EXPERIMENTAL STUDY OF VELOCITY AND LENGTH OF ELONGATED GAS BUBBLES IN HORIZONTAL AND SLIGHTLY INCLINED TWO-PHASE GAS-LIQUID FLOW

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Abstract. *This paper reports an experimental study of the measurement of the velocities and lengths of elongated gas bubbles using a high speed ultrasonic system in cocurrent horizontal and slighttly inclined upward and downward flow. The circular pipeline test section is made of* 25.6 mm *stainless steel, followed by a transparent acrylic tube with the same inner diameter. The upward two-phase flow is at* $5°$ *and* $10°$ *and the dwonward at* $-2.5°$ *and* $-5°$*. In upward flow the superficial velocity of liquids and gas respectivively varied from* 0.22 *to* 1.08 m/s *and* 0.76 *to* 2.07 m/s*, while in downward flow respectively from* 0.81 *to* 1.62 m/s *and* 0.74 *to* 2.02 m/s*. For each inclination angle, nine combinations of superficial gas and liquid velocities were studied. Ultrasonic measurement point were developrd at acrylic tube, which is aproximately at atmosferic pressure. The ultrasonic technique is compared with visualization technique with good agreement.*

Keywords: *intermittent flow, translational velocity, bubble length, ultrasonic system, visualization*

1. INTRODUCTION

Two-phase flow is a significant industrial process in many fields of engineering. The measurement of interfacial parameters of two-phase gas-liquid flow is of great importance to thermal hydraulic behavior in nuclear reactors and in many heat exchangers. Intermittent gas-liquid flow is a quite common pattern flow and is characterized by the alternation of liquid slugs with some gas entrainment and elongated gas bubbles. The knowledge of its interfacial parameters is important to the design of safety and efficient equipments. Among many intermittent two-phase flow parameters, the elongated gas bubble velocity (Taylor bubble velocity) and its length are very important parameters to be measured. Many techniques have been developed to measure two-phase flow parameters, and they can be classified into two general types: intrusive and non-intrusive. The ultrasonic techniques are non-intrusive and proved to be one of the most reliable methods for two-phase flow measurements, offering more practical applications, (Lynnworth, 1979, Lynnworth and Mágori, 1980).

In this paper, a series of experiments on air-water two-phase flow were conducted to measure the velocities and lengths of elongated gas bubbles. In a circular pipe test section made of 25.6 mm stainless steel, followed by a transparent acrylic pipe with the same diameter using a high speed ultrasonic system. The experiments were performed at horizontal, upward ($5°$ and $10°$) and downward ($-2.5°$ and $-5°$) intermittent flow regime.

2. EXPERIMENTAL FACILITIES

2.1 TEST SECTION

The experimental development was performed in the Thermal-Hydraulic Laboratory of Nuclear Engineering Institute (IEN/ CNEN). The inclined two-phase flow test section consists of a water flow looping, a feed compressed air system, an air-water mixer, an inclined pipe test section and a separation air atmospheric tank, as show in fig. 1a. The horizontal and inclined tube is made of a 6.0 m long stainless steel 316 pipe with an inner diameter of 25.6 mm, followed by a transparent Plexiglas tube 1.8 m long with the same inner diameter. Distilled water is circulated axially through the venturi mixer, coming from an existing single-phase water loop, which is equipped with a centrifugal pump and a metering rig. Air is injected into the mixer by a compressor through a flow line equipped with an appropriate instrumentation. The air-water mixture goes out from the mixer and through the stainless steel tube along its length until the transparent Plexiglas tube where it can be visually observed. The air is measured in the single-phase lines by means of rotameters and the water is measured by means of turbine flow meters.

2.2 HIGH SPEED ULTRASONIC SYSTEM

The high speed ultrasonic system utilizes the pulse-echo model and consists of: a computer (PC), an Ultrasonic Pulser/Receiver equiped with 100MHz A/D Board for PCI Bus with up to four outputs multiplexer, and up to four ultrasonic transducers. The ultrasonic transducers were assembled along the acrylic pipe witn two at the top and two at the bottom. Fig. 1b shows the assembly of the ultrasonic transducers. The ultrasonic signals were digitalized in the board, from each transducer, in time intervals of 10 ns. The buffer memory was settled to plot 8000 points per transducer on the computer screen at each 10 ns. In the experiments the board generated an excitation frequency equal to 240 Hz with a pulse time generated on each transducer of 1.09 ms. The high speed ultrasonic system is described in CunhaFilho et al. (2009).

