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

MEASUREMENT OF INTERFACIAL PARAMETERS OF SINGLE TAYLOR BUBBLES RISING IN CLOSED VERTICAL AND SLIGHTLY INCLINED TUBES USING ULTRASONIC AND VISUALIZATION TECHNIQUES

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Abstract. *The present paper reports an experimental study of single Taylor bubbles rising in water-glycerin mixtures in vertical and slightly inclined tubes. The velocities and lengths of the rising bubbles were measured by using the pulse-echo ultrasonic technique and a high speed video camera. The bubble profiles and the equilibrium thicknesses δ of the liquid films around the bubbles were measured by the ultrasonic technique. The inclination angles studied were 0^o, 2.5^o, 5^o, 7.5^o, 10^o and 15^o from the vertical position. It was observed, for all liquids studied, that the bubble velocity U_b decreased and the film thickness δ increased with increasing viscosity. Furthermore, the bubble velocity increased with increasing inclination angle θ and the influence of the inclination angle on velocity tends to decrease when the liquid viscosity increases. The measurements also indicated that for lower viscosity liquids, the inclination angle has no influence on the length of bubbles generated from the same air volume (air pocket length $L_0 = 20$ cm). However, for higher viscosity liquids, it was observed a tendency of the bubble length to decrease when the inclination angle increases.*

Keywords: *Ultrasonic Technique, Visualization Technique, Rising Velocity, Liquid Film Thickness, Taylor Bubble*

1. INTRODUCTION

Slug flow is characterized by elongated bubbles, also called Taylor bubbles, which occupy nearly the entire cross-section of the pipe and a liquid slug between successive bubbles. This flow pattern can be found in different applications, especially in nuclear, chemical and petroleum engineering. Figure 1 presents a schematic of a Taylor bubble flowing vertically in a liquid. 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 has steady thickness (δ).

The knowledge of the Taylor bubble's structure and its motion is very important to the 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. 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.

Although power generation is one of their main applications, nuclear reactors are also used in desalination plants and marine propulsion. In nuclear propulsion, the ship is propelled by turbines that move by action of the steam produced in

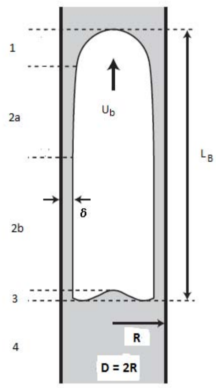

Figure 1. Schematic of a Taylor bubble flowing vertically in a liquid.

the steam generator, in a similar way to that found in PWR reactors. In nuclear power reactors, two-phase steam-water flow occurs mainly in horizontal and vertical pipes or channels. On the other hand, the freedom of movement found in watercrafts , especially in submarines, makes possible the occurrence of inclined two-phase flow in the reactor core. Thus, the nuclear industry needs to understand the behavior of inclined two-phase flow in order to ensure a good design and safety of reactors where such a condition can occur.

Llewellin *et al.* (2012) defined the dimensionless film thickness $\delta' = \delta/R$ (R is the inner tube radius) and found that this parameter is a function only of the dimensionless parameter $N_f = \rho_L\sqrt{gD^3}/\mu_L$. These authors proposed a purely empirical model based on the adjustment of the curve δ' vs N_f for their experimental data, along with those obtained by Nogueira *et al.* (2006), to estimate the equilibrium film thickness δ. This model can be defined by the following relationship:

$$\delta' = 0.204 + 0.123\tanh(2.66 - 1.15\log N_f) \tag{1}$$

According to these authors, this empirical model shows excellent agreement with experimental data in the range of $10^{-1} < N_f < 10^5$.

One of the first studies about the effects of the influence of inclination angle on interfacial parameters of Taylor bubbles can be attributed to Zukoski (1966). This author verified that the bubble velocity increased when inclination angle increases from the vertical position, reaching a maximum value in the range of 40^o to 60^o and returning to decrease until the horizontal position.

Bendiksen (1984) observed the same qualitative behavior of the influence of inclination on the bubble velocity and proposed a correlation to estimate this influence. According to him, the bubble velocity at a determined inclination U_θ depends only on the bubble velocities in the vertical U_V and horizontal U_H positions and on the inclination angle θ.

