Characterization of Velocity and Shape of Rising Bubbles in a Stagnant Liquid Vertical Column by Ultrasonic and Visualization Techniques

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Abstract. *The present paper reports a preliminary study of velocities of rising bubbles in a stagnant water vertical column. Rising bubble velocities were measure by using the pulse-echo ultrasonic technique and high speed digital camera visualization technique, which have been used in previous studies of two-phase gas-liquid flow in horizontal and slightly inclined circular tubes. Four types of rising bubbles were identified by flow visualization. We found that velocities of three types of rising bubbles agree reasonably well with available correlations, while velocities of one type of rising bubbles differ significantly from correlations.*

Keywords: *Ultrasonic Technique, Visualization Technique, Rising Bubble, Vertical Column.*

1. INTRODUCTION

Multiphase flow are encountered in a wide variety of engineering systems in the nuclear, oil, petrochemical and aerospace industry, among others. For example, in nuclear industry, the two-phase flow parameters need to be constant controlled at the primary reactor cooling system or during emergency core cooling of nuclear reactors.

The knowledge of heat transfer in gas-liquid flow is important in these industrial applications and this is directly related to the structure of the multiphase flow. For example, slug flow, which is one of the common flow patterns in gas-liquid flow, is accompanied by fluctuations in pipe temperature. The high pipe wall temperature results in "dryout", which causes damages in the chemical process equipments, convectional and nuclear power generating systems, refrigeration plants and other industrial devices (Ghajar, 2005).

The motion of long, bullet-shaped bubbles, also known Taylor Bubbles, rising in stagnant liquid is of fundamental importance in gas-liquid two-phase flow´s theory.

The rising velocity of a single isolated bubble in a liquid column depends on buoyancy and drag forces. Interactions between forces duo to surface tension, viscosity, inertia and buoyancy produce various effects which are quite often related with different bubble shapes and trajectories.

The pioneering works of Dumitrescu (1943) and Davies and Taylor (1950) analysed the velocity of bubbles in a circular vertical tube initially full and sealed on the top and established that the rising velocity of such bubble is:

$$u_0 = 0.35\sqrt{gD} \tag{1}$$

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

Experiments described by Nicklin et al. (1962) show that long bubbles of finite length rise relative to the ahead liquid 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.(1). In a tube open at the top, the expansion of the slug 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_0 relative to the liquid above it, the velocity in space is greater by an amount which depends on the length of the bubble.

In this work two nonintrusive techniques were used to measure the rising bubble velocities in a stagnant liquid vertical column sealed on the top: the pulse-echo ultrasonic technique and the visualization technique with high speed video camera. The parameters measured by this techniques were presented and discussed, especially the rising velocities of the bubbles, which are compared with the velocity predicted by Eq.(1).

2. EXPERIMENTAL FACILITIES

The data analysed in this work were obtained from a stagnant liquid vertical column sealed on the top located at the Thermo-Hydraulic Laboratory of the Nuclear Engineering Institute (LTE/IEN). Figure(1) presents this apparatus.

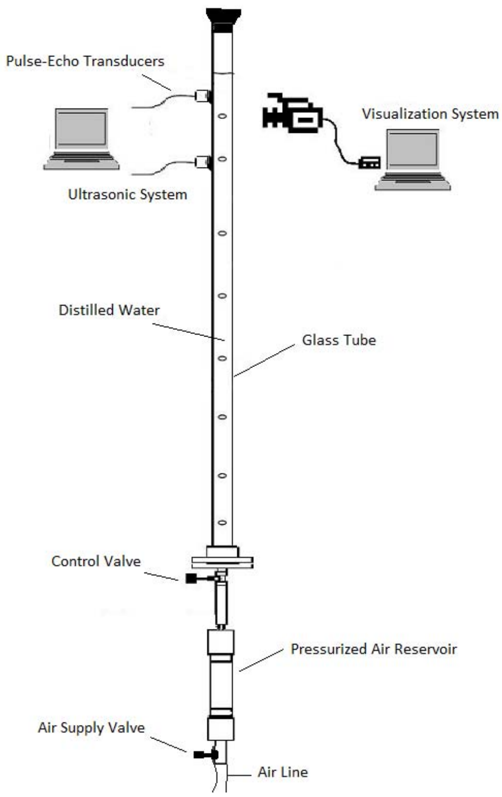

Figure 1. Schematic of the stagnant liquid vertical column used in this work

The vertical column consists of a glass tube of 1.5 m long with inner diameter of 24.37 mm connected by flanges with a system of air injection. Air is injected and trapped into an air reservoir by acting on the supply valve to eliminate the instability effects of the compressed air line. The bubbles are formed by acting on the control valve to inject air at the glass tube filled with distilled water. The temperature of the water is controlled by a thermometer immersed in it on the top of the tube.

