ULTRASONIC MEASUREMENTS OF BUBBLE SHAPE AND LIQUID FILM THICKNESS OF A TAYLOR BUBBLE RISING IN A STAGNANT WATER COLUMN

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ABSTRACT

The present paper reports a preliminary study of direct measurement of the equilibrium thickness of the falling film around a Taylor bubble in a stagnant water column, using the pulse-echo ultrasonic technique. The experiments were conducted in an acrylic tube of 1.8 m long with inner diameter of 25.21 mm and wall thickness of 6.8 mm. A Taylor bubble was formed by the inversion of the pipe, sealed at the ends and partially filled with water to leave an air pocket of length $L_0$. The rising Taylor bubble was detected by a transducer located 400 mm from the top of the pipe. Ten measurements were made for each of the four channels of the ultrasonic system, using the same settings of the system parameters, totaling 40 measured bubbles. A simplified Brown’s model for the thickness around a Taylor bubble was used to calculate a reference value of the parameter being measured. We found that the values directly measured by the ultrasonic technique were in good agreement with the reference value calculated and thus conclude that the pulse-echo ultrasonic technique can be applied to directly measure the thickness of the falling film around the Taylor bubbles in acrylic tubes. The errors between the experimental and the reference values were in the order of 10%.

1. INTRODUCTION

Multiphase flow are encountered in a wide range of systems 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 [1].

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 flowing in a liquid. Following Llewelin et al. [2], a typical Taylor bubble can be divided into four regions: (1) an approximately hemispherical nose, (2) a body region surrounded by a falling liquid film, (3) a tail region, and (4) a wake region. The body region 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 constant thickness ($\delta$).

Figure 1: Schematic of a Taylor bubble flowing in a liquid, [2].

Nicklin et al. [3] determined a quantity equivalent to the volume of liquid surrounding elongated bubbles of various lengths and plotted it against bubble length. They found a straight line relationship between this two quantities and also observed that, for their experimental conditions, this linearity was broken for very short bubbles ($L_b < 6D$) because the bubbles are too short for the falling film to achieve the equilibrium thickness. Thus, it is considered that for the film around a Taylor bubble reaches its equilibrium thickness, the bubble must have a length greater than 6 times the internal diameter ($L_b > 6D$).

Brown [4] theoretically deduced an expression for the velocity profile in a stabilized free-falling laminar film around a Taylor bubble rising through a co-current flowing liquid. In this work, the film thickness were calculated by:

$$\delta = \left(\frac{3\nu}{2g(R - \delta)} \left[(R - \delta)^2U_B - R^2U_L\right]\right)^{1/3},$$

(1)
where $\delta$ denotes the film thickness, $\nu$ the kinematic viscosity of the liquid, $g$ the gravity acceleration, $R$ is the tube radius, $U_B$ the rising bubble velocity, and $U_L$ is the mean liquid velocity.

Assuming a plane wall geometry ($\delta \ll R$), the above equation can be simplified, yielding:

$$\delta = \left[ \frac{3\nu R}{2g} (U_B - U_L) \right]^{1/3}. \quad (2)$$

The rising velocity of a single isolated bubble in a liquid column depends on buoyancy and drag forces. Interactions between forces due to surface tension, viscosity, inertia and buoyancy produce various effects which are quite often related with different bubble shapes and paths. The pioneering works of Dumitrescu [5] and Davies and Taylor [6] analyzed the velocity of elongated bubbles in a circular vertical tube initially filled with liquid and sealed on the top and established that the rising velocity of such bubble is:

$$U_B = 0.35 \sqrt{gD}, \quad (3)$$

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

Experiments described by Nicklin et al. [3] show that long bubbles of finite length rise relative to the liquid ahead of them at a velocity approximately equal to that of the Dumitrescu or Taylor bubble. If the tube is sealed on the top and there is no flow of liquid across a section ahead of the bubble, bubbles of all lengths rise roughly at a velocity given by Eq. 3. In a tube open at the top, the expansion of the bubble due to the change of static head as it rises gives the liquid above it an upward velocity. Since the bubble rises at the characteristic velocity $U_B$ relative to the liquid above it, the velocity in space is greater by an amount which depends on the length of the bubble.