This work presents a study of single Taylor bubbles rising in vertical and slightly inclined tubes. The objective of the study is the use of the visualization technique using high speed video camera and the pulse-echo ultrasonic technique to measure the bubble velocities, the bubble lengths, as well as the 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^o, 2.5^o, 5^o, 7.5^o, 10^o and 15^o 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.

2. EXPERIMENTAL APPARATUS

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 D 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. It is important to note that when the air pocket length L_0 are changed, the volume of air available to generate the Taylor bubbles also changes. In this way, the volume of the bubble can be controlled by varying L_0. The tube was attached to a device that allows to positioning the tube 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. Four ultrasonic transducers of 10 MHz and 6.35 mm diameter, Olympus piezoelectric-type

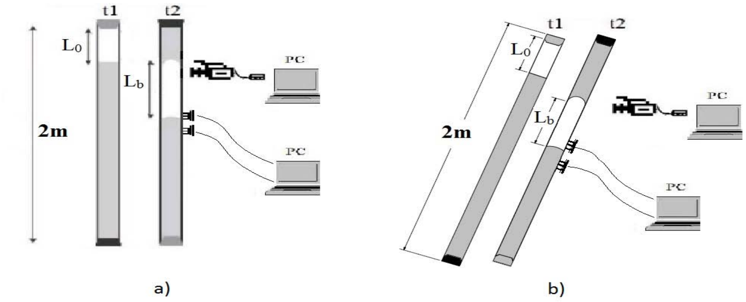

Figure 2. Schematic of the stagnant liquid column used in this work. a) Vertical and b) Slightly inclined.

transducers (Model V112), were mounted at the distance of ≈ 5 cm between them and they were located at 60, 65, 70 and 75 cm from the top, respectively. These transducers were positioned around the tube with angles of 90^o between them.

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 afterward to analyze in detail the bubble motion sequence.

3. EXPERIMENTAL PROCEDURES

This work was divided into two parts: (1) A study of bubbles rising vertically, using the pulse-echo ultrasonic technique, with focus on the measurement of the profiles and thicknesses of the liquid films and (2) a study of the inclined case, using the ultrasonic and the visualization techniques, with focus on the measurement of the lengths and velocities of the bubbles.

In the first part of the study, 250 bubbles (50 bubbles for each air pocket length L_0) were studied by using 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. The use of different L_0 allowed the determination of the equilibrium region of the liquid films, especially for low viscosity liquids, since, in these cases, the equilibrium conditions is only achieved for larger bubbles. In the second part, 10 bubbles were studied for each of the liquids. An air pocket length $L_0 = 20$ cm was used, in this case.

The percentages given in the compositions of the mixtures are by volume. During the experiments, the temperature remained between 24 and 26^oC. 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 (Chang and Morala (1990)). Figure 3 shows a typical echogram registered by the ultrasonic system when an acrylic tube full with some liquid is analyzed.

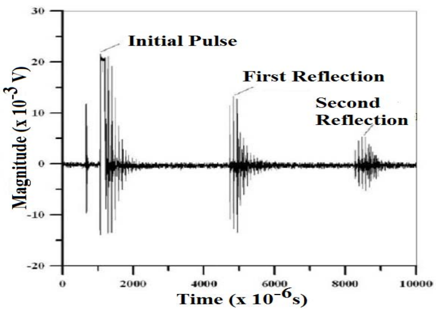

Figure 3. Typical echogram of the ultrasonic system.

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.

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 an interface and travels back the same distance until being 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: $\delta = T_f c_L/2$, where T_f is the transit time at the film region (Fig. 1) 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: $2D/T_{r12}$, where D is the inner tube diameter and T_{r12} is the measured transit time between the emission and the return of the sound wave after being reflected by the diametrically opposed inner wall of the tube filled with the desired liquid.

The bubble rising velocities were determined by the relation: $U_b = \Delta Z/\Delta t$, where ΔZ is the distance between two transducers and Δt 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: $L_b = U_b(t_t - t_n)$, where U_b is the measured bubble velocity and $(t_t - t_n)$ 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 Matlab software 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 calculates 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 of 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 (ρ_L) and viscosity (μ_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^{o}C. Table 1 summarizes the experimental conditions, including the liquid densities (ρ_L), the liquid viscosities (μ_L), and the Dimensionless Inverse Viscosity Numbers (N_f), defined as $N_f = \rho_L\sqrt{gD^3}/\mu_L$, for each of the liquids used.

