq 2100$ and $Fr_m \geq 3.5$, then $C_1 = 1.2$ and,

$$C_2 = \frac{0.345}{\left(1 + \frac{3805}{Eo^{3.06}}\right)^{0.58}} sin(\beta) \tag{6}$$

If $Re_m \geq 2000$ and $Fr_m < 3.5$, then $C_1 = 1.0$; or if $Re_m < 2000$ then $C_1 = 2.0$ and,

$$C_2 = \left(0.542 - \frac{1.76}{Eo^{0.56}}\right) cos(\beta) + \frac{0.345}{\left(1 + \frac{3805}{Eo^{3.06}}\right)^{0.58)}} sin(\beta) \tag{7}$$

Where Fr_m is the Froude number, Re_m is the Reynolds number, both calculated on the mixture velocity gas-liquid, Eo is the Eötvos number and β the inclination angle of the pipe with the horizontal.

In Eq. (1) and Eq. (2), C_1 and U_d are considered constants for all given operating conditions. It is also assumed that the translational velocity of the Taylor bubble is linearly dependent on the mixing velocity, however, this assumption is only an approximation which is often the subject of theoretical and experimental verification.

3. EXPERIMENTAL PROCEDURE

An experimental apparatus was constructed as a closed circuit for measurements of translation velocity of the gas phase. The circuit is formed by PVC pipes and a vertical acrylic tubular test section through which gas and liquid circulate continuously. The liquid phase is distilled water which through the work provided by a pump circulates freely in part of the experimental apparatus. At the base of the vertical column, representing the test section, the gas phase formed by compressed air is released into the acrylic tube mixing with the water stream. The two fluids cross the test section where the measurements are performed by the two techniques used.

The operating principle of the conductive probe is based on the difference in electrical conductivity between the liquid and gas phases. The liquid phase has a conductive character and the gas phase has an insulating character. The probe thus identifies two different states, conduction and non-conduction, generating a signal similar to that of a square wave when a bubble passes through it. When processed and treated, the signals provide the void fraction, size, velocity and frequency of the bubbles. The accuracy of measurements is limited by the acquisition rate of the data acquisition board (Silva, 2007).

The probe is inserted into the acrylic tube of the test section, through a T connection, so that the sensor tips are in the acrylic tube. The probe is mounted and fixed to a stainless steel hollow support, and this in turn is fixed to the T by means of a hexagonal head screw, in such a way that all this formed assembly can be manipulated in the radial direction of the tube so that the probe is positioned well into the center of the pipe. In the inner circular section of the T connection was installed a metal ring, to which is connected externally a small bar fixed by a screw in which the connection of the ground wire is made. When the gas-liquid interface passes, the formed circuit has the condition of operating by the passage of the electric current from the sensors to the metal ring and from this to the ground wire. The probe sensor tips are located near the position where the ring is installed.

The data acquisition board, which has a maximum acquisition rate of 20 kHz, is connected to the computer, where the program is used to register the number of channels to acquire the signals, which in this work are two. The frequency of acquisition of 20 kilohertz per sensor and the established acquisition time by the defined plate in ten minutes. After this step, the data collection was started by the conductive probe technique. After ten minutes of acquisition, the program closes the data collection and generates a file with the registered voltage values, which will be treated separately by a computational code to obtain the desired parameters.

The fast-film measurement procedure starts from a camera that has the possibility of filming at up to 1000 frames per second and was used to produce two minutes films, which in turn were processed in commercial software. In order to obtain the videos, it was necessary to install special reflectors with halogen lamps of 150 W each, the result of which is