Equation 3 is a very well accepted relation to the velocity of a Taylor bubble rising in circular vertical tubes sealed on the top. Azevedo et al. [7] measured the rising velocity of isolated Taylor bubbles in such kind of tube, using the visualization and the pulse-echo ultrasonic techniques, and found a good agreement between the experimental results and the value calculated by this equation.

Quantitative experimental data for the equilibrium thickness of the falling film around a Taylor bubble are scarce in the literature and according Llewelin et al. [2] only one systematic study was made by Nogueira et al. [8] using an optical technique.

In this work, the pulse-echo ultrasonic technique was used to observe the elongated bubble profile and to directly measure the equilibrium thickness of the falling film around a Taylor bubble rising in a stagnant water vertical column sealed at the ends. The parameters measured by this technique were presented and discussed. They were also compared with the theoretical value defined by Eq. 2.
2. EXPERIMENTAL FACILITIES

The data analyzed in this work were obtained from a vertical column partially filled with stagnant water located at the Thermo-Hydraulic Laboratory of the Nuclear Engineering Institute (LTE/IEN/CNEN). Figure 2 illustrates the experimental apparatus.

![Schematic of the stagnant liquid vertical column used in this work.](image)

The vertical column consists of an acrylic tube of 1.8 m long with inner diameter of 25.21 mm and a wall thickness of 6.8 mm sealed at the ends. A Taylor bubble was formed by the inversion of the pipe partially filled with water to leave an air pocket of length $L_0$. The rising bubble was detected by a pulse-echo ultrasonic transducer located 400 mm from the top of the pipe. For this work the air pocket has a length of 400 mm to ensure a bubble length where the film thickness reaches an equilibrium condition ($L_b > 6D$).

The high speed ultrasonic system consists of a generator/multiplexer board, transducers and a computer (PC) with a LabView software developed at the Nuclear Engineering Institute to control the measurement system and able to work up to four ultrasonic transducers in pulse-echo or transmission modes. An ultrasonic transducer of 10 MHz and 6.35 mm diameter, Panametrics piezoelectric-type transducers (Model M112), was mounted at the top of the acrylic tube.

The generator/multiplexer board controlled by the software provides signal generation,
data acquisition and analysis of the ultrasonic signals. The board generated an excitation frequency equal to 187 kHz and the pulse time generated on each transducer was 4.4 ms. The ultrasonic signals were digitalized in the board, from each transducer, in time intervals of 10 ns.

3. EXPERIMENTAL PROCEDURES AND RESULTS

The main objective of this work is to perform direct measurement of the equilibrium thickness of the liquid film around a Taylor bubble using the pulse-echo ultrasonic technique. For this purpose, an ultrasonic transducer has been properly positioned near the top of the acrylic tube to make possible to detect the passage of the Taylor bubble and observe its profile.

The pulse-echo ultrasonic technique is based on the fact that ultrasound waves are reflected when crossing discontinuities of a medium as a gas-liquid interface. Therefore, reflection can be used to observe the Taylor bubble profile and to measure the falling film thickness around the bubble based on the transit time.

The elongated bubble profile can be observed directly from the ultrasonic signals analyzed and digitalized by the ultrasonic system. Figure 3 presents the ultrasonic signals that represent the detection of the passage of one Taylor bubble, where it is possible to observe the bubble profile.

![Figure 3: Taylor bubble profile observed from the ultrasonic signals generated by the ultrasonic system.](image)

In this figure, the four regions of the elongated bubble, described in Fig. 1, can be observed and identified. The observed bubble presents an approximately hemispherical nose, a body surrounded by a falling liquid film, a tail region and a wake region. For the
purpose of this work, the subregion of the body of the bubble, where the film thickness is constant (2b), is the region of major importance.

By using a method based on the transit time between the pulse emission and its return after its reflection on the gas-liquid interface, it is possible to measure the equilibrium thickness of a falling film around a Taylor bubble. The film thickness is determined by the half of a product between the transit time at region 2b (Figs. 1 and 3) and the sound velocity in the liquid phase. Note that the transit time registered by the system refers to the twice of the distance equivalent to the film thickness.

