EXPERIMENTAL STUDY OF SINGLE TAYLOR BUBBLES IN CLOSED VERTICAL AND SLIGHTLY INCLINED TUBES

Marcos Bertrand de Azevedo
Jose Luiz Horacio Faccini
Instituto de Engenharia Nuclear (IEN/CNEN), CEP 21941-906, Rio de Janeiro, Brazil
bertrand@ien.gov.br; faccini@ien.gov.br

Pedro Andrade Maia Vinhas
Departamento de Engenharia Nuclear, Escola Politecnica, Universidade Federal do Rio de Janeiro, CEP 21945-970, Rio de Janeiro, Brazil
mvinhas@poli.ufrj.br

Jian Su
Programa de Engenharia Nuclear, COPPE, Universidade Federal do Rio de Janeiro, CEP 21945-970, Rio de Janeiro, Brazil
sujian@nuclear.ufrj.br

Abstract. The present paper reports a study of single Taylor bubbles rising in vertical and slightly inclined tubes, using the pulse-echo ultrasonic technique and a high speed video camera. The inclination angles studied were 0°, 2.5°, 5°, 7.5°, 10° and 15° from the vertical position. Water, glycerin and water-glycerin solutions were used as working fluids to evaluate the influence of the liquid properties, especially viscosity, in the measured parameters. The measured results showed good agreement with correlations available in the literature and reveals that the procedures and techniques developed at the laboratory are well adjusted. It was observed that the bubble velocity decreases and the film thickness increases when viscosity increases. Furthermore, the bubble velocity increases when the inclination angle increases from the vertical position, in the inclination range studied.

Keywords: Ultrasonic Technique, Visualization Technique, Liquid Film Thickness, Taylor Bubble, Stagnant Liquid

1. INTRODUCTION

Gas-liquid two-phase flow is an important and complex form of multiphase flows and is encountered in a whole range of industrial applications such as pipeline systems for the transport of oil-gas mixtures, evaporators, boilers, condensers, sewage treatment plants, air-conditioning and refrigeration plants, cryogenic plants, among others. In the nuclear industry, the two-phase flow parameters need to be controlled at the primary reactor cooling system during the normal operation or during the emergency core cooling of nuclear reactors. Slug flow is one of the common flow patterns in gas-liquid flow and can be accompanied by fluctuations in pipe temperature. The high pipe wall temperature results in dryout, which may cause damages in the nuclear power generating systems and other industrial devices (Ghajar (2005)).

Slug flow is characterized by long bullet-shaped bubbles, also called Taylor bubbles or elongated bubbles, which occupy nearly the entire cross-section of the pipe and a liquid slug between successive bubbles. The liquid moves around the bubbles in a thin film and expands at the rear of the bubble, inducing a liquid wake. Figure 1 presents a schematic of a Taylor bubble rising in a vertical liquid column. A typical Taylor bubble can be divided into four parts: (1) an approximately hemispherical nose, (2) a body surrounded by a falling liquid film, (3) a tail, and (4) a wake. The body can be further subdivided: (2a) around the upper part, where the developing film is accelerating and thinning, and (2b) around the lower part, where the forces acting on the film are in equilibrium and the film thickness (δ) and the velocity profile are steady.

The knowledge of the Taylor bubble’s structure and its motion, including in stagnant liquid, is of fundamental importance in gas-liquid two-phase flow’s theory, which is applied to allow the elaboration of a good design and the optimization and safety analysis of equipments and processes. Furthermore, the understanding of the mechanics of liquid films is of great importance in situations involving two-phase flow where heat and mass transfer occur, which is absolutely relevant to the nuclear, petroleum and chemical industries. Among the factors affecting these transfer rates, there are the transfer coefficient and the interfacial transfer area, that depends on the wave motion at the gas-liquid interface and on the liquid film thickness.

Thus, the measurement of the flow parameters is absolutely important for understanding the flow’s structure. The development of instruments for the measurement of gas-liquid two-phase flows with a high degree of accuracy, performance and safety has stimulated the research of new methods and techniques able to measure them. Among these techniques, there are the visualization technique with high speed video camera and the ultrasonic technique.
De Azevedo, M. B., Vinhas, P. A. M., Faccini, J. L. H. and Su, J.
Experimental Study of Single Taylor Bubbles in Closed Vertical and Slightly Inclined Tubes

Figure 1. Schematic of a Taylor bubble flowing vertically in a liquid.

