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DESIGN AND CONSTRUCTION OF AN EXPERIMENTAL APPARATUS FOR VELOCITY DETERMINATION OF A GAS BUBBLE FLOWING IN STAGNANT LIQUID

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Abstract. *Multiphase flows have been studied for many decades, due to their applications in industry sectors, such as in petroleum activities, in the nuclear energy sector, in refrigeration cycles, among other applications. This flow type occurs mainly during the transport of mixtures containing gases, liquids, and solids. It can be of the same substance (multiphase) or distinct and immiscible substances (multicomponent). The gas-liquid flows are often classified into three main patterns: dispersed, separated, and intermittent. The study of an elongated gas bubble flowing in the stagnant liquid inside pipes is of great importance for the analysis and understanding of multiphase flow models. Much of the knowledge about flow patterns have been obtained empirically, which makes evident the importance of studying and improving experimental methods related to the theme. This work aims to carry out the design and construction of an experimental apparatus for visualizing and determining the velocity of a gas bubble flowing in stagnant liquid, as seen in other works in the literature. The apparatus consists of a structure of aluminum profiles and acrylic tubes, which are fixed employing metallic clamps, as well as ball valves, among other materials. Through this apparatus, it is possible to verify the influence of the diameter and inclination of the pipe, as well as the liquid viscosity, in the ascension velocity of a gas bubble. The gas bubble velocity was determined by processing videos, recorded in the testing section of the apparatus, for two different inclinations, concerning horizontal (90° and 45°), and showed satisfactory agreement with the literature. The apparatus proves to be functional, simple to build, low cost, easy to operate, and capable of adaptations and improvements. Besides, simplified methodologies were developed for the construction and operation of the apparatus, which is functional for several applications in the experimental study of tubular flows, helping in the analysis and understanding of various flow-related phenomena.*

Keywords: *multiphase flow, dimensional analysis, tubes—fluid dynamics.*

1. INTRODUCTION

Multiphase flow is a phenomenon that has been studied for many decades due to its occurrence in many practical applications, for example, oil and gas industries, thermoelectric generation, and refrigeration cycles. This flow type occurs mainly during the transport of mixtures containing gases, liquids, and solids, which can be of the same substance (multiphase) or distinct and immiscible substances (multicomponent). The importance of studying this phenomenon is due to the need for industries to predict head and heat losses, to the dimensioning of pipes and pumping systems, to optimize production processes and reduce costs. In many situations, due to the high complexity of multiphase flow modeling with more than two phases, the system can be simplified to a two-phase flow depending on the relative amount of phases present in the pipeline, which simplifies calculations and understanding (Lima, 2011).

According to Bratland (2010), one of the most challenging aspects of the study of two-phase flows is the fact that they can take many different shapes or patterns. For example, gas-liquid flows are often classified into three main patterns: dispersed, separated, and intermittent. However, these flows can still have more specific classifications. Figure 1a presents six gas-liquid flow patterns in horizontal pipes: dispersed bubble, annular with droplets, elongated bubble, slug, stratified, and stratified wavy. Figure 1b shows five gas-liquid flow patterns in vertical pipes: dispersed bubbles, slug, churn, annular, and annular with droplets.

In some of these patterns, the gas phase appears as a sequence of elongated bubbles (e.g., the slug pattern) or as a cluster of scattered bubbles. Understanding the kinematics and dynamics of the bubbles allows one to analyze, in a relatively simple way, fundamental parameters in more complex flows (Wallis, 1969). Thus, the study of the behavior of an elongated bubble, which is also called the Taylor bubble (Davies and Taylor, 1950) is of great importance for modeling, analyzing, and understanding these more complex flows.

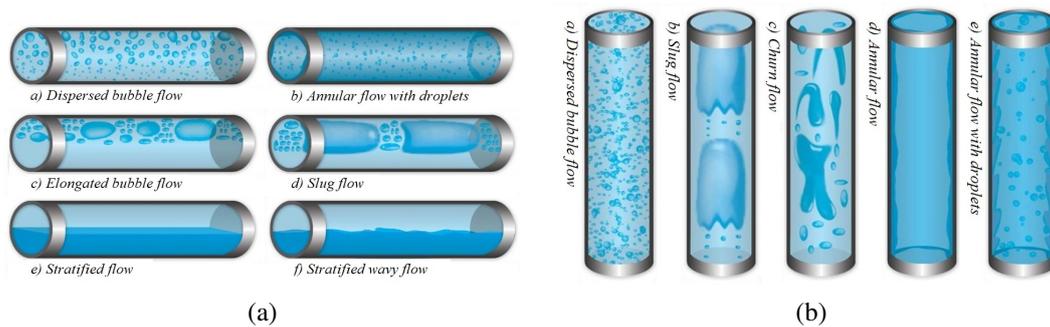


Figure 1. Gas-liquid flow patterns in horizontal (a) and vertical (b) pipes (Bratland, 2010).