Before presenting the results of the measurements performed in this work, it is important to have a reference value of the parameter being measured. This can be done using the simplified Brown’s model, defined by Eq. 2. Table 1 presents the values of each parameter used to estimate the thickness of a falling film around a Taylor bubble for the experimental apparatus and conditions used in this work. This reference value will be called $\delta_{ref}$.

**Table 1: Parameters used to estimate the equilibrium thickness of a falling film around a Taylor bubble for the experimental apparatus and conditions used in this work.**

<table>
<thead>
<tr>
<th>$\nu_{water}$ (25°C) (m²/s)</th>
<th>R (m)</th>
<th>$g$ (m/s²)</th>
<th>$U_B$ (m/s)</th>
<th>$U_L$ (m/s)</th>
<th>$\delta_{ref}$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.95 × 10⁻⁷</td>
<td>0.012605</td>
<td>9.81</td>
<td>0.1740</td>
<td>0</td>
<td>669</td>
</tr>
</tbody>
</table>

In Table 1, $R$ is the inner radius of the tube ($D = 2R$), the bubble rising velocity $U_B$ was calculated using the Eq. 3 and the liquid velocity $U_L$ was zero because there is no net flow of the liquid phase in this experiment. According to Eq. 2, the film thickness around the Taylor bubble can be estimated as 669 µm for the experimental conditions adopted. This will be the reference value used in this work.

Ten measurements (10 different bubbles) were made for each of the four channels of the ultrasonic system, using the same settings of the system parameters, totaling 40 measured bubbles. This was done to check if there were significant differences in the results obtained from the different channels. Tables 2 to 5 present the values of the equilibrium film thickness measured for each bubble in the different channels of the ultrasonic system.

To determine the values of these thicknesses, it was not used the transit time at only one acquisition point on the bubble interface, but an average of the transit time at acquisition points in the equilibrium region of the film (region 2b at Fig. 3). So the values presented in Tables. 2 to 5 are mean values of the equilibrium film thicknesses at different acquisition points for each bubble and the standard deviations correspond to this points.

It is important to note that the experimental procedures adopted to form all of the 40 bubbles had the same characteristics and because of this, the expected value for the thickness of the film around each of the bubbles can be considered similar for all the cases. The results presented in these tables correspond to absolutely the same procedures.
and the only difference is the channel of the system to which the ultrasonic transducer was connected.

Table 2: Equilibrium film thickness measured for 10 bubbles using channel 1 of the ultrasonic system

<table>
<thead>
<tr>
<th>Bubble</th>
<th>δ (µm)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>723</td>
<td>717</td>
<td>724</td>
<td>717</td>
<td>721</td>
<td>714</td>
<td>715</td>
<td>717</td>
<td>723</td>
<td>715</td>
<td></td>
</tr>
<tr>
<td>Stand. Dev.</td>
<td></td>
<td>27</td>
<td>30</td>
<td>32</td>
<td>26</td>
<td>32</td>
<td>24</td>
<td>25</td>
<td>28</td>
<td>28</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 3: Equilibrium film thickness measured for 10 bubbles using channel 2 of the ultrasonic system

<table>
<thead>
<tr>
<th>Bubble</th>
<th>δ (µm)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>734</td>
<td>720</td>
<td>734</td>
<td>719</td>
<td>725</td>
<td>738</td>
<td>730</td>
<td>727</td>
<td>727</td>
<td>742</td>
<td></td>
</tr>
<tr>
<td>Stand. Dev.</td>
<td></td>
<td>32</td>
<td>23</td>
<td>32</td>
<td>21</td>
<td>27</td>
<td>35</td>
<td>30</td>
<td>28</td>
<td>29</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 4: Equilibrium film thickness measured for 10 bubbles using channel 3 of the ultrasonic system

<table>
<thead>
<tr>
<th>Bubble</th>
<th>δ (µm)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>734</td>
<td>728</td>
<td>722</td>
<td>728</td>
<td>736</td>
<td>732</td>
<td>739</td>
<td>735</td>
<td>735</td>
<td>741</td>
<td></td>
</tr>
<tr>
<td>Stand. Dev.</td>
<td></td>
<td>32</td>
<td>29</td>
<td>24</td>
<td>29</td>
<td>31</td>
<td>28</td>
<td>31</td>
<td>30</td>
<td>33</td>
<td>37</td>
</tr>
</tbody>
</table>