The technique using the high speed video camera can be classified as an optical technique and it is based on the
detection of the gas-liquid interface. The light emitted by each phase should present different characteristics, as color or
intensity, in such a way that light gradients are generated at the interfaces. This technique can be applied to observe and
determine the flow pattern and, in the case of slug flow, can be used to measure some flow’s parameters as the bubble’s
velocity and length. The parameters measured by this technique generally exhibit good accuracy, but a very good lighting
is required, specially for higher speeds of filming. Another problem is that its application, as the major part of the optical
techniques, is limited to transparent pipes or components and can not be used with opaque fluids.

Ultrasonic technique is non-intrusive, presents low costs and can be applied at high pressures and temperatures. An-
other advantage of this technique is that it can be applied to pipes and containers of different materials and to transparent
or opaque fluids. There are three ultrasonic methods able to perform gas-liquid flow measurements: the Doppler shift, the
transmission and the pulse-echo methods. The Doppler shift method, or technique, has a relative advantage when applied
to low void fraction liquid flow velocity measurements in a two-phase system (Chang and Morala (1990) and Lynworth
(1980)).

The principle used for the transmission method is based on the influence of flow velocity on transmission time (con-
trapropagating transmission method) to measure the liquid phase velocity in very low void fraction two-phase flow or
using the attenuation of sound pulses in the flow to determine the velocity and sizes of the rising bubbles (Chang and
Morala (1990) and Morala et al. (1984)).

Pulse-echo method were used to observe the location and size of bubbles, because of its ability to determine the gas-
liquid interfaces. This method can also be applied in a liquid film thickness measurement and characterization of flow
patterns (Chang and Morala (1990), Matikainen et al. (1986) and De Azevedo et al. (2013)).

This work presents a study of single Taylor bubbles rising in vertical and slightly inclined tubes. The objective of
the study is to develop and optimize the use of the visualization technique using high speed video camera and the pulse-
eco ultrasonic technique to measure the bubble velocities, the bubble lengths, the bubble profiles and the thicknesses
of the liquid films falling around Taylor bubbles rising in vertical and slightly inclined tubes closed at the ends. The
inclination angles studied were 0, 2.5, 5, 7.5, 10 and 15° from the vertical position. By measuring the flow parameters,
a better understanding of the structure and movement of Taylor bubbles, as well as of the slug flow structure, might be
obtained. Water, glycerin and water-glycerin solutions were used as working fluids to evaluate the influence of the liquid
properties, especially viscosity, in the measured parameters. Finally, the measured parameters may be compared with
some appropriate correlations available in the literature to estimate them.

2. EQUIPMENTS

The experimental data were obtained from a column partially filled with stagnant liquid located at the Thermo-
Hydraulic Laboratory of the Nuclear Engineering Institute (LTE/IEN/CNEN). Figure 2 illustrates the vertical and slightly
inclined column that consists of an acrylic tube of 2.0 m long with inner diameter of 24 mm sealed at the ends. A Taylor
bubble was formed by the inversion (\( t_1 \) to \( t_2 \)) of the pipe partially filled with liquid to leave an air pocket of length \( L_0 \). By
using a motion restrict or properly positioned, it is possible to stop the inversion at the desired inclination angle.

The high speed ultrasonic system used to measure the flow parameters consists of a generator/multiplexer board,
transducers and a computer (PC) with a LabView software developed at the IEN to control up to four transducers in pulse-
echo or transmission modes. Two ultrasonic transducers of 10 MHz and 6.35 mm diameter, Olympus piezoelectric-type transducers (Model V112), were mounted at the distance of 10 cm between them and they were located at 50 cm and 60 cm, respectively, from the top of the tube, except when glycerin was used as working fluid. In this case, the transducers were located at 70 cm and 80 cm from the top, respectively.

The visualization system is formed by a high speed video camera Olympus i-Speed 2 (maximum resolution 800 x 600 active pixels), zoom lenses, an acquisition and image analysis software (Olympus i-Speed Software Suite) and a laptop. The system is able to achieve images at a rate up to 1000 frames per second with maximum resolution and up to 33000 frames per second with minor resolution. The sequence of images displayed on the laptop screen were stored in a computer file and used afterwards to analyze in detail the bubble motion sequence.