Much of the knowledge about flow patterns have been obtained empirically. Therefore, the variety of system configurations and practical situations of interest highlight the importance of studying and improving experimental techniques and measurement instruments to determine important characteristics of this flow type with satisfactory precision. The data obtained empirically in multiphase flows can be used both for the design of systems and for the development of flow models for simulations.

In this context, the main goal of the present work was to design and build an experimental apparatus to visualize and determine the velocity of an elongated gas bubble flowing in stagnant liquid. This apparatus allows analyzing the influence of both the diameter and the inclination of the tube, as well as properties of fluids, such as the liquid viscosity. In addition to the main goal, preliminary experimental tests were carried out and compared against literature data to verify the operability of the apparatus.

2. LITERATURE REVIEW

Many studies on Taylor bubbles flowing in stagnant liquid were already conducted and are available in the literature, many of which are depicted next. One of the first experiments on elongated bubble velocity was developed by Davies and Taylor (1950), who studied the rise of elongated air bubbles in stagnant liquid (water and nitrobenzene) inside a large tank and also in clear glass vertical pipes. Three glass tubes with a length of 180.0 cm and diameters of 1.23 cm, 2.16 cm, and 7.94 cm were lifted vertically over a sink and filled by placing the lower ends over a basin filled with water and applying suction to the upper ends. After the water level reached the top, the upper ends were closed, while the lower ends were opened, allowing the liquid to come out as a bubble formed and ascended towards the top. Ascension velocities were calculated by measuring the passage time of the bubble nose between two horizontal marks placed on the tubes at determined positions.

Nicklin *et al.* (1962) performed experiments using a 2.54 cm tubing vertically positioned in which the fluids were also air and water. Zukoski (1966) carried out experiments to analyze the influence of liquid viscosity, surface tension, and inclination angle on the movement of the elongated bubbles. Different liquids used, such as water, carbon tetrachloride, mercury, glycerin, ethyl alcohol, and mixtures of these compounds. Also, pipe diameters ranged from 5.0 cm to 17.8 cm, most of them made of glass. Bubble velocities were calculated by measuring the time intervals taken by the bubbles to pass through a given tube length. It was found that the bubble length is not related to the bubble velocity in cases where the length is at least three times the bubble diameter. It was also observed that the bubble ascension velocity is not influenced by viscosity for inclinations from 30° to 90° concerning the horizontal.

Maneri and Zuber (1974) carried out experiments by injecting pressurized air from a cylinder, which was controlled by a valve, into three different glass tanks filled with stagnant liquid. By tilting these tanks up to 90° , measured with a protractor from the vertical, it was possible to analyze the influence of fluid properties on inclined two-dimensional gas-liquid flows. Data was obtained through photography and backlighting techniques. It was observed that there was no difference between the terminal velocities of the bubbles in vertical flows in water and methanol. On the other hand, in inclined flows, changes observed in the bubble nose related to the inclination angle showed that the surface tension effect is considerable. It was concluded that the inclined flow in large diameters is independent of the fluid properties for inclinations from 0° to 10° . However, for inclinations from 10° to 30° , the flow begins to be influenced by fluid properties. Finally, from 30° to 90° the flows are influenced by fluid properties for large diameters.

Bendiksen (1984) carried out experiments in an apparatus of transparent acrylic tubes supported by a structure of aluminum bars. The pipes were pivoted in a way that allowed inclinations up to angles of 180° relative to the horizontal. They had lengths of 10 m, 7 m, and 4 m with internal diameters of 1.92 cm, 2.42 cm, and 5.0 cm. The experiments covered different liquid flows and also the stagnant liquid case. Bubble velocities were measured using emitter/detector transistors arbitrarily positioned along the tubes and connected to an electronic circuit. The average velocities of the bubbles were calculated as a function of the distance and time measured between transistors through the signal variation. A correlation was proposed for the Froude number (Fr) as a function of the pipe inclination concerning the horizontal (θ), the Froude

number calculated for the horizontal flow (Fr_H), which equals 0.542, and the vertical pipe Froude number (Fr_V), which is 0.345. Equation (1) presents such correlation, which was compared against empirical values observed in its author experiments and also against values proposed by Zukoski (1966), showing around 1% deviation.