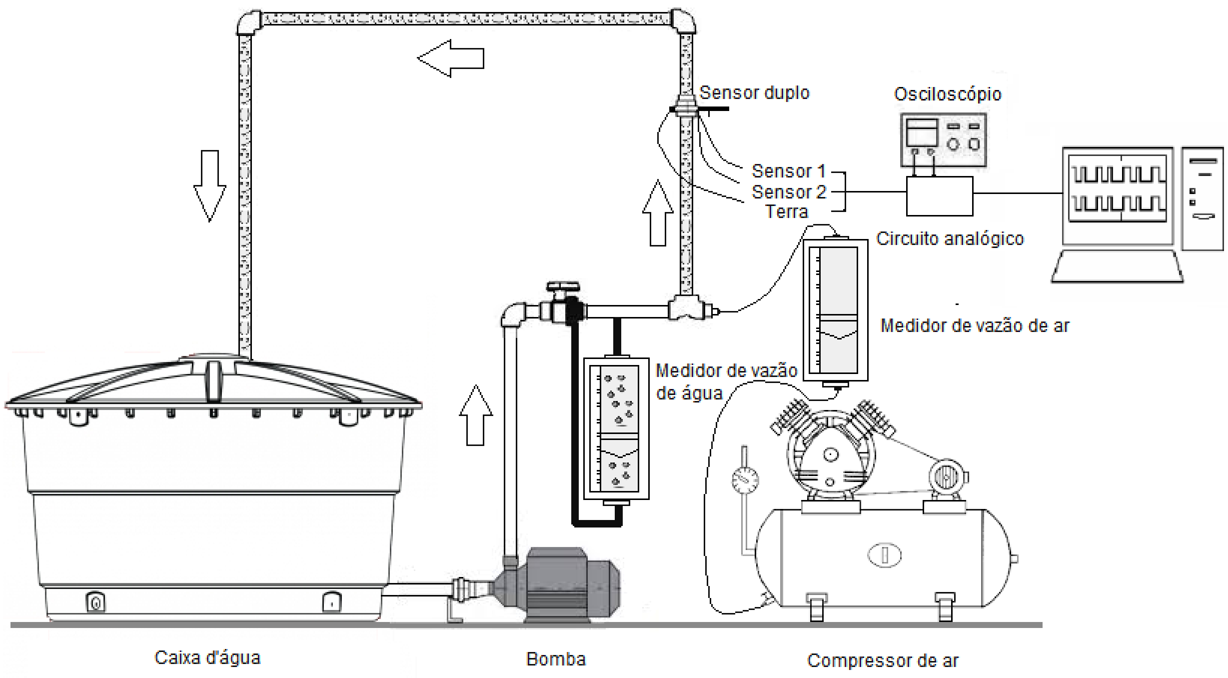

Figura 2. Experimental apparatus (dos Santos, 2016).

to gain sharpness due to the speed at which the camera is operating. The two reflectors were installed 0.5 meters from the acrylic case on each side at both measuring stations. Uniform illumination over the entire housing was achieved by diffusive surfaces installed between the reflectors and the box that directed the light.

In order to neutralize the curvature effect provided by the transparent tubing of the test section causing distortion in the images, an acrylic box of dimensions 200 x 150 x 100 millimetres was placed in the acrylic tube of the test section. To achieve neutralization of the tube's curvature the box was completely filled with water, resulting in a image of the bubble as of a flat figure. A metal ruler with a scale in millimetres was attached to the side of the acrylic tube inside the box, in order to verify the displacement of the elongate bubble between its markings, serving as a reference for the measures of velocity and size of the bubble.

The experiment was carried out in two stages, whose intention was to take the values of the flow parameters for a pipe with internal diameter D of 19 mm. Each stage corresponds to a different measuring station on the same pipe; the first one located at 1m from the air injection, called station 1, which can also be referenced by the ratio between the measurement height X (taken from the air injection) and the internal diameter of the pipe D, thus defining , $X/D = 53$, as the parametrized length for the first stage of the experiment (lower station); and the second located 2 m from the air injection denominated station 2, being defined in the same way as for the previous $X/D = 105$, as parametrized length for the second stage of the experiment (upper station).

For both stations, therefore, the acquisition of the flow parameters was carried out using the conductive probe measurement technique and the fast filming measurement technique, in order to evaluate and compare the values for the parameters obtained by them, in view of the hydrodynamics of the continuous slug flow.

4. RESULTS AND DISCUSSION

In the graph of Fig. (3), the values obtained experimentally for the translation velocity of the elongated bubble are plotted by the two measurement techniques versus the velocity of the mixture, for the two measurement stations and for all the flow conditions used in the experiment, as a form to compare them with the values provided by empirical correlations for this same parameter, mainly regarding the values obtained for the terms C_1 and U_d (the drift velocity) of Eq. (4), which are very representative for the characterization of the flow. The experimental values are plotted together with their respective linear adjustments and with the correlations of Nicklin (1962) and Mazza *et al.* (2010). The latter presents corrections for the values of C_1 and for the C_2 term of the drift velocity.

For the correlation of Nicklin (1962), it was assumed that $C_1 = 1.2$, which denotes the regime as turbulent, and $C_2 = 0.35$, which considers only the inertial effects of the flow, that is nothing more than the Froude number obtained at the drift velocity. It is observed that the estimate given by this correlation is above the experimental values obtained by the two techniques, the value of $U_d = 0.151$ m/s theoretical, is higher than the values obtained for this velocity experimentally