3. EXPERIMENTAL PROCEDURES

The stagnant liquid column used in the present work is similar to that used by Llewellin et al. (2012) to study Taylor bubbles in vertical tubes. These authors measured the bubble length ($L_b$) and plotted the relationship between the bubble length ($L_b$) and the initial length of the air pocket ($L_0$) for each suite of data (inner tube diameter and working fluid). They found a linear relationship between $L_b$ and $L_0$:

$$L_b = \alpha + \beta L_0,$$

where $\beta = (1 - \delta')^{-2}$ and $\alpha$ is a constant related to the length of the nose and tail regions. $\delta'$ was the dimensionless film thickness defined as $\delta' = \delta/R$.

Using this procedure, Llewellin et al. (2012) determined the liquid film thicknesses around Taylor bubbles. According to them, the results were in good agreement with the values measured by Nogueira et al. (2006) employing optical techniques. This methodology was also used in the present work to determine this parameter for vertical tubes.

In this work, 250 bubbles (50 bubbles for each air pocket length $L_0$) were studied by using the ultrasonic technique with distilled water as working fluid. For the other fluids, 50 bubbles (10 bubbles per $L_0$) were studied for each of them. The air pocket lengths $L_0$ used to generate the bubbles were 40, 30, 25, 20 and 15 cm, except for 100% glycerin, where the $L_0 = 40$ cm was replaced by an $L_0 = 10$ cm, because of the high length of the bubble generated by the first one. For the experiments using visualization technique, only pure water and pure glycerin were used for vertical tubes and only pure water was used for inclined tubes. 60 bubbles (30 bubbles for each $L_0$) were studied for each of these liquids. The air pocket lengths $L_0$ used were 20 and 10 cm, in that case.

It is important to note that, in this stage of the study, the ultrasonic and the visualization techniques were not applied together during the experiments, but, considering the characteristics of the experimental apparatus, it can be expected that the bubble parameters would be the same for each set of working liquid and air pocket $L_0$ used to generate the bubbles.

The percentages given in the compositions of the mixtures are by volume. During the experiments, the temperature remained between 24 and 26°C. The procedures related with each of the techniques used in this work are described bellow.

3.1 The Pulse-echo Ultrasonic Technique

The pulse-echo ultrasonic technique is based on the high difference between the acoustic impedances of the gas and liquid phases, which allow that almost 99% of the incident wave is reflected by a gas-liquid interface. Thus, the location of a gas-liquid interface can be determined by measuring the transit time between the emission of a wave and its return after being reflected. The transit time can be obtained by the time interval between two consecutive reflections. Figure 3 shows a typical echogram registered by the ultrasonic system when an acrylic tube full with some liquid is analyzed.

In Fig. 3, one can observe the initial pulse that corresponds to the excitation of a transducer positioned at the outer wall of the tube. After crossing the tube wall thickness, it can be observed the signal related to the reflection at the tube
inner wall (first reflection). Then, the pulse crosses all the internal tube diameter and is reflected by the inner tube wall on the other side of the tube (second reflection). Thus the best signal of the passage of the bubble can be detected between the first and the second reflections and the bubble profile can be obtained by the difference of the maximum intensity of the first reflection and the maximum intensity points at the gas-liquid interface of the bubble. Note that the system requires two reference points to perform the measurement of the transit time between two reflections. Fig. 4 presents typical ultrasonic signals that represent the detection of the passage of one Taylor bubble rising vertically in a liquid, where it is possible to observe the bubble profile with its four distinct regions.

In Fig. 4, it can be observed a noise in front of and behind the bubble. This can be attributed to the fact that the adjustment of the ultrasonic system was made to obtain the best signals at the region close to the tube wall. In other words, the system was adjusted with only one reference point (the inner tube wall). Thus, while the bubble is not detected by the transducer, the system do not have the second reference point to perform a measurement, generating the noise observed at the figure.