$$Fr(\theta) = Fr_H \cos \theta + Fr_V \sin \theta \quad (1)$$

The Froude number (Fr) defined by Eq. (2) is the dimensionless parameter directly related to the velocity of the elongated bubble. It correlates the forces of inertia and buoyancy acting on the Taylor bubble.

$$Fr = \frac{V_T}{\sqrt{gD \frac{\Delta\rho}{\rho_L}}} \quad (2)$$

Where V_T is the elongated bubble velocity, g is the gravity acceleration, D is the pipe's inner diameter, and $\Delta\rho = \rho_L - \rho_G$ is the difference between the densities of the liquid, ρ_L , and gas, ρ_G , phases.

Weber *et al.* (1986) performed experiments to calculate the velocity of the Taylor bubble in seven glass tubes with internal diameters of 0.60 cm, 0.81 cm, 0.91 cm, 1.05 cm, 1.35 cm, 2.21 cm, and 3.73 cm. Pipe inclinations ranged from 15° to 90° concerning the vertical in addition to performing experiments with horizontal pipes, totaling seven inclinations. Distilled water-based fluids with different physical properties were used. The lower end of the tubes was closed with a rubber stopper, while the upper end was connected with a metal clamp to a flexible hose. After filling the tubes with liquid through the hose, the stopper was removed from the lower end, allowing the liquid to come out while air come in to form the Taylor bubble. The bubble ascension velocities were determined by the time recorded between certain marks on the tubes. Weber *et al.* (1986) were able to observe that correlation by Bendiksen (1984) was discrepant concerning the experimental results obtained with more viscous fluids. It was proposed a new correlation for which was claimed a decrease in the discrepancy against the experimental values from 15% to 10%.

Carew *et al.* (1995) performed semi-empirical studies in which was proposed a correlation that describes the movement of bubbles in inclined tubes. The experiment used different tube diameters (2.5 cm, 4.5 cm, and 7.0 cm) that were attached to a structure. Tubes partially filled with the liquid of interest were closed at both ends with screw caps and rapidly rotated to the inclination of interest, forming an ascending air bubble. The Taylor bubble velocity was measured automatically by a digital stopwatch which was started and stopped by two optical infrared sensors. It could be observed that the increase in viscosity or surface tension results in a decrease in the ascension rate.

Shosho and Ryan (2001) experimentally studied the movement of elongated bubbles in inclined tubes. The pipes used in the experiments were 1.22 m long with internal diameters of 1.27 cm, 1.91 cm, 2.54 cm, 3.18 cm, and 3.81 cm. Each tube was tested with inclinations of 5°, 15°, 30°, 45°, 60°, 75°, and 90° relative to the horizontal. Bubble ascension velocities were measured utilizing a manual stopwatch. The length used to calculate the velocities started at the middle of the tube and ended at the upper end (0.61 m). The experiments were carried out using different Newtonian and non-Newtonian liquids, including water and various mixtures of corn syrup with water to cover a wide range of viscosities.

van Hout *et al.* (2002) carried out experiments with two-phase flows in the slug pattern. Using two parallel transparent plastic tubes with a length of 10 m and internal diameters of 2.4 cm and 5.4 cm, it was possible to incline the system from the horizontal to the vertical. Bubble velocities were measured using image processing techniques obtained by a camera and fiber optic probes. It was observed that extrapolations from stagnant liquid bubble flow to slug flow were inadequate. However, the experimental results were in agreement with the literature about the stagnant liquid case, with a deviation smaller than 10% relative to the Bendiksen (1984) correlation.

Gokcal *et al.* (2009) experimentally studied the effects of high viscosity oil on the drift velocity of air bubbles in horizontal and inclined tubes. The experimental system had a pipe 18.9 m long and an inner diameter of 5.08 cm, in which a section of 9.15 m consisted of clear acrylic and was used to measure the drift velocity in horizontal flow. Another tube of 3.05 m in length and an inner diameter of 5.08 cm, made of acrylic, was added to the apparatus and could be tilted up to 90° concerning the horizontal. Water and oil were used in the experiments, and the oil was heated or cooled to reach the desired viscosity. Bubble slip times were recorded using laser sensors and their velocities were calculated.

Gómez-Bueno (2010) carried out an experimental study of air-water flows in inclined pipes. It was used a pipe with an inner diameter of 25.4 mm and 9 m in length. Table 1 lists Froude number (Fr) values of the elongated air bubble in stagnant water obtained experimentally for differed pipe inclinations (θ).