4.1 Rising Bubbles in Vertical Tubes

As commented earlier, this part of the work was focused on the measurement of the profiles and thicknesses of the liquid films around Taylor bubbles by using the pulse-echo ultrasonic technique. Figure 4 presents the liquid film profiles of bubbles generated from an air pocket length $L_0 = 15$ cm rising in liquids with different viscosities. It can be observed that the thinner films occur for fluids of low viscosities and that the film thicknesses increase with viscosity increasing. Consequently, to maintain the original air volume, the lengths (L_b) of the bubbles generated from the same air pocket length (L_0) are higher for the fluids with higher viscosities. This behavior was observed for all L_0 used to generate the

Table 1. Experimental Conditions.

Liquid	Water	Glycerin	ρ_L (kg/m^3)	μ_L (N.s/m^2)	N_f
1	100%	0%	997	0.0009	12900
2	80%	20%	1060	0.0017	7321
3	50%	50%	1144	0.0068	1952
4	20%	80%	1217	0.0629	224
5	0%	100%	1261	0.9875	15

D = 0.024m; g = 9.81 m/s^2

bubbles.

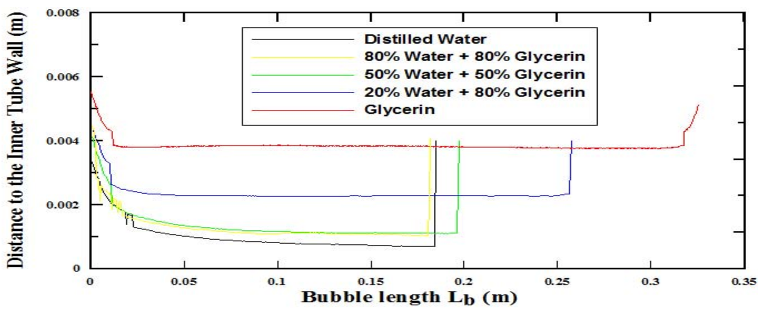

Figure 4. Liquid film profiles of bubbles generated from an air pocket length $L_0 = 15$ cm rising vertically in liquids with different viscosities.

In Fig. 5, it is presented the experimental measured values of δ' compared with Llewellin *et al.* (2012)'s model, defined by Eq.1.

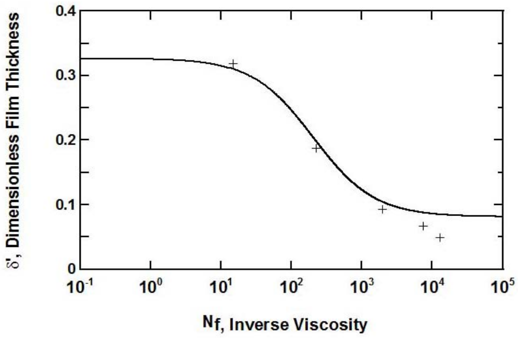

Figure 5. Experimental Measured Values of δ' plotted against inverse viscosity number N_f. $+$, Experimental Measurements; solid line, Llewellin *et al.* (2012)'s model

Figure 5 indicates that the experimental measurements of the equilibrium thickness of the liquid film using the pulse-echo ultrasonic technique show a very good agreement with Llewellin *et al.* (2012)'s model, for low and intermediate N_f. For high N_f, the model tends to overestimate δ'. In a recent work, De Azevedo *et al.* (2015) showed that the methodology used by Llewellin *et al.* (2012) was not adequate to measure the equilibrium thickness of liquid films around Taylor bubbles rising in low viscosity liquids, or high N_f. In other words, the values measured by them, on these conditions, did not correspond to the equilibrium thicknesses of the films. For high and intermediate viscosities, or low and intermediate N_f, the methodology presents good estimates.