It is important to note that in the pulse-echo ultrasonic technique, the transit time between two points corresponds to the time interval that the pulse is emitted, travels some distance, is reflected in a interface and travels back the same distance until be detected by the same transducer. Thus, the distance between the emission point and the interface where the pulse is reflected corresponds to a half of the total path of the ultrasonic wave.

By using a method based on the transit time, it is possible to measure the equilibrium thickness of the falling film around a Taylor bubble. The film thicknesses were determined by the relation: \[ \delta = \frac{T_f c_L}{2}, \] where \( T_f \) is the transit time at the film region (Figs. 1 and 4) and \( c_L \) is the sound velocity in the liquid phase (De Azevedo et al. (2013)).

In order to determine the liquid film thickness, the sound velocity through the water, glycerin and glycerin-water solutions should be known. The sound velocities in the working liquids were measured by the relation: \[ 2D/T_{12}, \] where \( D \) is the inner tube diameter and \( T_{12} \) is the measured transit time between the first and second reflections (Fig. 3). As commented previously, these reflections correspond to diametrically opposed inner walls of the tube.

The bubble rising velocities were determined by the relation: \[ U_b = \frac{\Delta Z}{\Delta t}, \] where \( \Delta Z \) is the distance between two transducers and \( \Delta t \) is the time interval between the moments that a reference point of the bubble is detected by each of these two transducers (De Azevedo et al. (2012)).

The lengths of the bubbles were determined by the relation: \[ L_b = U_b(t_f - t_n), \] where \( U_b \) is the measured bubble velocity and \( (t_f - t_n) \) is the time interval between the moments that the tail and the nose of the bubble are detected by the
same transducer.

To processing and analyzing the ultrasonic signals, it was developed a LabView program (VI) able to open the archive type TXT and identify the profile (gas-liquid interface), the nose and the tail of the elongated bubbles, in each of the transducers used during the data acquisition. By knowing the sound velocity in the liquid, the distance between the transducers, the acquisition frequency and the number of acquisition points, the program can calculate the desired parameters according to the expressions commented earlier.

3.2 The High Speed Video Camera

The processing and analysis of the technique applying the high speed video camera consists in using a Matlab software, developed at the LTE/IEN, to convert the stored pictures of the type AVI in binary arrays of pixel columns, with values 1 (white) or 0 (black). The white values characterize the bubbles and the black ones characterize the rest of the image. By using the arrays, the software identifies the object of greater length within the framework as the bubble to be analyzed. Then the software calculate the propagation velocity and the length of the bubble.

To make the calculations, the Matlab software uses a calibration made using the Olympus commercial software (Olympus i-Speed Software Suite), that consists in the conversion of the units from pixel/frame to the international system (m/s). To calculate velocity, eight regions are defined. The position and the time that each bubble passes through each of these regions are only considered if the bubble passes through at least five regions. This procedure ensures that the bubble has passed along the whole length of the tube. The terminal velocity of each bubble can be defined by the slope (angular coefficient) of the linear relationship of the position vs time. The lengths are calculated by the product of the propagation velocity by the permanence time of the bubble in each of the regions. The values generated are allocated and saved in a spreadsheet of XLS type.

4. EXPERIMENTAL RESULTS

The density ($\rho_L$) and viscosity ($\mu_L$) of the glycerin-water mixtures were calculated by using correlations given by Cheng (2008) that calculate the fluid properties of glycerin-water mixtures in the range of 0-100% volume fractions and temperatures in the range from 0 to 100°C. Tab. 1 summarizes the experimental conditions, including the liquid densities ($\rho_L$), the liquid viscosities ($\mu_L$), and the Dimensionless Inverse Viscosities ($N_f$), defined as $N_f = \frac{\rho_L \sqrt{gD^3}}{\mu_L}$, for each of the liquids used.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Water</th>
<th>Glycerin</th>
<th>$\rho_L$ (kg/m$^3$)</th>
<th>$\mu_L$ (N.s/m$^2$)</th>
<th>$N_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100%</td>
<td>0%</td>
<td>997</td>
<td>0.0009</td>
<td>12900</td>
</tr>
<tr>
<td>2</td>
<td>80%</td>
<td>20%</td>
<td>1060</td>
<td>0.0017</td>
<td>7321</td>
</tr>
<tr>
<td>3</td>
<td>50%</td>
<td>50%</td>
<td>1144</td>
<td>0.0068</td>
<td>1952</td>
</tr>
<tr>
<td>4</td>
<td>20%</td>
<td>80%</td>
<td>1217</td>
<td>0.0629</td>
<td>224</td>
</tr>
<tr>
<td>5</td>
<td>0%</td>
<td>100%</td>
<td>1261</td>
<td>0.9875</td>
<td>15</td>
</tr>
</tbody>
</table>