The high speed video camera and de pulse-echo transducers are located near de top of the glass tube to measure the terminal velocity of the bubbles. In this study, the bubbles are formed and injected at the tube one at a time what facilitates the measurements and the comparison of the results obtained by the two techniques used.

2.1 The High Speed Ultrasonic System

The high speed ultrasonic system consists of a generator/multiplexer board, transducers and a computer (PC) with a based on 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. The two ultrasonic transducers of 10 MHz and 6.35 mm diameter, Panametrics piezoelectric-type transducers (Model M112), were mounted at the top of the glass tube in a fixed position from each other of 140 mm. 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.

2.2 The Visualization System

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 analyse in detail the bubble motion sequence.

3. EXPERIMENTAL RESULTS

Four different types or shapes of air bubbles are used in this work. Table(1) presents the definition of the different types of bubbles and Fig.(2) shows pictures to visualize this different shapes.

Table 1. Definition of the different types of bubbles used in this work.

Type 1	Small bubbles with diameter and length lower than the tube diameter
Type 2	Bullet-shaped bubbles with so short length
Type 3	Bullet-shaped bubbles with length of about a tube diameter
Type 4	Bullet-shaped bubbles with length larger than two tube diameters

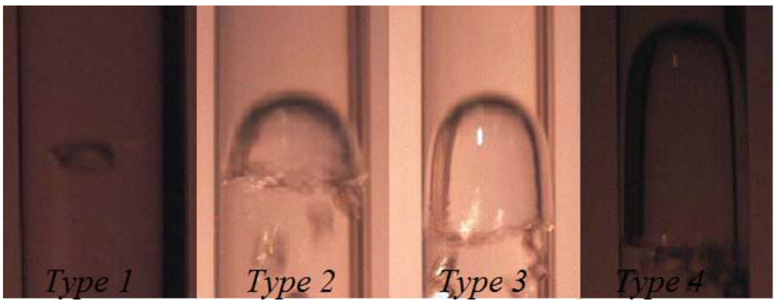

Figure 2. Pictures of the different types of bubbles

During all experiments, the water temperature was maintained at 27^{o}C.

3.1 Bubble Velocity Measurement by Ultrasonic System

The gas bubble can be detected by the transducers due to change in ultrasonic wave time propagation (Chang and Morala, 1990). So the ultrasonic technique has been used to measure many of the two-phase air-water flow parameters [(Faccini, 2008),(Cunha Filho et al., 2010a) and (Cunha Filho, 2010b)]. The bubble rising velocity can be determined by the relation:

$$u_b = \Delta Z / \Delta t \quad (2)$$

where ΔZ is the distance between the transducers and Δt is the time interval between the moments that the bubble is detected by the two transducers.

Figure(3) shows signals processed for measuring ultrasonic velocity. Each signal on the screen represents the moment that each of the transducers detect the passage of the bubble. As we know the distance between the transducers and the processing software is able to identify the elapsed time between the two signals. Thus it is possible to calculate bubble velocity.

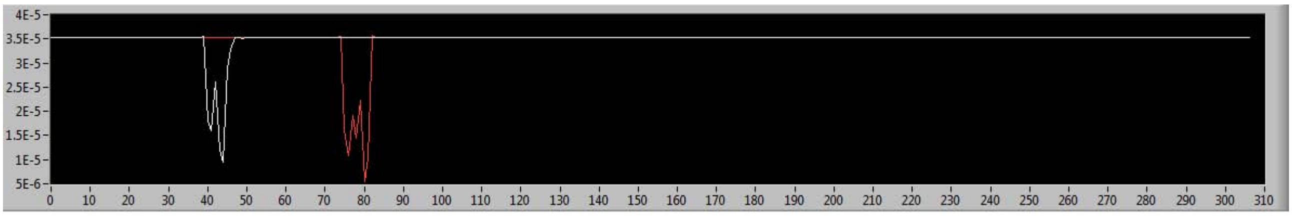

Figure 3. Ultrasonic signals processed to bubble velocity measurements

Table(2) presents the bubbles rising velocities measured by pulse-echo ultrasonic technique for the different bubble types and Fig.(4) shows the velocity distribution of the samples for the different types of bubbles.