Jeyachandra *et al.* (2012) extended the work of Gokcal *et al.* (2009), using the same experimental apparatus, but with different tube diameters and more viscosity variations (high viscosity oils) to study two-phase slug flow. Tubes with internal diameters of 50.8 mm, 76.2 mm, and 152.4 mm were used. Drift velocities were determined by optical sensors in the 152.4 mm tube, while laser sensors were used in the other pipes.

Moreiras *et al.* (2014) analyzed the drift velocity of large bubbles in viscous stagnant fluids. An acrylic tube 3.05 m in length and 50.8 mm in diameter was used. Through a pulley system, the inclination of the tube could vary from 0° to 90° relative to the horizontal. The working fluids were air and mineral oil which was heated or cooled to obtain the desired properties. The bubble drift velocity was determined utilizing image treatment. A high-speed digital camera was able to record its passage between two markings on the tube separate by a known distance.

Table 1. Froude numbers (Fr) of the elongated air bubble in stagnant water as a function of the inclination (θ) of a 25.4 mm diameter pipe (Gómez-Bueno, 2010).

| Inclination, θ ($^\circ$) | Fr (experimental) | Correction factor | Fr (corrected) |
|------------------------------------|---------------------|-------------------|------------------|
| 90 | 0.356 | 0.968 | 0.345 |
| 75 | 0.413 | 0.969 | 0.401 |
| 60 | 0.460 | 0.971 | 0.447 |
| 45 | 0.492 | 0.974 | 0.479 |
| 30 | 0.493 | 0.980 | 0.483 |
| 15 | 0.464 | 0.988 | 0.459 |
| 5 | 0.436 | 0.995 | 0.434 |

Vinhas (2015) studied the movement of Taylor bubbles in a column of stagnant liquid inside an acrylic tube with an internal diameter of 24.0 mm and 2.0 m in length. The experiments were carried out with the tube alternating between six angles from the vertical: 0° , 2.5° , 5° , 7.5° , 10° , and 15° . The working fluids used were distilled water and 100% glycerin. The velocity and other properties of the bubbles were obtained through image processing utilizing a high-speed digital camera.

Lizarraga-Garcia *et al.* (2016) performed experiments to obtain an analytical model of film drainage and rupture criterion for Taylor bubbles in the slow-flowing fluid inside inclined round tubes. The experiments used a polycarbonate tube with a diameter of 12.7 mm, with inclinations of 5° , 15° , 30° , 37.5° , 45° , 60° , 75° , and 90° concerning the horizontal. The liquids were methanol, ethanol, and three mixtures of distilled water and methanol. To determine the bubble ascension velocity and other properties, a high-speed digital camera was used with subsequent image processing.

de Azevedo *et al.* (2020) experimentally studied rising Taylor bubbles in slightly inclined acrylic tubes of 2.0 m in length and diameters of 19.0 mm, 24.0 mm, and 34.0 mm. These tubes were partially filled with stagnant liquids, such as distilled water, pure glycerin, and mixtures of water and glycerin. The properties of the bubbles were determined by processing images and videos obtained with high-speed digital cameras, as well as ultrasonic signal transducers installed in their experimental apparatus.

Cerqueira *et al.* (2019) presents the development of an experimental apparatus to study vertical slug flow using particle image velocimetry (PIV), high-speed camera and laser diode photocell. This apparatus allows the study of the Taylor bubble with or without the presence of dispersed bubbles in the liquid stream under controlled conditions. According to the authors, most industrial slug flows are characterized by dispersed bubbles flowing alongside to the Taylor bubbles, although this phenomenon is neglected by most studies in order to obtain a "well behaved" Taylor bubble. This apparatus was applied by Cerqueira and Paladino (2020) and important results were obtained, as it was revealed that the dispersed bubble volume fraction affected the Taylor bubble velocity and the PIV technique allowed the acquisition of turbulence statistics around the Taylor bubbles, which might support the implementation and validation of CFD models.

Table 2 summarizes the main characteristics of the works on Taylor bubble velocity in stagnant liquid referred to in this literature revision. This description is restricted to pipe lengths, diameters, and inclinations, working fluids, and measurement techniques. The design and construction of the experimental apparatus, as well as the experimental activities carried out in the present work, were based on these several works.

3. MATERIALS AND METHODS

This section presents the design of the experimental apparatus built to determine the elongated bubble velocity and also explains the experiment that was carried out to compare the obtained results against empirical data from the literature.