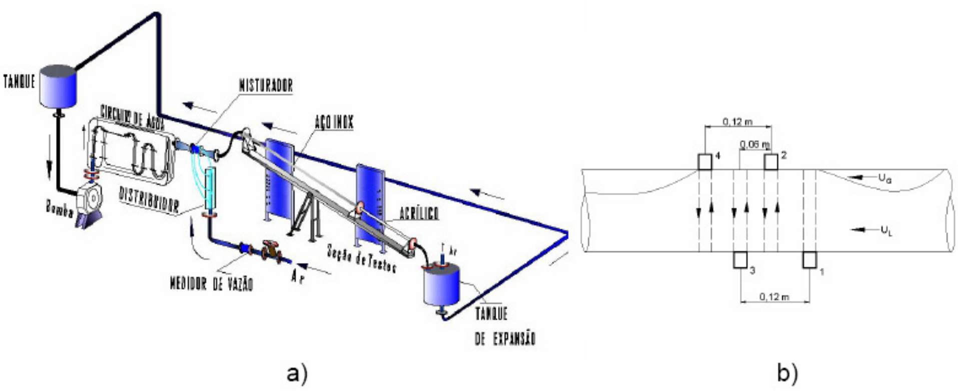

Figure 1. a) Experimental facilities, b) Schematic assembly of four transducers.

The intermittent two-phase flow (slug flows) is characterized by a liquid slug, which sometimes is very aerated, an elongated gas bubble on the top side and a liquid film under it. The gas-liquid interface is detected by the ultrasonic transducers due to the high acoustic impedance difference between the phases that generate high reflection of the ultrasonic wave. The start and end of the elongated gas bubble is monitored by the ultrasonic transducers due to the changes in the ultrasonic wave time propagation. Figure 2a shows a typical ultrasonic waveform obtained by the ultrasonic system. The ultrasonic travel time (Δt_Y) corresponds to the total time of the ultrasonic wave traveling through the liquid film, reflecting back from the air-water interface and returning to the ultrasonic transducer along the same way. The red line plot represents the ultrasonic signal of the first ultrasonic transducer and the blue line plot the last one.

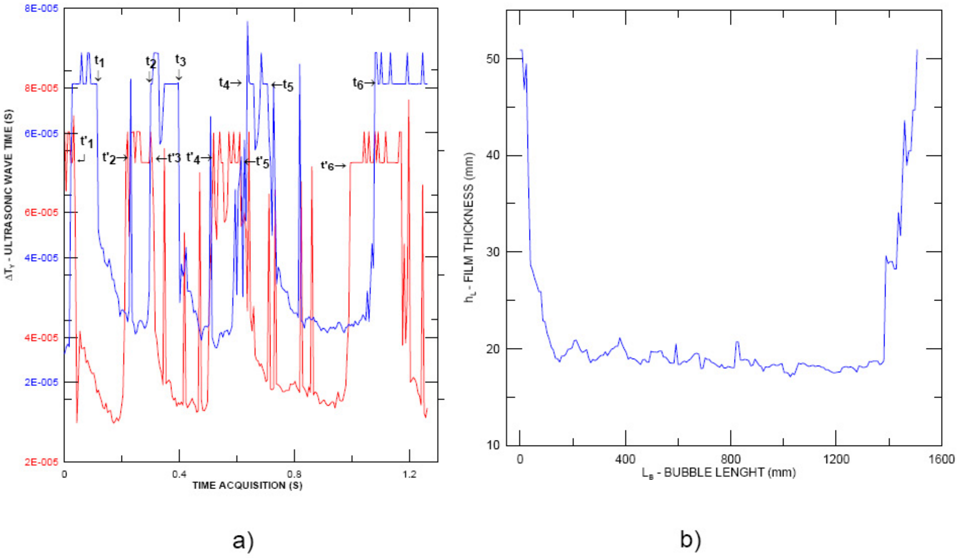

Figure 2. a) Typical ultrasonic waveform, b) Typical elongated bubble shape.