Table 2. Ultrasonic technique measured velocities for different bubble types.

Bubble	Velocity (m/s)	Standard Deviation	Discrepancy to Theoretical Value
Type 1	0.2425	0.0069	0.4175
Type 2	0.2073	0.0094	0.2120
Type 3	0.2061	0.0048	0.2048
Type 4	0.2064	0.0077	0.2065

Theoretical Velocity: 0.1711 m/s
Number of Samples: 50 per type of bubble

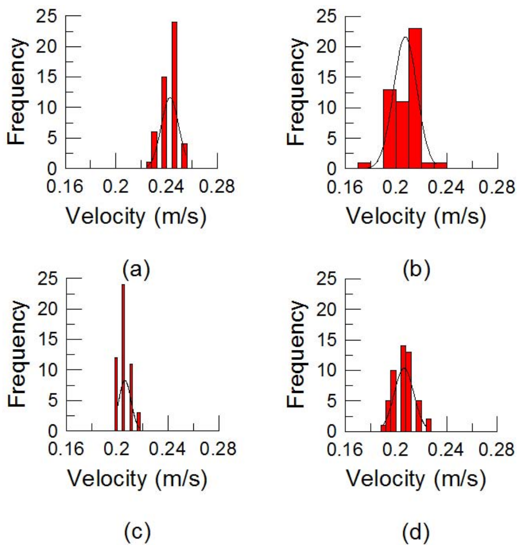

Figure 4. Distribution of ultrasonic measured velocities for the different types of bubbles. a) Type 1; b) Type 2; c) Type 3 and d) Type 4

3.2 Bubble Velocity Measurement with High Speed Camera

The gas bubble can be filmed with the high speed video camera with a known recording speed (frames per second) and the recorded videos can be processed with the image analysis software (Olympus i-Speed Software Suite) to measure many of the two-phase air-water flow parameters (Cunha Filho, 2010b).

The software presents a pair of axes situated at de shooting plan, which allows to determine the position and velocity of a point of interest in relation to a calibrated reference. The procedure of image processing consists in determining a reference point in the air-water interface, for example the nose of the bubble. Moving up the frames, a new point is selected on the new interface, enabling the software to calculate the displacement and the speed of that interface. Figure(5) presents a picture of the image analysis software used to process the bubbles recorded films with the displacements of the bubble nose interface chosen as reference.