4.2 Rising Bubbles in Inclined Tubes

At this part of the work, it is presented the measurements of the velocities and lengths of elongated bubbles generated from air pocket lengths $L_0 = 20$ cm, rising in vertical and slightly inclined tubes. These parameters were measured by using the ultrasonic technique and the high speed video camera, simultaneously, and the results obtained by the two techniques showed very good agreement. The values presented in the sequence of this work correspond to those measured by the video camera. Figure 6a presents the variation of the Froude number ($Fr = U_b/\sqrt{gD}$) with the inclination angle of the tube θ for the different liquids used. It can be observed that Fr tends to increase when θ increase from 0^o to 15^o. These results are in agreement with the qualitative behavior of the influence of inclination angle on the bubble velocity observed by Zukoski (1966) and Bendiksen (1984).

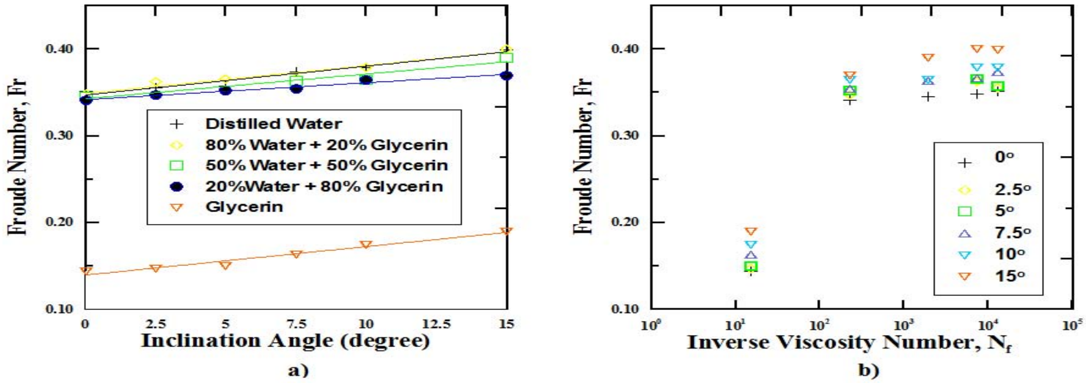

Figure 6. Variation of Fr with: a) the inclination angle θ for the different liquids used; b) the inverse viscosity number N_f for each inclination angle θ

Figure 6a also indicates that the influence of the inclination angle on the bubble velocity tends to decrease when the liquid viscosity increases and that Fr for glycerin is much smaller than those for the other liquids studied.

The variation of Fr with the inverse viscosity number N_f for each inclination angle θ is presented in Fig. 6b. Once more, it can be observed that for each liquid used, or each N_f, Fr tends to increase with θ. Furthermore, the qualitative influence of the viscosity on Fr, for different θ, revealed to be quite similar, with a smooth variation of Fr with N_f, for intermediate and high N_f (or intermediate and low viscosities) and a strong decrease of Fr with N_f, for low N_f (or high viscosities).

The influence of the inclination angle θ on the bubble length L_b for the different liquids used as working fluid can be viewed in Fig. 7a. This figure shows that for lower viscosity liquids, θ has virtually no influence on the length of bubbles generated from the same air pocket length $L_0 = 20$ cm. However, for the higher viscosity liquids, it can be observed a tendency of decreasing L_b when θ increases.

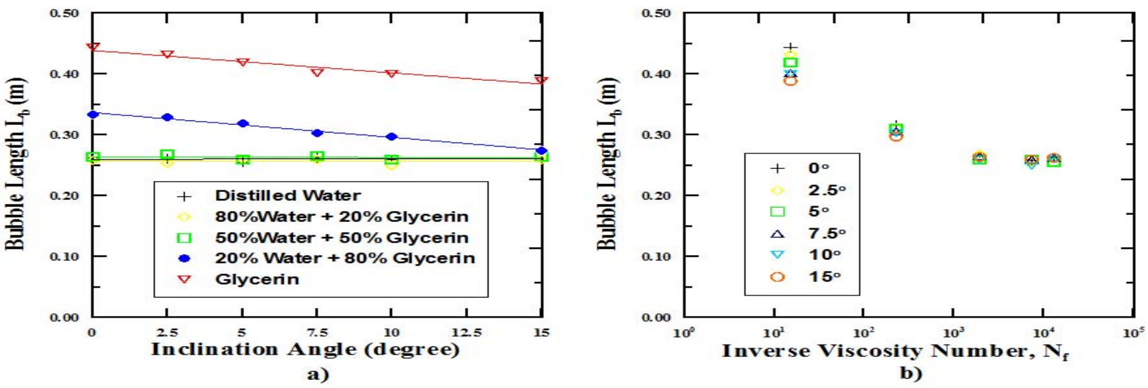

Figure 7. Variation of the bubble length L_b with: a) the inclination angle θ for the different liquids used; b) the inverse viscosity number N_f for each inclination angle θ