Observing the Tables 2 to 5, it is possible to verify that the equilibrium film thickness were compatible with the reference value calculated by the simplified Brown’s model (Eq. 2). To quantify the agreement of the experimental measurements with the reference value, Tab. 6 presents the mean values of the equilibrium film thicknesses measured $\bar{\delta}$ and the average of the standard deviations $\bar{\sigma}$ for each of the ultrasonic system channels and their relative errors $e_{rel}$ to this reference value. The relative error was calculated by the following relation:

$$e_{rel} = \frac{\bar{\delta} - \delta_{ref}}{\delta_{ref}},$$

(4)

Table 6 shows that the values measured for the equilibrium film thickness in each of the four channels, considering their standard deviations, do not differ significantly.
Table 5: Equilibrium film thickness measured for 10 bubbles using channel 4 of the ultrasonic system

<table>
<thead>
<tr>
<th>Bubble</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ (µm)</td>
<td>729</td>
<td>731</td>
<td>734</td>
<td>738</td>
<td>731</td>
<td>735</td>
<td>726</td>
<td>735</td>
<td>734</td>
<td>740</td>
</tr>
<tr>
<td>Stand. Dev.</td>
<td>30</td>
<td>31</td>
<td>32</td>
<td>33</td>
<td>37</td>
<td>31</td>
<td>29</td>
<td>33</td>
<td>33</td>
<td>37</td>
</tr>
</tbody>
</table>

Table 6: Mean equilibrium film thickness for each of the ultrasonic system channels and their relative errors for the reference value

<table>
<thead>
<tr>
<th>Channel</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ (µm)</td>
<td>718.6</td>
<td>729.6</td>
<td>733.0</td>
<td>733.3</td>
</tr>
<tr>
<td>σ</td>
<td>27.9</td>
<td>29.2</td>
<td>30.4</td>
<td>32.6</td>
</tr>
<tr>
<td>e_rel</td>
<td>0.0741</td>
<td>0.0905</td>
<td>0.0956</td>
<td>0.0911</td>
</tr>
</tbody>
</table>

Table 7 presents the mean value of the equilibrium film thickness for all of the 40 bubbles and its relative error to the reference value. The results presented reveal that the values of the experimentally measured film thickness are in good agreement with the expected reference value. The relative errors $e_{rel}$ between the measured values and the reference one are in the order of 10%.

Table 7: Mean equilibrium film thickness for the 40 measured bubbles and its relative error for the reference value

<table>
<thead>
<tr>
<th></th>
<th>δ (µm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>δ (µm)</td>
<td>728.6</td>
<td></td>
</tr>
<tr>
<td>σ</td>
<td>30.0</td>
<td></td>
</tr>
<tr>
<td>e_rel</td>
<td>0.0890</td>
<td></td>
</tr>
</tbody>
</table>

The results presented in Tables 2 to 7 reveal that the pulse-echo ultrasonic technique is able to be applied in the direct measurement of the equilibrium film thickness around a Taylor bubble.

4. CONCLUSIONS

A preliminary experimental study was conducted to verify the feasibility and perform direct measurements of the falling film thickness around a Taylor bubble using the pulse-echo ultrasonic technique.

The major conclusions of this work are:
• There are no significant differences between the values of the equilibrium thickness of the falling film around a Taylor bubble measured in each of the four channels of the ultrasonic system.

• The equilibrium film thickness directly measured by the pulse-echo ultrasonic technique presents good agreement with the reference value calculated by the simplified Brown’s model (Eq. 2). The relative errors between the experimental measured values and the reference value are in the order of 10%.

• The pulse-echo ultrasonic technique can be applied to directly measure the equilibrium thickness of the falling film around a Taylor bubble, particularly in acrylic tubes.

The present work is still in progress and the authors intend to:

• Enhance the ultrasonic technique to direct measurement of the equilibrium thickness of this type of film, improving its accuracy.

• Using an adequate stagnant liquid column, develop a pulse-echo ultrasonic technique to directly measure the equilibrium thickness of the falling film around a Taylor bubble in tubes fabricated with other materials.

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REFERENCES


