EXPERIMENTAL INVESTIGATION OF THE BUBBLE CHARACTERISTICS IN AN HORIZONTAL SLUG FLOW

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Abstract. *The shapes of elongated bubbles are investigated experimentally for air-water flow in a horizontal 0.0508m pipe at atmospheric conditions. Digital imaging and shadow techniques are used for visualization of the liquid-gas interface. A set of photo gates are used for synchronization of the acquisitions. This allowed us to adopt ensemble average procedures. Thereby, a set of quantitative data about the shape of front and tail parts of the bubble could be obtained. The range of flow rates covered regimes at the transition from elongated bubble to slug flow. The experimental findings are in agreement with the visual observations that are frequently reported in the literature. It is observed a linear relation between the radial location of the bubble and the Froude number. A shift towards the center of the pipe occurs as the Froude numbers increases and such a behavior reflects a competition between viscous and inertia effects.*

Keywords: *horizontal slug flow, optical technique, image processing.*

1. INTRODUCTION

The simultaneous flow of gas and liquid in ducts occurs frequently in several industrial applications. In particular, in the oil and gas industry it is common that the flow of gas and oil occur in the intermittent slug flow regime. Slug flow regime is characterized by the alternate flow of liquid slugs and gas bubbles. Significant capital losses can occur when the slug flow regime prevails due to the elevated pressure levels generated by the passage of liquid slugs that can, for safety reasons, require production shut down. Also, slug flows can induce severe transient loads on the structures with potentially catastrophic consequences.

The increasing demand for energy, observed during last decades, have motivated an intense investigation about the flow characteristics of slugs in order to increase safety and profit margins in operation of pipelines. The maps proposed by Baker (1954) and Mandhane (1974) were developed to provide a quick estimation of occurrence of each flow pattern. Such maps were based on visual observations under different velocities of liquid and gas. The map proposed by Mandhane, suggests that transition from regimes of elongated bubble to slug occurs when the gas velocity is higher than a threshold. However, there is not a straight definition of such a threshold, especially for the case of horizontal pipes (Sanchis et. al 2011). Also the characteristics of the flow are also not completely understood within transition. According to Fagundes Netto et. al. (1999), noticeable changes in the front and the tail of bubbles are observed close to the transition. They suggest using the angle of hydraulic jump at the rear of the bubble as a criterion to define this threshold.

According to Kadri et. al (2009), the flow pattern and the bubble characteristics may depend of many parameters involved in formation and development of the intermittent flow. This can turn the phenomenon sensitive to different test rigs and may result in a scattering of the experimental data found in the literature. In order to reduce influence of the slug development, it is typical to have test rigs longer than 300 pipe diameters (D). In some cases, even very long pipe lines are used. For instance, the work Kadri et. al (2009) describes an apparatus with approximately 2600D. Indeed, long lines reduce significantly the influence of transients but on the other hand they involve high costs, and their real need is somehow controversy. Therefore, it is important to assess test rigs to ensure that no influence of developing slugs is present in the measurements. In the work of Nydal et. al. (1992) the statistical data about the slugs were used to qualify their results.

The goal of the current work is to investigate the shape of the rear and the front of the bubbles in the transition from elongated bubble to slug flow using procedures based on image shadow techniques (Nogueira et al., 2003) combined with a high speed digital camera. This can provide more complete description of the bubble dynamics at transition, when compared to measurements from standard wire probes such as used in the work of Fagundes Netto et. al. (1999). Standard wire probes are able to measure only the total wetted area by assuming that liquid fills only the lower section of the tube. Recently, the development of high speed image acquisitions combined with techniques for image analysis added a new perspective to address the problem.

The work involves also the assessment of a test rig used in the experimental campaign. This task was done prior to the main tests on the bubble images in order to ensure that no influence of the test rig was present during measurements.

2. EXPERIMENTAL FACILITY

The experiments are performed in an horizontal pipe with internal diameter of 0.0508 m and length of approximately 23 m (L/D ≈ 450). An schematic of the apparatus is shown in figure 1. For a better quality of the images acquired during the measurements it was chosen tubes made of Fluorinated Ethylene Propylene (FEP). This material was previously used in the work of Hewitt et al. (1990) and it proved to reduce the light scattering at the wall due to matching of refractive indexes of FEP and water. Air and water are injected in the section with a "Y" junction located at the inlet of the test pipe. The water flows in a closed loop and a pump provides superficial liquid velocities up to 0.5 m/s. The flow rates of air and water are measured using calibrated turbines, CONTECH® model SVTG G19 and SVTL L19, with experimental uncertainty estimated in 1% and 0.5%, respectively. At the end of the line the mixture is separated in two vessels from where the water is returned to the pump inlet, while the air is removed from the loop by a vent.