Figure 7b shows the variation of L_b with N_f for each inclination angle θ. It is observed that L_b increases when the liquid viscosity increases (or N_f decreases), for all inclination angles θ. Furthermore, the influence of N_f on L_b showed to be quite small, for intermediate and high N_f (lower viscosity liquids). For lower N_f, L_b tends to increase strongly with N_f decreasing. This behavior of L_b with θ and N_f can be related to changes in the shape of elongated bubbles rising in those conditions.

In Fig. 8, it can be seen the ultrasonic signals for a bubble rising in a 5^o inclined tube containing a 20% water and 80% glycerin mixture. Considering an inclined tube, the white and red signals correspond to the profiles of the films on the lateral sides of the bubble. These signals suggest that the bubble could present a lateral symmetry. The green signal corresponds to the film profile on the bottom of the bubble. In that region, the film thickness is higher because of the buoyancy force effects, that deviate the bubble from the tube axis. Finally, the blue signal corresponds to the film at the top of the bubble. This qualitative behavior was observed for all liquids and inclination angles studied, except of course, for the vertical condition (0^o), where the film admittedly presents symmetry in all directions around the bubble.

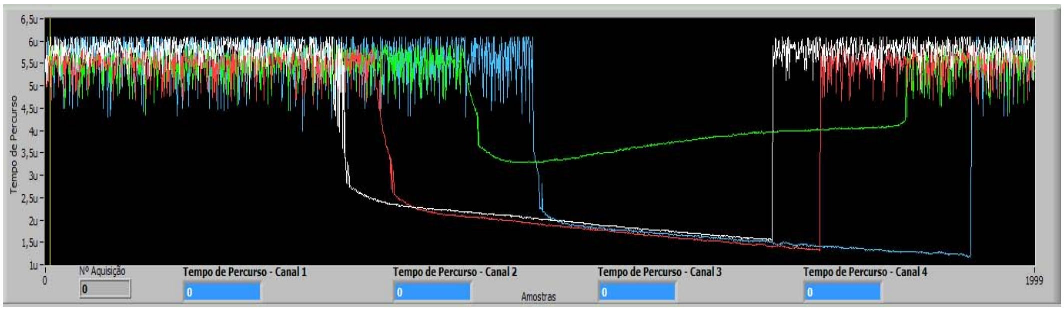

Figure 8. Ultrasonic signals for a bubble rising in a 5^o inclined tube containing a 20% water and 80% glycerin mixture.

In Fig. 8, it can be observed a noise in front of and behind each signal of 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.

Thus, due to the complexity of the shapes assumed by Taylor bubbles rising in different liquids and inclination angles, it seems reasonable to try to understand the behavior of these bubbles considering their profiles in these four specific locations: the lateral sides, the bottom and the top of the bubble rising in inclined tubes.

Figure 9 presents the film profiles of the bottom of bubbles rising in inclined tubes containing pure water. It can be seen that for $\theta = 2.5^o$, the bubble suffers the effect of buoyancy force, but maintains the shape similar to that of vertical case (0^o). From $\theta = 5^o$, the bubble shape presents a transition to a more sinuous profile finding in the cases of inclination angles of 7.5^o, 10^o and 15^o. This figure indicate that the bubble lengths did not change significantly with inclination angle for water (low viscosity liquid).