$D = 0.024m; \ g = 9.81 \text{ m/s}^2$

4.1 Bubble Velocities in Vertical Tubes

The rising velocities of Taylor bubbles in all liquids were measured by using the ultrasonic technique, and by using the visualization technique for bubbles in pure water and glycerin, in the case of vertical tubes. Table 2 presents the bubble velocities $U_{US}$ with their standard deviations $\sigma_{U_{US}}$, measured by the ultrasonic technique, the bubble velocities ($U_{Cam}$) with their standard deviations $\sigma_{U_{Cam}}$, measured by the visualization technique and the relative errors between the values measured by these two techniques $e_{US-Cam}$.

For each liquid, the measured bubble velocities revealed to be independent of the bubble lengths (values do not shown), with the relative error between the highest and the lowest measured values lower than 2%. This is in agreement with Nicklin et al. (1962) that asserted that long bubbles of all lengths rise, in closed tubes, at a velocity given by:

$$U_0 = 0.35\sqrt{gD} \quad (2)$$

where $D$ is the inner tube diameter and $g$ is the gravitational acceleration.

Table 2 also shows that the Nicklin et al. (1962)’s relation (Eq.2) works well for low viscosity liquids (water or diluted mixtures) and that the bubble velocity decreases when viscosity increases. It can be observed also that the relative error between the values measured for water by each of the measuring techniques $e_{US-Cam}$ is very small, which indicates that
De Azevedo, M. B., Vinhas, P. A. M., Faccini, J. L. H. and Su, J.
Experimental Study of Single Taylor Bubbles in Closed Vertical and Slightly Inclined Tubes

Table 2. Measured Bubble Velocities in Vertical Tubes.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>(U_{bUS}) (m/s)</th>
<th>(\sigma_{U_{bUS}}) (m/s)</th>
<th>(\sqrt{gD})</th>
<th>(U_{bCam}) (m/s)</th>
<th>(\sigma_{U_{bCam}})</th>
<th>(\frac{U_{bUS}}{\sqrt{gD}})</th>
<th>(\frac{U_{bCam}}{\sqrt{gD}})</th>
<th>(e\frac{U_{US-Cam}}{U_{Cam}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Water</td>
<td>0.1683</td>
<td>0.0032</td>
<td>0.347</td>
<td>0.1706</td>
<td>0.0003</td>
<td>0.352</td>
<td>1.35</td>
<td></td>
</tr>
<tr>
<td>80% Water</td>
<td>0.1679</td>
<td>0.0025</td>
<td>0.346</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>50% Water</td>
<td>0.1629</td>
<td>0.0015</td>
<td>0.336</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>20% Water</td>
<td>0.1531</td>
<td>0.0015</td>
<td>0.315</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>100% Glycerin</td>
<td>0.0624</td>
<td>0.0008</td>
<td>0.129</td>
<td>0.0798</td>
<td>0.0015</td>
<td>0.164</td>
<td>21.80</td>
<td></td>
</tr>
</tbody>
</table>

\(D = 0.024m\) for all experiments; & \(g = 9.81 m/s^2\); & \(U_{Nicklin} = 0.1698 m/s\).

* \(e\frac{U_{US-Cam}}{U_{Cam}} = \left(\frac{|U_{bUS} - U_{bCam}|}{U_{bCam}}\right) \times 100\)

the experimental procedures were very well adjusted for the two techniques, both in data acquisition and in the processing and analysis of data.

In the case of glycerin, it is possible to observe a greater relative error between the values measured by the two techniques. This may be attributed to the large length of the bubbles used in the experiments applying the ultrasonic technique. Because of this, the transducers were positioned close to the center of the tube’s length, in order to detect the passage of the whole bubble. Thus, the bubbles could not reach their terminal velocities when they were detect by the transducers, which would explain the different velocity values measured by the two techniques, for this working fluid.