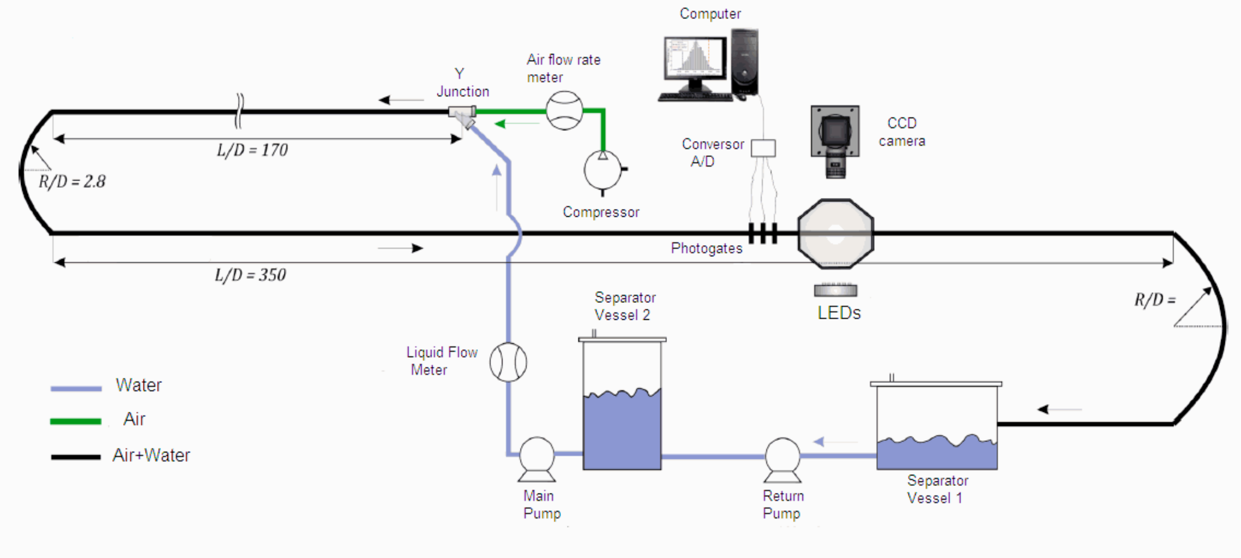


Figure 1. Schematic drawing of the experimental set-up.

The measurement section is located at a distance of approximately 400D from the inlet. It is composed of three infrared gate sensors, PASCO® model ME-9204B, a CCD camera (Motion Pro X3™), a panel of LEDs, and a visualization box. The infrared gates are used to measure bubble velocities and lengths. The velocity information extracted from the sensors is used in real time to provide a proper delay for synchronization of image acquisitions. Thereby, images of front and rear of the bubble are phase-locked with the bubble passage. Downstream from the sensors the FEP tube is encased with a visualization box filled with water in order to reduce refractive indexes mismatches. Opposite the camera, there is a panel of high power white LEDs which provided background illumination.

3. ASSESSMENT OF THE SET-UP

The assessment of the apparatus is important to ensure that no bias is introduced into results by the curves adapted to the rig in order to extend its length. A comparison of the results from present work against some benchmarks from the literature is used for validation of the set-up.

The phase velocities covered within this framework can be observed in the map of flow patterns proposed by Mandhane (see figure 2). It can be observed that the range of experiments covers a region of transition from elongated bubble to slug and it is located between cases of very long slugs, observed in the work of Kadri, and hydrodynamic slugs, studied by Nydal. Although this range of parameters covers a gap from the literature, it still enables a comparison with other works.

At first, it is analyzed the mean length of the liquid slugs. It is well know from the literature that liquid slugs under development present shorter lengths when compared to fully developed ones. The results depicted in figure 3 shows a transient behavior from long to short slugs for increasingly higher mixture velocities. For high mixture velocities experimental results asymptotically approaches the lengths observed by Nydal. On the lower end the values of mean lengths assume values towards the observations of Kadri. This behavior is in agreement with expectations and suggests well developed slugs.

The shedding frequency of the slugs is also an important parameter to characterize the intermittent flow. According to Nydal et. al. (1992), the frequency of non developed slugs displays a probability density distribution with two peaks, which can affect the mean frequency. In figure 4, the current findings are compared against an empirical correlation proposed in the work of Fossa et. al. 2003. That correlation is based on the Strouhal number of the flow. Fossa used experimental results from many works reported in the literature for the extraction of the coefficients of the correlation. In addition, experimental results found in Wang et al. (2007) for a pipe with approximately 2600D are also included in the figure as a second reference. Both works are considered as good benchmarks. The agreement with the current work is excellent, giving further support to the idea of developed slugs.