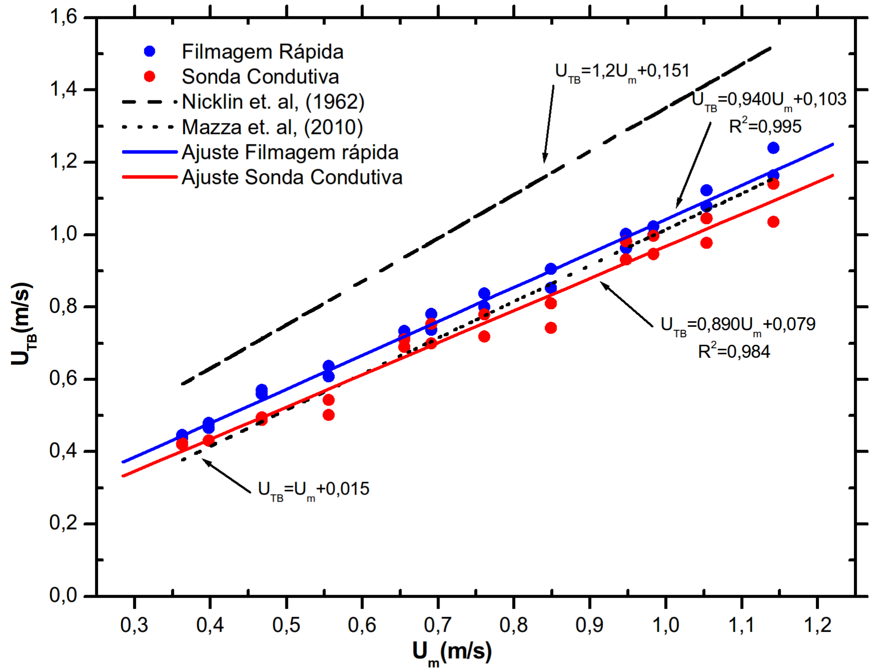

Figura 3. Comparison of the experimental translation velocities of the elongated bubble obtained by the two measurement techniques with the empirical correlations on the literature.

through the linear adjustments of the points that represent experimental measurements, equal to 0.103 m/s for fast filming and equal to 0.079 m/s for the conductive probe. The experimental C_1 value obtained by the adjustments for both the conductive probe equal to 0.890 and for fast filming equal to 0.940 are also lower than the value attributed in the literature.

Table (1) shows the values for the Reynolds number based on the mixing speed for all the flow conditions experienced, as well as the values of the Froude number, which is fundamental for the drift velocity.

Tabela 1. Values of Reynolds numbers and Froude number for the flow conditions of the experiment.

U_{SL} = 0,293 m/s		
U_{SG} (m/s)	Reynolds number (Re)	Froude Number (Fr)
0,07	7726	0,841
0,105	8474	0,922
0,176	9969	1,085
0,263	11838	1,288
U_{SL} = 0,585 m/s		
U_{SG} (m/s)	Reynolds number (Re)	Froude Number (Fr)
0,07	13957	1,519
0,105	14705	1,6
0,176	16200	1,763
0,263	18069	1,966
U_{SL} = 0,878 m/s		
U_{SG} (m/s)	Reynolds number (Re)	Froude Number (Fr)
0,07	20188	2,197
0,105	20935	2,278
0,176	22431	2,441
0,263	24300	2,644

As already mentioned, the term C_1 represents the ratio of maximum and mean velocity of the velocity profile, and this value increases from 1.2 when the regime is turbulent up to 2.0 when the regime is laminar. The values obtained experimentally for C_1 by the two techniques are smaller then 1.2, leading to the conclusion that the regime is very turbulent, which would translate into the mean velocity profile being greater than the maximum velocity. The level of turbulence in the liquid piston may be generating values of instantaneous velocities that are considerably different from the mean velocities. Thus, perhaps this is the explanation for the experimental C_1 values being smaller than that of the Nicklin (1962) correlation.

Mayor *et al.* (2007) have reached a similar conclusion about this condition for the rate between velocities in the piston of liquid in slug flow with controlled injection of bubbles.

In relation to drift velocity U_d and in particular to the term C_2 adopted with a value of 0.35 in Nicklin's correlation, only when the inertial effects should be taken into account, perhaps it needs a more careful analysis, because the increase of the surface tension for smaller diameter pipes is important for reducing the drift velocity.

For the correlation of Mazza *et al.* (2010), it is verified that the adjustments defined for the experimental data best approximate the straight line that represents it. The values obtained for C_1 experimentally by the two techniques are 0.940 for fast filming and 0.890 for conductive probe, and this time are closer to that obtained by this correlation which is equal to 1.0. This value is obtained because the Froude number is smaller than 3.5 and the Reynolds number is greater than 2100 (for all flow conditions) which are interrelated parameters for this correlation. The values obtained experimentally for the deviation velocity U_d for the two techniques are 0.079 and 0.103 for conductive probe and fast filming respectively, are also closer to the value of 0.015 provided by this correlation.

The best fit of the correlation of Mazza *et al.* (2010) to the experimental values of C_1 and U_d may be due to the fact that for all the flow conditions of the experiment the interfacial effects, as a function of the high superficial velocity of the liquid compared to the surface velocity of the gas, influence the values of the two terms of the correlation, making them smaller than those of Nicklin (1962) that does not take into account such effects. By obselues of the Froude number of table 1 for all flow conditions it can be observed that they are much larger than the value considered in the Nicklin (1962). correlation that considers it equal to 0.35 and is calculated on the drift velocity. Since, for the correlation of Mazza *et al.* (2010), the Froude number is calculated on the velocity of the mixture, suggests that its influence must be taken into account, since, for values above 1.0 of this number the regime is considered as supercritical.

5. CONCLUSIONS

In this paper measurements were made in the vertical section of an experimental apparatus to obtain the two-phase flow parameters, through the conductive probe and image techniques in an air-water mixture under various flow conditions in intermittent continuous slug flow. In order to establish conclusions, the results given by the two measurement techniques were compared to each other and with empirical correlations found in the literature. It was verified that some aspects pertinent to the condition of measurement of each technique in obtaining each parameter of the flow, as well as, the better adaptation of the model of Mazza *et al.* (2010) to the conditions of the studied flow.

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