4.2 Bubble Velocities in Inclined Tubes

Table 3 presents the bubble velocities (\(U_{b\text{Angle}}\)) with their standard deviations (\(\sigma_{U_{b\text{Angle}}}\)), measured by the visualization technique at different inclination angles for distilled water.

Table 3. Measured Bubble Velocities for Water in Vertical and Slightly Inclined Tubes.

<table>
<thead>
<tr>
<th>Angle</th>
<th>(U_{b\text{Angle}}) (m/s)</th>
<th>(\sigma_{U_{b\text{Angle}}}) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.1705</td>
<td>0.0003</td>
</tr>
<tr>
<td>2.5°</td>
<td>0.1723</td>
<td>0.0003</td>
</tr>
<tr>
<td>5°</td>
<td>0.1735</td>
<td>0.0017</td>
</tr>
<tr>
<td>7.5°</td>
<td>0.1815</td>
<td>0.0006</td>
</tr>
<tr>
<td>10°</td>
<td>0.1836</td>
<td>0.0015</td>
</tr>
<tr>
<td>15°</td>
<td>0.1938</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

Table 3 shows clearly that the bubble velocity increases when the inclination angle from the vertical position increases, for the range studied in the present work. As in the case of vertical tubes, the bubble velocities measured for each of the inclination angles revealed to be independent of the bubble lengths (values do not presented). Although only two different bubble lengths were studied, this fact is in agreement with observations made by Zukoski (1966) and Weber et al. (1986).

According to Weber et al. (1986), the first correlation for the velocity of an elongated bubble in an inclined tube can be attributed to Bendiksen (1984). But this correlation has some limits to be applied. Thus, Weber et al. (1986) proposed a correlation similar to that of Bendiksen (1984) adding a correction factor. According to these authors this correlation has a good agreement with experimental data available at that time. This correlation is written according to the Froude number \((Fr = U_b/\sqrt{gD})\) and is presented here adjusted to inclinations \(\theta\) from the vertical position (0°):

\[Fr = Fr_H \sin \theta + Fr_V \cos \theta + Q.\] (3)

The correction term \(Q\) is a function of \(\Delta Fr\), the difference in Froude numbers between the vertical and horizontal orientations:

\[\Delta Fr = Fr_V - Fr_H\] (4)

and the inclination angle. For \(\Delta Fr \leq 0\),

\[Q = 0\] (5)

while for \(\Delta Fr > 0\),

\[Q = 1.37(\Delta Fr)^{2/3} \cos \theta(1 - \cos \theta).\] (6)
Weber et al. (1986), in their work, used $Fr_V = 0.35$, as proposed by Nicklin et al. (1962) and $Fr_H = 0.54$ as proposed by Benjamin (1968). But according to van Hout et al. (2002) this value of $Fr_H$ is more adequate to be applied for tubes of high diameters. These authors considered that for tubes with inner diameter similar to that used in the present work, the value of $Fr_H = 0.37$, as proposed by Zukoski (1966), is more adequate. Thus they applied the Weber et al. (1986)’s correlation (Eqs. 3 to 6), using $Fr_V = 0.35$ and $Fr_H = 0.37$ to make a comparison with their experimental results. Figure 5 shows the relationship $Fr$ vs $\theta$ for distilled water. In this figure it can be observed the Weber et al. (1986)’s correlation, using $Fr_V = 0.35$ and $Fr_H = 0.37$, the experimental results obtained by van Hout et al. (2002), using two different measurement techniques and a tube with the inner diameter equal to that used in the present study ($D = 0.024$ m) and the results obtained in this work, using a high speed video camera.

![Figure 5. Relationship between Froude number and inclination angle for distilled water.](image)

The results presented in Fig. 5 confirm the tendency of velocity increase when the inclination angle increases, for the inclination range studied in this paper (0° to 15° from the vertical position). The experimental results have a good agreement with the predictions made by the Weber et al. (1986)’s correlation. The relative errors between the theoretical and experimental values are less than 10%. This figure also shows that there is a very good consistency between the experimental results obtained in this work and those obtained by van Hout et al. (2002), using the same inner tube diameter.