3.1 Experimental apparatus

The experimental apparatus designed and built to determine the Taylor bubble ascension velocity is composed of an aluminum profile structure, a transparent acrylic tube fixed by metallic clamps, an acrylic sheet with bores to allow pipe inclination, and ball valves to release the gas phase held inside the second section of pipe. The apparatus was designed to allow sensors for velocity measurement to be attached in future works. Figure 2 shows the representation of the apparatus with the details of ball valves, metal clamps, and sensors.

An important part of the apparatus is the structure, which supports the tube filled with various liquids and must do so in a robust way while being light and inexpensive. A material that meets these requirements is aluminum, which was used in the structure of the experiment by Bendiksen (1984). Thus, extruded aluminum structural profiles were used to build the structure of the present apparatus. The structure geometry has a format similar to that used in the construction of the Carew *et al.* (1995) experiment, in which a given position in the middle of the pipe is pivoted to the center of the structure in a way

Table 2. Summary of experiments on bubble velocity available in the literature concerning pipe lengths (L), diameters (D), and inclinations (θ), working fluids, and measurement techniques.

| Reference | L (m) | D (mm) | θ (°) | Working fluids | Measurement techniques |
|---------------------------------------|----------------|-------------------|--------------|--|---|
| Davies and Taylor (1950) | 1.8 | 12.3; 21.6; 79.4 | 90 | Air and water | Stopwatch |
| Nicklin <i>et al.</i> (1962) | – | 25.4 | 90 | Air and water | – |
| Zukoski (1966) | – | 50.0–178.0 | 0–90 | Air and various liquids | Stopwatch |
| Maneri and Zuber (1974) | 0.914 | ^a | 5–90 | Air, water, and methanol | Photography |
| Bendiksen (1984) | 4.0; 7.0; 10.0 | 19.2; 24.2; 50.0 | -90–90 | Air and water | Transistors |
| Weber <i>et al.</i> (1986) | 1.2 | ^c | 0–90 | Air and various liquids | Stopwatch |
| Carew <i>et al.</i> (1995) | – | 25.0; 45.0; 70.0 | 0–90 | Air and various solutions | Infrared sensors |
| Shosho and Ryan (2001) | 1.22 | ^d | 5–90 | Air and various Newtonian and non-Newtonian liquids | Stopwatch |
| van Hout <i>et al.</i> (2002) | 10.0 | 24.0; 54.0 | 0–90 | Air and water | Optical fiber probes and camera |
| Gokcal <i>et al.</i> (2009) | 18.9; 3.05 | 50.8 | 0–90 | Air, water, and oil | Laser sensors |
| Gómez-Bueno (2010) | 9.0 | 25.4 | 0–90 | Air and water | Impedance probes |
| Jeyachandra <i>et al.</i> (2012) | 18.9; 3.05 | 50.8; 76.2; 152.4 | 0–90 | Air, water, and oil | Laser and optical sensors |
| Moreiras <i>et al.</i> (2014) | 3.05 | 50.8 | 0–90 | Air and mineral oil | Video processing |
| Vinhas (2015) | 2.0 | 24.0 | 0–15 | Air, distilled water, and 100% glycerin | Video processing |
| Lizarraga-Garcia <i>et al.</i> (2016) | – | 12.7 | 5–90 | Air, methanol, ethanol, and three mixtures of distilled water and methanol | Video processing |
| Cerqueira <i>et al.</i> (2019) | 2.0 | 26.2 | 90 | Air and water | Particle image velocimetry (PIV), high-speed camera and laser diode photocell |
| de Azevedo <i>et al.</i> (2020) | 2.0 | 19.0; 24.0; 34.0 | 75–90 | Air, distilled water, pure glycerin, and mixtures of water and glycerin | Video processing and ultrasonic signals |

^a Rectangular area: (63.5; 152.4; 863.6) × (9.53; 12.7).

^b 19.4; 25.4; 31.9; 38.4; 44.5; 45.5; 56.7.

^c 6.0; 8.1; 9.1; 10.5; 13.5; 22.1; 37.3.

^d 12.7; 19.1; 25.4; 31.8; 38.1.

that allows its rotation. In the present apparatus, the pivot point of the tube is located about 1 m above the structure base, allowing the use of tubes up to 2 m in length.