The velocities of the bubble nose V_{NB} and bubble tail V_{TB} were obtained by the equations:

$$V_{NB} = \sum \frac{\Delta Z}{\Delta T_{Ni}} = \sum \frac{\Delta Z}{t_i - t'_i}\,, \tag{1}$$

$$V_{CB} = \sum \frac{\Delta Z}{\Delta T_{Ci}} = \sum \frac{\Delta Z}{t_i - t_i'} , \tag{2}$$

in which:

- ΔZ is the distance between the two transducers which, in this research, is $0,12\ m$,
- ΔT_{Ni} is the time interval between the moments when the same edge of the bubble nose was detected by the transducers,
- ΔT_{Ci} is the time interval between the moments when the same edge of the bubble tail was detected by the transducers.

The mean elongated bubble velocities V_{MB} calculated by the average of the bubble nose velocity V_{NBi} and the bubble tail velocity V_{CBi} is, represented by:

$$V_{MB} = \sum \frac{V_{NBi} + V_{CBi}}{2} . \tag{3}$$

The elongated bubble lenght is calculated by equation:

$$L_B = \sum \frac{V_{MBi} \Delta T_{Bi}}{Ni} . \tag{4}$$

which:

- V_{MBi} is the mean elongated bubble velocity,
- ΔT_B is the time interval between the moments of the passage of nose and tail of the elongated bubble by one of the transducers,
- Ni is the number of measured bubbles.

Figure 2b shows a typical elongated bubble shape obtained by the ultrasonic system.

2.3 HIGH SPEED ULTRASONIC SYSTEM

The visualization system is formed by a monochrome digital high-speed camera with a CCD sensor (maximum resolution 480 x 420 pixels), zoom lenses, a PCI controller board of 12 bits, an image acquisition and analysis program and a computer. The frequency range of the frames varied according to the superficial velocities of the phase, in this research, a range between 250 and 500 frames per second. was used The sequence of images displayed on the computer monitor could be stored in a computer file and then, retrieved to analyze the flow motion sequence in detail.

Fig.3 shows three frames of the tail bubble motion: The one on the left shows the selected interface used as reference while the following depict the changes of positions of it.

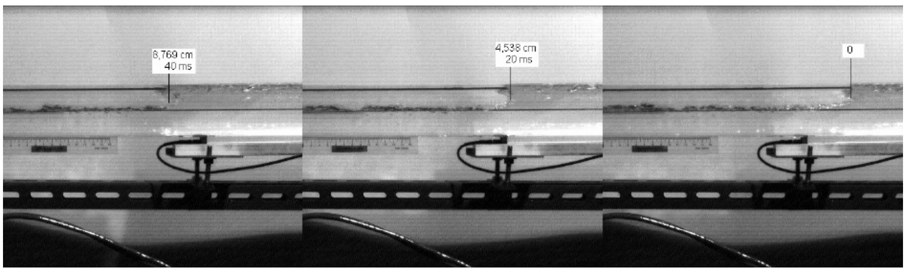

Figure 3. Tail bubble motion.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The elongated bubble velocity and lenght were measured in horizontal, upward ($5°$ and $10°$) and dwonward ($-2.5°$ and $-5°$) air-water two-phase flow. In upward flow the superficial velocity of liquids and gas varied respectivily from 0.22 to $1.08\ m/s$ and from 0.76 to $2.07\ m/s$ and in downward flow the superficial velocity of liquids and gas were varied respectivily from 0.81 to $1.62\ m/s$ and from 0.74 to $2.02\ m/s$. For each inclination angle, nine combinations of superficial gas (U_{GS}) and liquid (U_{GS}) velocities were studied. The measured results using ultrasonic and visualization technique were compared and showed a good agreement. The comparison was made by means of equation 5, which represents the relative difference between the results of both techniques. In most studied cases the relative difference between the ultrasonic and visualization techniques for measured bubble velocities was below 10% and the relative difference for measured elongated bubble lenght was below 15%.

$$\epsilon = \frac{|x - x_{ref}|}{x_{ref}} 100\,, \tag{5}$$

(x_{ref}) is the parameters measured by ultrasonic technique.

Figures 4a and 4b show the variation of bubble nose velocity as a function of superfical gas velocity in upward two-phase flow and fig.5a and 5b in downward two-phase flow. The vertical lines represent the uncertain measure. A linear relationship between the bubble nose velocity and superficial gas velocity was observed.