4.3 Liquid Film Thickness in Vertical Tubes

The film thicknesses were determined from the measured bubble lengths by the method proposed by Llewellin et al. (2012), as previously described in this paper (Eq.1), for the case of vertical tubes. Figure 6 shows the relationship between $L_b$ and $L_0$ for distilled water and glycerin.

![Figure 6. Relationship between $L_b$ and $L_0$ for distilled water and glycerin for vertical tubes.](image)

According to Nicklin et al. (1962) and Llewellin et al. (2012), the linear relationship observed in Fig. 6 would indicate that only the cylindrical part of the body of the bubble (region 2b in Fig. 1) changes length as gas volume changes. The nose, the upper part of the body and the tail remaining unchanged. Thus, these authors concluded that the $L_b$ vs $L_0$
linearity indicates that the film reached its equilibrium condition. Nicklin et al. (1962) observed, for their experimental conditions, that this linearity was broken for \( L_b < 6D \) and considered that this break could be attributed to insufficient bubble lengths to allow the development of the falling film. Figure 7 shows the superposition of the body region of Taylor bubbles with different lengths \( (L_b) \), generated from different air pocket lengths \( (L_0) \), for the 50% distilled water and 50% glycerin mixture.

![Figure 7](image)

Figure 7. Superposition of the body region of Taylor bubbles with different lengths \( (L_b) \) for 50% distilled water and 50% glycerin mixture.

Figure 7 shows a very good superposition of the ultrasonic signals of elongated bubbles with different lengths rising in 50% water and 50% glycerin mixture. This good superposition was observed for all liquids studied, revealing that the growth of the bubbles only affects the rear of its profile.

Considering the profile of the body of Taylor bubbles (2a and 2b in Fig. 1), two variables can be defined. One of them is the averaged film thickness \( \delta_{avg} \) that consists of an average of the measured thickness values at all this region (2a and 2b in Fig. 1). The other is the equilibrium film thickness \( \delta_{eq} \) that occurs at the region of the film where the velocity profile and its thickness are steady (2b in Fig. 1).

Llewellin et al. (2012) defined the dimensionless film thickness \( \delta'/R \) and found that this parameter is a function only of the dimensionless parameter \( N_f = \rho L \sqrt{gD^3/\mu L} \), called Dimensionless Inverse Viscosity. Table 4 presents the \( N_f \), the averaged thickness measured values \( (\delta_{avg}) \), the equilibrium thicknesses \( (\delta_{eq}) \), the standard deviations \( (\sigma_{\delta_{eq}} \text{ and } \sigma_{\delta_{avg}}) \), the thicknesses determined graphically \( (\delta_{graph}) \), applying Eq. 1, and the relative errors \( e_{eq-avg} \) and \( e_{graph-\delta_{eq}} \) for each working fluid used in the present work. The value of \( \delta_{avg} \) presented in this table was measured for bubbles generated from air pockets of length \( L_0 = 15 \text{ cm} \). It is important to notice that for shorter bubbles the region of the bubble’s body where the film is still thinning (region 2a at Fig. 1) has a strong influence on the averaging and this effect is more pronounced in fluids where thinner films are found. This can be observed in Tab. 4, where it is apparent that the film thickness \( (\delta_{eq} \text{ and } \delta_{avg}) \) increases with viscosity increasing \( (N_f \text{ decreasing}) \) and the relative error between \( \delta_{eq} \) and \( \delta_{avg} \) \( (e_{eq-\delta_{avg}}) \) increases with viscosity decreasing \( (N_f \text{ increasing}) \).

Table 4. Experimental values for liquid films falling around Taylor bubbles rising in vertical tube.