The inclination of the tube may be set by rotation of the clamp around the central screw used to attach the pipe to the structure. This clamp is located near the middle section of the liquid-filled tube. A second clamp, identical to the first one,

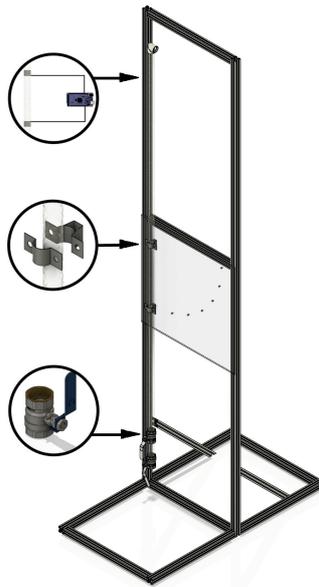


Figure 2. Representation of the experimental apparatus for the determination of the Taylor bubble ascension velocity with the details of ball valves, metal clamps, and sensors.

is used to properly attach the tube section to the frame to avoid vibrations that could hinder the development of the gas bubble during the experiments. Both clamps are attached to a transparent acrylic sheet mounted in the central region of the apparatus. This acrylic sheet also features bores that allow the second pipe clamp to be attached at inclinations of 0° , 30° , 45° , 60° , 75° , and 90° concerning the horizontal.

The pipe is the main part of the experimental apparatus, as it is inside it that the phenomenon to be studied occurs. To visualize the elongated bubble, the pipe must be manufactured in a transparent material, in addition to having a low cost. Therefore, the present apparatus uses acrylic tubes, as in the experiments by Bendiksen (1984) and van Hout *et al.* (2002). The tubes must be of sufficient length to allow full development of the Taylor bubble and measurement of its velocity. The apparatus was built for the use of two different pipe sizes, both 2 m long, one of 12.7 mm in internal diameter and another of 25.4 mm. These dimensions are similar to those used by Davies and Taylor (1950), which were enough for the complete development of the bubble.

The gas phase, which may be substituted by a less dense immiscible liquid, is released from the bottom of the acrylic tube and the bubble develops naturally as it moves upwards due to buoyancy forces. For gas retention, it was used a 0.1 m long tube of polyvinyl chloride (PVC) mounted between two PVC ball valves. The upper valve is the connector between the larger acrylic pipe section, where the stagnant liquid is held, and the smaller section of PVC pipe, where the gas volumes are initially held, being responsible for the gas release and initiation of the bubble ascension process. These valves can release or retain the flow of a system easily and immediately. Also, they are easy to install and inexpensive.

The following list of materials should allow the assembling of a similar experimental apparatus: 10 m of aluminum profiled bars; 20 corner joints, “T” joints, or internal bushings for the assembly of the aluminum structure; 45 screws, nuts, and washers (sizes and quantities may vary); two transparent acrylic tubes about 2 m long and with internal diameters of 12.7 mm and 25.4 mm; two PVC tubes 0.1 m long with nominal diameters of 12.7 mm and 25.4 mm, respectively; two ball valves of 12.7 mm inner diameter and another two with 25.4 mm internal diameter; one transparent acrylic sheet with the approximate dimensions of 560 mm by 560 mm and 5 mm thickness; two 90° pipe elbows with nominal diameters of 12.7 mm and 25.4 mm. Tools and consumables used during the assembly process are not on the list.

The experimental apparatus is currently installed in the Didactic Fluid Mechanics Laboratory (LabMF) of the Academic Department of Mechanics (DAMEC) from the Ponta Grossa campus of the Federal University of Technology—Paraná (UTFPR). To ease the carrying out of numerous measurements in sequence, making it quickly, accurately, and low in cost, the experimental apparatus developed in this project can be adapted in future works to use impedance sensors. This type of sensor is frequently used in the literature to detect the passage of elongated gas bubbles due to the different conductance characteristics of the gas and liquid mediums. An electronic prototyping platform must be programmed to collect the signals from the sensors and it must start and pause a timer related to the acquisition of these signals. This procedure indirectly measures the velocity of the elongated bubble through the time interval recorded by the stopwatch and the linear distance between the sensors. The electronic prototyping platform may also be programmed to allow automatic recording of the velocity and pipe inclination data for each measurement performed on the system. The design and simulation of this type of sensor are already being carried out for its future construction and subsequent installation in the experimental apparatus (Seifert and Lima, 2020a,b).

3.2 Determination of the bubble velocity

Due to time constraints, this work used video recording and processing to determine the ascension velocity of the elongated bubbles, similar to the work done by Vinhas (2015). Each test was recorded by a cell phone camera (1080p and 60 fps) and the bubble rise times were measured by analyzing the videos. A dark background was placed behind the pipe in the testing section to contrast the image of the bubbles and better visualize its passage. The video analysis was performed using the Shotcut application, which is a free multi-platform video editor. The average ascension velocities of the bubbles were determined as a function of the time intervals taken by them to travel the linear distance between two marks on the pipe, which was 0.5 m.