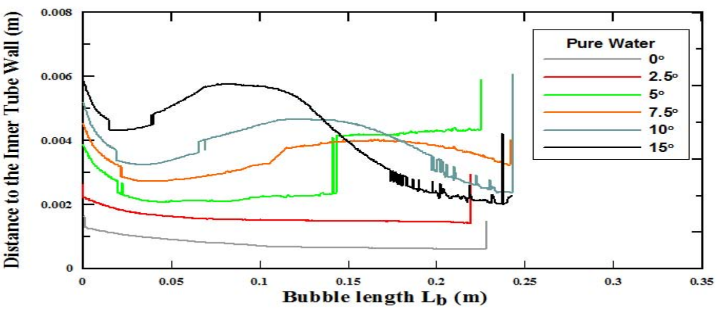

Figure 9. Film profiles of the bottom of bubbles rising in inclined tubes containing pure water.

On the other hand, the film profiles of the bottom of bubbles rising in pure glycerin are presented in Fig. 10. It is clear that the behavior of those profiles for high viscosity liquids are different from that for low viscosity ones (pure water). Just as observed in the case of pure water (Fig. 9), the bubbles rising in glycerin (Fig. 10) suffer the effect of buoyancy force, but the film profile did not change with inclination angle increasing. It can be seen that when θ increases, the film profile tends to present an inclination with respect to the tube axis, which causes a decrease of the measured bubble length, especially for the higher angles. Apparently, this tendency has a limit, since the profiles for the bubbles rising in inclination angles of 10^o and 15^o presented an superposition of their signals.

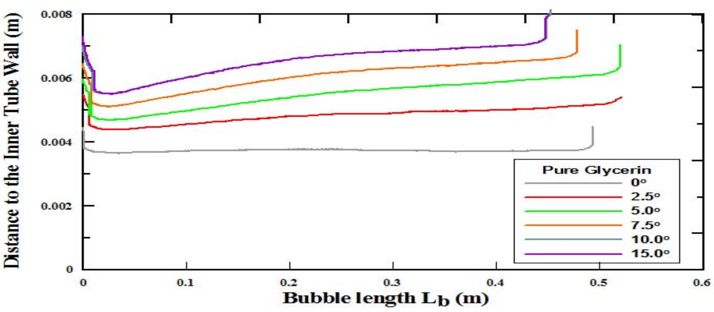

Figure 10. Film profiles of the bottom of bubbles rising in inclined tubes containing pure glyerin.

5. CONCLUSIONS

This work presented an experimental study of the movement of single Taylor bubbles rising in vertical and inclined tubes. The profiles and the equilibrium thicknesses of the liquid films around the bubbles rising vertically were measured by using the pulse-echo ultrasonic technique. For bubbles rising in vertical and inclined tubes, it was measured the velocities U_b and lengths L_b of bubbles generated from an air pocket length $L_0 = 20$ cm and the profiles of the liquid films around them, in four specific positions.

For bubbles rising in vertical tubes, the liquid film profiles indicated that the thinner films occur for fluids of low viscosities and that the film thicknesses increase with viscosity increasing. Consequently, to maintain the original air volume, the lengths L_b of the bubbles generated from the same air pocket length L_0 are higher for the fluids with higher viscosities.

It was showed that the experimental measurements of the film thickness using the pulse-echo ultrasonic technique show a very good agreement with Llewellin *et al.* (2012)'s model, for low and intermediate N_f. For high N_f, the model tends to overestimate δ'.

The results revealed that the velocity tends to increase when θ increase from 0^o to 15^o, for all liquids used, which is in agreement with the literature. It was also observed that the influence of the inclination angle on the bubble velocity tends to decrease when the liquid viscosity increases.

The measurements of bubble lengths indicated that for lower viscosity liquids, θ has virtually no influence on the length of bubbles generated from the same air pocket length $L_0 = 20$ cm. However, for the higher viscosity liquids, a tendency of decreasing of L_b can be observed when θ increases.

Finally, the measurements indicated that L_b increases when the liquid viscosity increases (or N_f decreases), for all inclination angles θ. Furthermore, the influence of N_f on L_b showed to be quite small, for intermediate and high N_f (lower viscosity liquids). For lower N_f, L_b tends to increase strongly with N_f decreasing. This behavior of L_b with θ and N_f can be related to changes in the shape of elongated bubbles rising in those conditions.

6. ACKNOWLEDGEMENTS

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

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8. RESPONSIBILITY NOTICE