<table>
<thead>
<tr>
<th>( N_f )</th>
<th>100% Water</th>
<th>80% Water</th>
<th>50% Water</th>
<th>20% Water</th>
<th>100% Glycerin</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta_{avg} \ (\mu m) )</td>
<td>864</td>
<td>1033</td>
<td>1239</td>
<td>2282</td>
<td>3834</td>
</tr>
<tr>
<td>( \sigma_{\delta_{avg}} \ (\mu m) )</td>
<td>161</td>
<td>139</td>
<td>178</td>
<td>51</td>
<td>19</td>
</tr>
<tr>
<td>( \delta_{eq} \ (\mu m) )</td>
<td>589</td>
<td>809</td>
<td>1119</td>
<td>2258</td>
<td>3834</td>
</tr>
<tr>
<td>( \sigma_{\delta_{eq}} \ (\mu m) )</td>
<td>11</td>
<td>06</td>
<td>11</td>
<td>11</td>
<td>19</td>
</tr>
<tr>
<td>( e_{eq-\delta_{avg}} \ (%) )</td>
<td>46.69</td>
<td>27.69</td>
<td>10.72</td>
<td>1.06</td>
<td>0</td>
</tr>
<tr>
<td>( \delta_{graph} \ (\mu m) )</td>
<td>740</td>
<td>-</td>
<td>1098</td>
<td>2355</td>
<td>3972</td>
</tr>
<tr>
<td>( e_{graph-\delta_{eq}} \ (%) )</td>
<td>20.40</td>
<td>-</td>
<td>1.91</td>
<td>4.12</td>
<td>3.47</td>
</tr>
</tbody>
</table>

\* \( e_{eq-\delta_{avg}} = (|\delta_{eq} - \delta_{avg}|/\delta_{eq}) \times 100 \)

Table 4 also shows that the Llewellin et al. (2012)'s methodology to determine the thickness of films falling around Taylor bubbles works better for high viscosity liquids (low \( N_f \)). In that cases, the relative errors between \( \delta_{eq} \) and \( \delta_{graph} \)
are quite small. However, for water, the error is relatively high. The value of $\delta_{\text{graph}}$ for the 80% water and 20% glycerin was not presented because of a strong instability observed at the bubble’s body, which resulted in bad ultrasonic signals, making impossible to determine the bubble lengths by this technique for the higher values of $L_0$ and $L_b$.

Llewelin et al. (2012) proposed a model to estimate the film thickness. The proposed model is purely empirical and based on the adjustment of the curve $\delta'$ vs $N_f$ for their experimental data combined with those obtained by Nogueira et al. (2006) and can be defined by the following relationship:

$$
\delta' = a + b \tanh(c - d \log N_f),
$$

(7)

where the values of the four constants are defined by the best fit: $a = 0.204$; $b = 0.123$; $c = 2.66$ e $d = 1.15$.

According to these authors, this empirical model shows excellent agreement with experimental data in the range of $10^{-1} < N_f < 10^5$. Figure 8 presents the experimental measured values of $\delta'$ plotted against inverse viscosity number $N_f$. In this figure, the Llewelin et al. (2012)’s model, defined by Eq.7, has also been plotted.

It can be observed from Fig. 8, that the experimental measurements of the film thickness using the pulse-echo ultrasonic technique show a very good agreement with Llewelin et al. (2012)’s model, for low and intermediate $N_f$. For high $N_f$, the model apparently tends to overestimate $\delta'$.

5. CONCLUSIONS

The experimental results obtained in the present work by measuring the parameters of a single Taylor bubble rising in vertical and slightly inclined tubes show a good agreement with appropriate correlations available in the literature, for both techniques applied. For the parameters that could be measured by the ultrasonic and the visualization techniques, the measured values showed very small relative errors between them, when water was used as working fluid, which indicates a good adjustment of the techniques to acquire, process and analyze the data. For glycerin, probably the data acquisition by the ultrasonic technique can be improved by using shorter bubbles or longer tubes, especially for velocity measurements.

The good agreement of the measured values for the thicknesses of falling films around the bubbles with the values determined by the Llewelin et al. (2012)’s method, in vertical tubes, also reveals that the pulse-echo ultrasonic technique procedures used to measure this parameter is feasible.

Thus, the experimental and measurement procedures or techniques that are been developed at the LTE/IEN showed to be reliable and this is fundamental to be applied in studies for a better understanding of the Taylor bubble and, consequently of the slug flow structure.

Studies in vertical and slightly inclined stagnant liquid columns, with different fluids, are still in progress at the laboratory and a two-phase vertical section is being assembled to allow the study of two-phase air-water continuous flow, in vertical and inclined tubes.

6. ACKNOWLEDGEMENTS

The authors are grateful to CNPq, FINP and FAPERJ for the financial support during the realization of the work.
7. REFERENCES


8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.