Water was used as the stagnant liquid to observe the rise of an elongated air bubble, their properties being evaluated at standard atmospheric temperature and pressure. Tests were carried out in the experimental apparatus using the transparent acrylic tube with a 25.4 mm inner diameter. Two tube inclinations were analyzed: vertical (90°) and inclined (45°). For each of these inclinations, 10 measurements were performed to determine average values and standard deviations for each of the two sets of data. The Froude numbers which correspond to the average velocities were also calculated according to Eq. (2). Fr is the dimensionless parameter directly related to the velocity of the elongated bubble, being presented by several works in the literature for comparison purposes. Experimental data obtained with the present tests were compared against experimental values from Gómez-Bueno (2010), which are shown in Tab. 1, and estimated values from correlation proposed by Bendiksen (1984), which is Eq. (1).

4. RESULTS AND DISCUSSION

Figures 3a and 3b show the section of bubble velocity measurement for the cases of vertical pipe and 45° inclined pipe, respectively. As shown in the figures, the images were taken at specific instants during the measurement procedure: 2.17 s after the bubble front passed the white band marking the pipe, in the vertical test, and 1.57 s in the case of inclined pipe. It is possible to observe noticeable differences in the bubble shape between the vertical and inclined cases, differences which were already described in several works in the literature (Maneri and Zuber, 1974; Couët and Strumolo, 1987; de Azevedo *et al.*, 2020; Cazarez-Candia and Benítez-Centeno, 2020; Massoud *et al.*, 2020). In addition, it is also possible to observe the formation of scattered bubbles at the elongated bubble tail in the vertical case. This phenomenon is due to the increase in turbulence caused by the film of descending liquid around the bubble (Wallis, 1969; Fernandes *et al.*, 1983; Taitel and Barnea, 1990; Fabre and Line, 1992; Bonizzi and Issa, 2003).

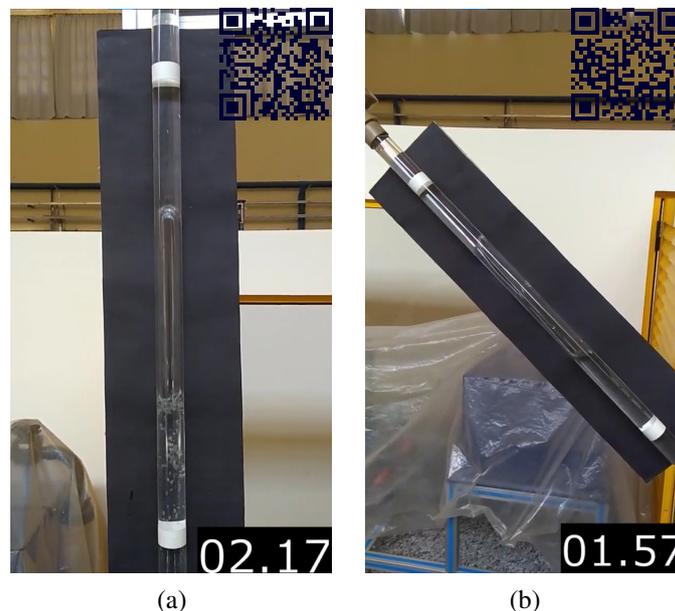


Figure 3. Tests carried out for the determination of the ascension velocity of an air elongated bubble in stagnant liquid water for vertical (a) and 45° inclined (b) pipes.

Table 3 shows the recorded rise time of the elongated air bubble and the respective average velocity values for each test carried out in this work. Tests from 1 to 10 correspond to the vertical case (90°), and tests from 11 to 20 correspond to the inclined case (45°).

Table 4 shows the average values and standard deviations of the velocities, as well as the Froude numbers calculated by Eq. (2) using such velocities. The vertical bubble velocity of 0.172 m/s is smaller than the elongated bubble velocity measured for the inclined case, which is 0.245 m/s. It is observed that the 45° inclined flow has a higher value of Fr than

Table 3. Experimental data gathered with the apparatus.