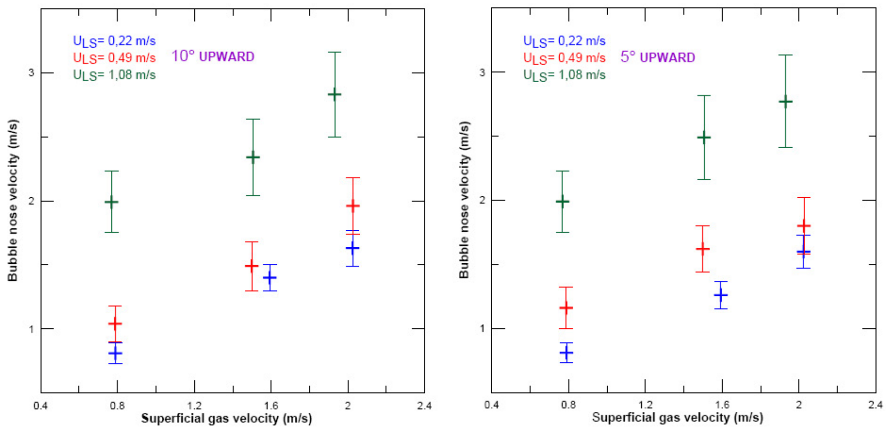

Figure 4. Bubble nose velocity as function of superfical gas velocity a) Upward $5°$, b) Upward $10°$.

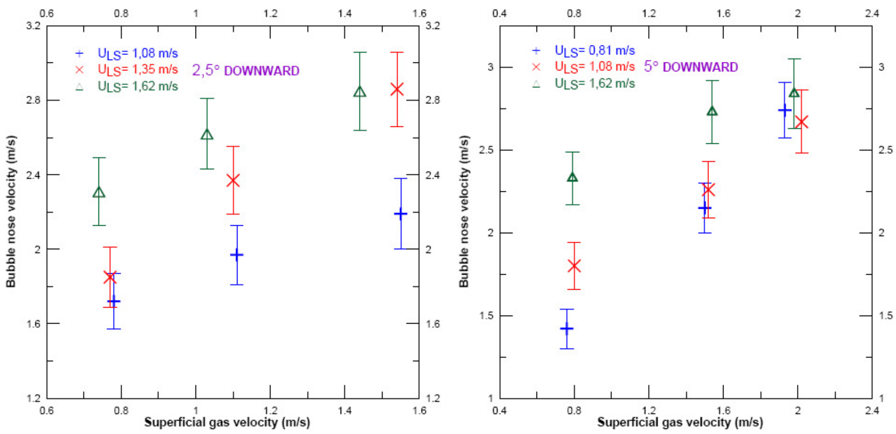

Figure 5. Bubble nose velocity as function of superfical gas velocity a) Downward $2.5°$, b) Downward $5°$.

The Pearson product-moment correlation coefficient (r) measure the strength of linear dependence between two variables. In the case of a perfect positive (increasing) linear relationship the value of (r) is +1. Table 1 shows the Pearson product-moment correlation coefficient between bubble nose velocity and superficial gas velocity for the different studied inclinations angles. The results show an almost perfect positive linear relationship between the bubble nose velocity (V_{NB}) and the superficial gas velocity (U_{GS}).

Table 1. Pearson product-moment correlation coefficient (r) between V_{NB} and U_{GS}.

$Horizontal$	$Upward\ 5°$	$Upward\ 10°$	$Downward\ 2.5°$	$Downward\ 5°$
$0.93 \leq r \leq 1.00$	$0.99 \leq r \leq 1.00$	$0.98 \leq r \leq 1.00$	$0.98 \leq r \leq 0.99$	$0.98 \leq r \leq 1.00$

Figures 6a and 6b show the variation of elongated bubble length as function of superfical gas velocity in upward two-phase flow measured by ultrasonic and visualiztion techniques. The uncertain measure is not shown in order to make the graph easier to analyse. Figures 7a and 7b show the relationship in downward two-phase flow using ultrasonic technique. The vertical lines represent the uncertain measure. Both in horizontal and upward flow, as the gas superficial velcity increase, so does the elongated bubble length. A linear relationship between them was observed. Both n downward flow $(-2, 5°)$ the same tendency as in horizontal and upward flow was not observed, and at $(-5°)$, a weak tendency of elongated bubble length increase as the gas superficial velocity increase occured.