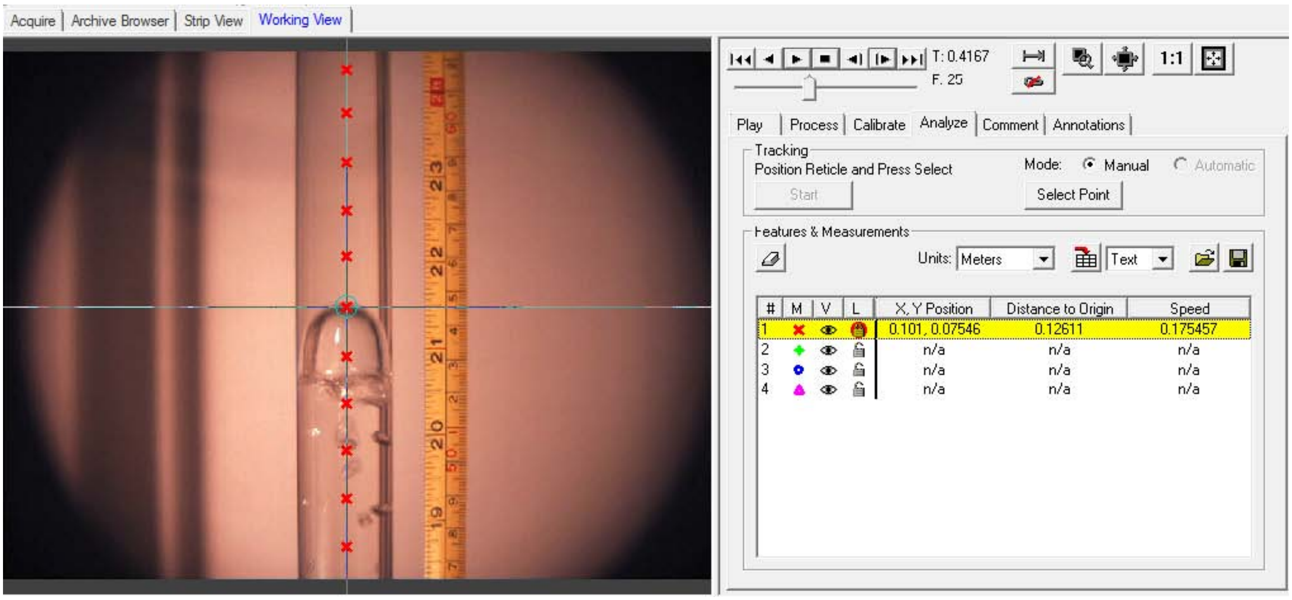

Figure 5. Recorded video processed to bubble velocity measurement

Each red mark in the Fig.(5) represents a reference point chosen in the air-water interface at the bubble nose and the metric scale is used as an external reference for calibrating the system. Highlighted in yellow can be observed the processed value of the speed between the last two points. Thus, the speed of each sample (each bubble) is defined as the average of the values obtained in such processing between each two points.

In this work the images were achieved at a rate of 60 fps (frames per second) and with a resolution of 800 X 600 active pixels.

Table(3) presents the bubbles rising velocities measured with high speed video camera for the different bubble types and Fig.(6) shows the velocity distribution of the samples for the different types of bubbles.

Table 3. Visualization technique measured velocities for different bubble types.

Bubble	Velocity (m/s)	Standard Deviation	Discrepancy to Theoretical Value
Type 1	0.2047	0.0056	0.1964
Type 2	0.1698	0.0013	0.0076
Type 3	0.1707	0.0008	0.0023
Type 4	0.1716	0.0015	0.0029

Theoretical Velocity: 0.1711 m/s
Number of Samples: 30 per type of bubble

Table(4) presents the discrepancy between the velocity values measured by ultrasonic and visualization techniques.

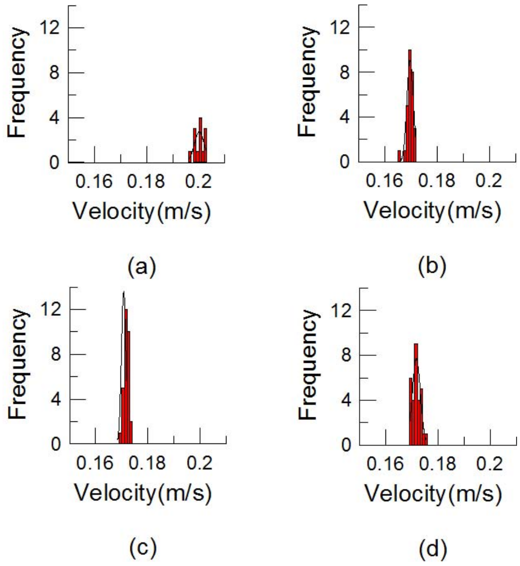

Figure 6. Distribution of visualization measured velocities for the different types of bubbles. a) Type 1; b) Type 2; c) Type 3 and d) Type 4

Table 4. Discrepancy between the velocity values measured by ultrasonic and visualization techniques.

Bubble	Discrepancy
Type 1	0.1847
Type 2	0.2208
Type 3	0.2074
Type 4	0.2028

4. DISCUSSION

Observing the Tables(2) and (3), it can be seen that the bubble velocities of type 1 are higher than those of the types 2, 3 and 4 and presents major discrepancy with respect to the theoretical value. This is not a surprise, since Eq.(1) is applicable to the so-called Taylor Bubbles, which have a bullet shape. Figure(2) shows that only bubbles of types 2, 3 and 4 present such a shape, although the type 2 presents very short lengths.

The explanation for this are the different effects caused by the various forces acting on the type 1 bubbles and on the bullet-shaped ones. This directly influences the movement of the bubbles, leading to different rising bubbles velocities. The forces involved in each case are not in the scope of this work and therefore they will be not discussed here.

In the Tables(2) and (3) can also be observed that, for both techniques used, the rising bubbles velocities of types 2, 3 and 4 are basically the same, ie, the discrepancy between them is too small, on the order of 0.5 percent. This is in agreement with Nicklin et. al (1962) and Zukoski (1966).