| Experiment (#) | Inclination, θ ($^{\circ}$) | Time, t (s) | Average velocity, V_T (m/s) |
|----------------|--------------------------------------|---------------|-------------------------------|
| 1 | 90 | 2.91 | 0.172 |
| 2 | | 2.91 | 0.172 |
| 3 | | 2.94 | 0.170 |
| 4 | | 2.91 | 0.172 |
| 5 | | 2.88 | 0.174 |
| 6 | | 2.94 | 0.170 |
| 7 | | 2.91 | 0.172 |
| 8 | | 2.91 | 0.172 |
| 9 | | 2.88 | 0.174 |
| 10 | | 2.91 | 0.172 |
| 11 | 45 | 2.04 | 0.245 |
| 12 | | 2.04 | 0.245 |
| 13 | | 2.04 | 0.245 |
| 14 | | 2.07 | 0.242 |
| 15 | | 2.04 | 0.245 |
| 16 | | 2.04 | 0.245 |
| 17 | | 2.01 | 0.249 |
| 18 | | 2.04 | 0.245 |
| 19 | | 2.04 | 0.245 |
| 20 | | 2.04 | 0.245 |

the vertical flow. This is due to changes in the balance between gravitational, surface tension, and friction forces as a result of inclination angle differences.

Table 4. Average values and standard deviations of the Taylor bubble velocities (V_T) and Froude numbers (Fr) obtained with the experimental apparatus.

| Inclination, θ ($^{\circ}$) | Average value of V_T (m/s) | Standard deviation of V_T (m/s) | Froude number, Fr |
|--------------------------------------|------------------------------|-----------------------------------|-------------------|
| 90 | 0.172 | 0.001 | 0.344 |
| 45 | 0.245 | 0.002 | 0.491 |

Table 5 presents a comparison between the Fr values obtained experimentally in this work with the experimental values obtained by Gómez-Bueno (2010) and the values estimated by the correlation proposed by Bendiksen (1984). The small deviations observed between experimental values are justified by the different methods for determining the bubble ascension velocity. Work by Gómez-Bueno (2010) was carried out using impedance probes, while this work depends on the quality of the recorded videos which may carry small parallax errors and variations in frame rate per second.

Table 5. Comparison of the Froude numbers (Fr) obtained experimentally in this work against values based on the literature.

| θ ($^{\circ}$) | Present work | Gómez-Bueno (2010) | | Bendiksen (1984) | |
|-------------------------|--------------|--------------------|------------------------|------------------|------------------------|
| | Fr | Fr | Relative deviation (%) | Fr | Relative deviation (%) |
| 90 | 0.344 | 0.345 | 0.23 | 0.345 | 0.23 |
| 45 | 0.491 | 0.479 | 2.51 | 0.627 | 21.72 |

Against the value from correlation proposed by Bendiksen (1984), which is Eq. (1), the experimental results for the vertical case (90°) showed negligible deviation. On the other hand, the experimental results for the inclined case (45°) showed a considerable deviation of 21.72%. The main reason for this discrepancy may be related to the fact that this correlation is based on experiments carried out solely for vertical (90°) and horizontal (0°) flows, which were then interpolated for inclined flows as a function of these limits and weighted by the inclination angle. Other works, such as those by Weber *et al.* (1986) and Gómez-Bueno (2010), also concluded that the correlation proposed by Bendiksen (1984) is discrepant about some experimental results, except for the limits.

5. CONCLUSIONS

To allow the visualization and determination of the velocity of an elongated gas bubble flowing in a stagnant liquid, the design and construction of an experimental apparatus were carried out satisfactorily in this work. With this apparatus, it was possible to observe the dynamics of the elongated bubble and some relevant effects, such as the shape of the elongated bubble and the formation of scattered bubbles in its tail. The experimental apparatus is currently installed in the Didactic Fluid Mechanics Laboratory (LabMF) of the Academic Department of Mechanics (DAMEC) from the Ponta Grossa campus of the Federal University of Technology—Paraná (UTFPR).

A simplified methodology for the construction and operation of a similar apparatus was presented. The apparatus is easy to build, inexpensive, simple to handle, and functional for various experimental studies of multiphase flows in pipes, adding to the analysis and understanding of phenomena related to gas-liquid flows.

Two sets of experiments were conducted to verify the operability of the apparatus for the inclinations of 45° and 90°. The results of these tests were compared against literature data from Gómez-Bueno (2010) and they agreed satisfactorily, with little deviations of 2.51% and 0.23% for inclined and vertical pipes, respectively. Deviations were up to 21.72% for the inclined case against values estimated from correlation by Bendiksen (1984), although it is known in the literature that this correlation is discrepant about some experimental results, except for the limits used for its proposition: horizontal and vertical pipes.

As possible points of improvement and themes for future works, it could be conducted additional experiments to verify the effects of pipe geometry, diameter, and inclination, as well as vary the properties of the fluids. This would provide relevant flow information and allow the development of correlations and model refinements. Additionally, impedance sensors or other instruments and techniques could improve the determination of the bubble velocity and other characteristics of these types of flow.

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