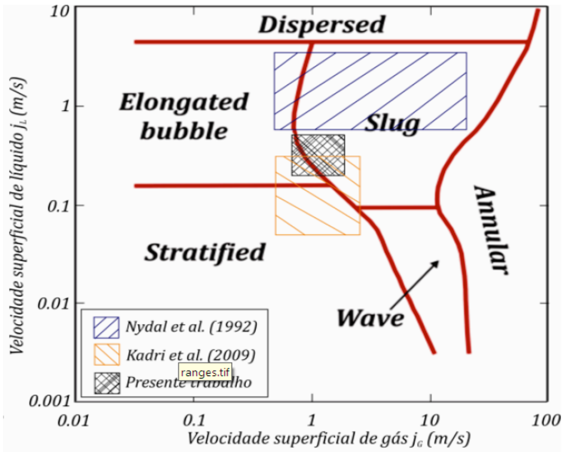


Figure 2: Map of flow patterns suggested by Mandhane and ranges covered by different work.

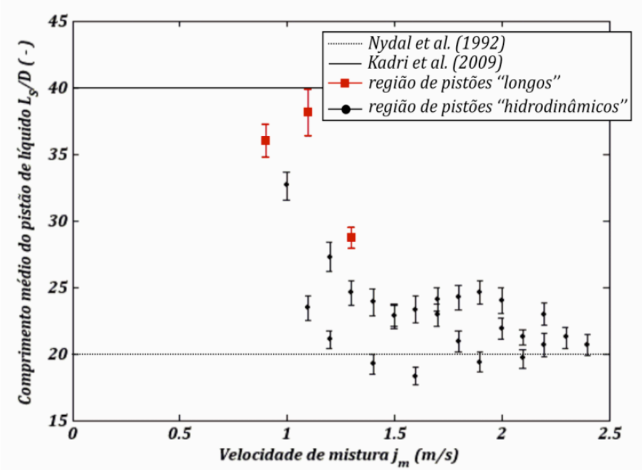


Figure 3: Lengths and comparison with very long (Kadri et al) and hydrodynamic slugs (Nydal et al.)

Finally, the translation velocities are checked against empirical correlations given in works of Bendiksen (1984) and Woods and Hanratty (1996), (see figure 5). Both correlations include terms related to the drift velocity. Again, results show a good agreement with the literature. Moreover, it is confirmed the importance of the drift velocity for low Froude numbers. The comparative analysis of the current measurements with data from the literature allows us to validate the test rig and to ensure that no bias is present in the flow. This enable the generalization of the results obtained with the optical techniques to cases of developed slugs.