Nicklin et. al (1962) assert that the rising velocity of a Taylor Bubble, in a stagnant liquid, is independent of its length and only can be modified by a net flow of liquid across a section above the bubble, which not occur with tubes sealed on the top. So this velocity is decided solely by the hydrodynamics of the nose, and is no way affected by the wake on its tail.

According Zukoski (1966), the velocity and bubble nose geometry, in closed tubes, have been found to be independent of the bubble length for lengths greater than a few tube radii. About this, it is important to mention that the bubbles of Type 2 were produced for this work visually with lengths smaller than a tube diameter and hence less than a bubble diameter. This leads to a small disagreement with Zukoski (1966) for the type 2 bubble, since its velocities measured by the two techniques were basically the same as those of type 3 and 4, indicating that even for very small lengths (lower than three bubble radii), the rising bubble velocity would still be independent of their lengths. This should only be verified and better discussed in future studies by measuring the rising bubble velocity with a precise control and measurement of the bubbles lengths in order to assess its real influence.

The values measured by visualization technique, shown in Tab.(3), indicate that the rising velocities of the bullet-shaped bubbles (types 2, 3 and 4) also exhibited very low discrepancy relative to the theoretical value defined by Eq(1). This means that the experimental procedure adopted for such measurements received appropriate adjustments and was able to perform the measurement of the rising velocities of the Taylor Bubbles with very good accuracy. Thus, it can be seen that visualization technique with high speed video camera presents itself as a powerful tool in measuring air-water two-phase flow parameters, in particular for measuring the bubbles velocities.

On the other hand, the values measured by the ultrasonic technique as it is shown in Tab.(2), indicated that the rising velocities of the Taylor Bubbles (type 2, 3 and 4) have a difference of about 20 percent relative to the theoretical value. Cunha Filho et al (2010a) in a work for measuring interfacial parameters of elongated bubbles in two-phase air-liquid flow in horizontal and slightly inclined circular pipes, showed discrepancies for different flow conditions ranging from approximately zero to 40.9 percent between the bubbles translational velocities measured by the ultrasonic technique and appropriates correlations. They concluded that the ultrasonic system was able to performing such measurements.

It is important to note that the measurement of the flow parameters, such as bubbles translational velocities in two-phase flows is much more complex than in the case of this work, where the rising velocity of a single bubble is measured in a stagnant liquid.

Table(4) reveals that the discrepancy between the values of Taylor Bubbles rising velocities (types 2, 3 and 4) measured by ultrasonic technique and visualization technique were also of about 20 percent. Cunha Filho et al (2010a) worked with discrepancies ranging between 0.2 and 28.6 percent for the values obtained by this two techniques. However Cunha Filho (2010b) was able to reduce these discrepancies to less than 10 percent, making adjustments in the measuring procedures of the ultrasonic technique, especially in the signal processing, using filters that reduce the noise of the signals recorded.

Therefore, it seems reasonable to assume that, for the present work, it is possible to improve the measuring procedure of the rising bubbles velocities by the ultrasonic technique, both in the data collection and in its processing. Thus reducing the discrepancy relative to the theoretical value and consequently to the values measured by the visualization technique.

It is necessary to emphasize that in this work, the ultrasonic technique and the visualization technique were used at different times and, therefore, a more accurate comparison between the values measured by them is only possible when they are used to measure the parameters of the same bubble in rising.

5. CONCLUSIONS

In this work two nonintrusive techniques (pulse-echo ultrasonic technique and visualization technique with high speed video camera) were used to measure the rising bubbles velocities in a stagnant liquid vertical column sealed on the top and the following conclusions have been deduced:

- As expected, the correlation assigned to Dumitresco (1943) and to Davis and Taylor (1950) and validated by Nicklin (1962), only proved suitable as a reference for the cases of bullet-shaped bubbles (types 2, 3 and 4).

- For the case of type 1 bubbles, the rising velocities measured by the two techniques were higher than those for the Taylor Bubbles.

- For bullet-shaped bubbles, the rising bubbles velocities showed to be independent of their lengths, in good agreement with Nicklin (1962) and Zukoski (1966).

- The visualization technique appeared as a powerful tool for this purpose.

- The ultrasonic technique is also a powerful tool, however the authors need to make adjustments to the measurement procedure using this technique in order to improve its accuracy.

6. ACKNOWLEDGEMENTS

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