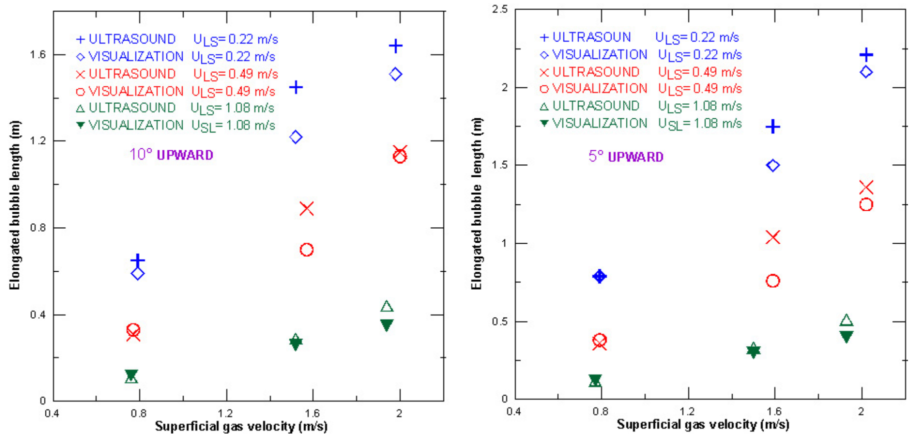

Figure 6. Elongated bubble length as function of superfical gas velocity a) Upward $5°$, b) Upward $10°$.

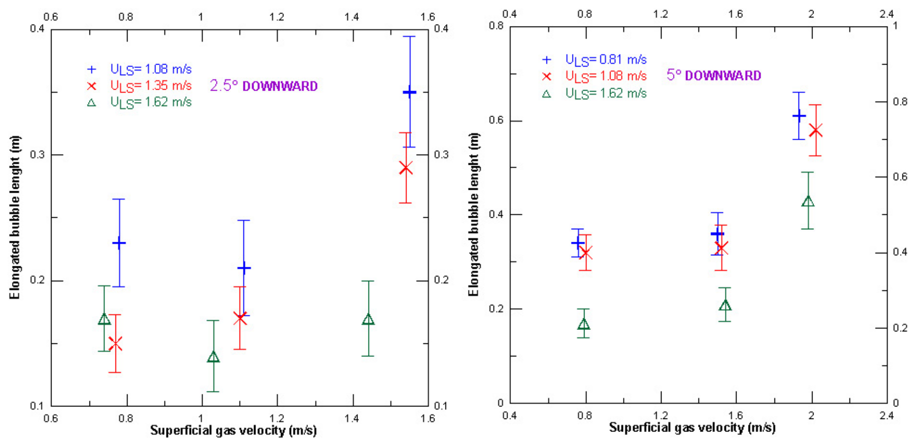

Figure 7. Elongated bubble length as function of superfical gas velocity a) Downward $2.5°$, b) Downward $5°$.

Table 2 shows the Pearson product-moment correlation coefficient between bubble nose velocity and superficial gas velotityfor the differents studied inclinations angles. In horizontal and upward flow the results show a good linear relationship between the elongated bubble length (L_B) and the superficial gas velocity (U_{GS}). In downward flow the linear relationship between the elongated bubble length and superficial gas velocity is not observed.

Table 2. Pearson product-moment correlation coefficient (r) between L_B and U_{GS}.

$Horizontal$	$Upward\ 5°$	$Upward\ 10°$	$Downward\ 2.5°$	$Downward\ 5°$
$0.84 \leq r \leq 1.00$	$0.99 \leq r \leq 1.00$	$0.98 \leq r \leq 1.00$	$0.40 \leq r \leq 0.90$	$0.82 \leq r \leq 0.86$

4. CONCLUSIONS

In this paper, a visualization and high speed ultrasonic techniques were used to measure the velocities and lengths of elongated gas bubbles in cocurrent horizontal and slighttly inclined upward ($(5°)$ and $(10°)$) and downward ($(-2, 5°)$ and $(-5°)$) flow. We conclude that:

- There is a good agreement between ultrasonic and visualization techniques.
- There is a positive linear relation between the translational bubble velocity and superficial gas velocity in all studied pipe inclinations.
- There is a positive linear relation between the elongated bubble length and superficial gas velocity in the studied horizontal and upward flows.

- It was not observed a linear relation between the elongated bubble length and superficial gas velocity in downward studied flows.

5. ACKNOWLEDGEMENTS

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