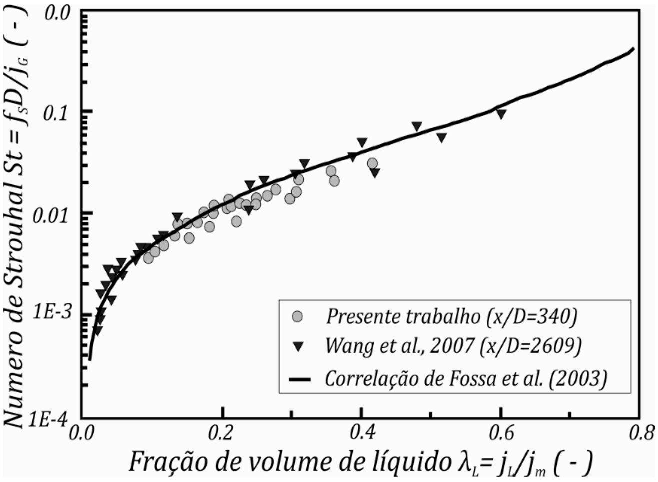


Figure 4: Non-dimensional shedding frequency of the slugs

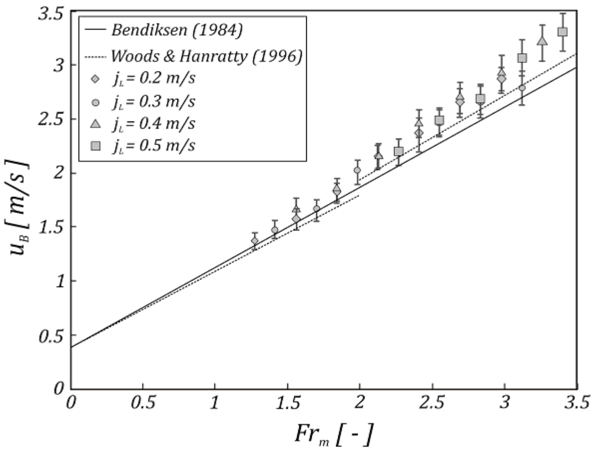


Figure 5:Velocity of the slugs

4. IMAGE PROCESSING

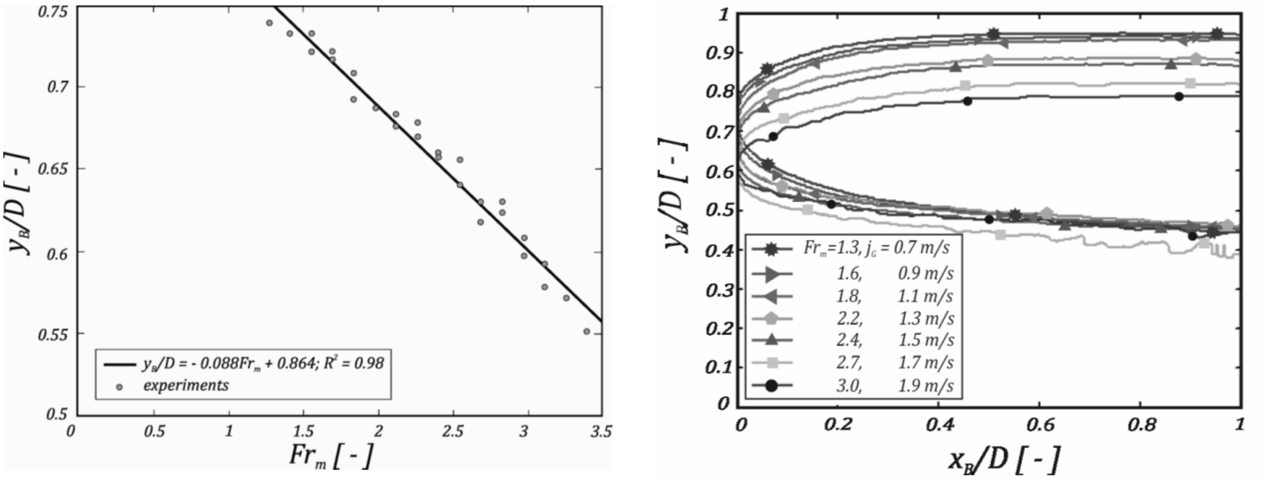
The shadow technique is used for identification of the bubble interface. The technique is an optical and non-intrusive method used to measure interfaces of two fluids with very different refraction indexes (Nogueira et al., 2003). It is based on the acquisition of images from the pipeline with a CCD camera. A strong and uniform background light is applied in the back of the pipe, so that light passing through line can be captured by the camera. Due to the difference of refraction indexes the light is attenuated in the region of the interface, enabling the observation of this region.

Prior to the acquisitions it is necessary to extract a reference image with a calibration target. Here, it was used a a semi-cylindrical target marked with an array of spaced dots. This target is introduced into the pipe filled with water.

After the adjustment of the camera focus to the plane of the target, the image correspondence from pixels to millimeters could be obtained. The phase locked trigger provided by the passage of bubbles through the photo gates is used to synchronize the image acquisitions. Thereby averaged images of the bubble front and tail could be extracted and analyzed.

5. BUBBLE SHAPES

It is reported in the works of Bendiksen (1984) and Woods and Hanratty (1996) that mean bubble nose velocity (u_B) is correlated with the mixture velocity (j_m) and the mixture Froude number (Fr_m). In the correlations there is a fraction of u_B which is accounted for the drift velocity (C_∞). However, the range where the drift plays a role is not yet clear. Woods and Hanratty (1996) suggested that C_∞ is related to the influence of inertia and gravity effects. Most of correlations proposed for the translational velocity are divided into discrete intervals, each of them containing different weights for the of the drift velocity. For instance, in the correlation given by Woods and Hanratty (1996) it is assumed that gravity dominates when the Froude is lower than 2, hence the contribution of C_∞ is maxima. For increasingly higher Froude numbers the effects of inertia become stronger and consequently the drift velocity loses its relevance. The competition between inertia and gravity is reflected on the location of the bubble nose. For increasingly influence of inertia effects, the bubble nose moves towards the center of the pipe and the relevance of the drift velocity tends to vanish. This can be inferred from the visual observations and the correlation for u_B reported in the work of Bendiksen (1984). The current results, shown in figure 6-(a), suggest a linear dependence of the mixture Froude number against the bubble nose position. The shapes of the bubble nose for different superficial velocities of gas (j_G) are shown in Fig. 6-(b), confirming the qualitative observations of Bendiksen. It is the first time that such behavior is so well described by an experimental technique. This can help to shed more light on the physics involved in the dynamics of slugs in pipe flows. Moreover, the results obtained can support the development of a unique correlation for the bubble velocity without need of many discrete intervals, which are useful for modeling the problem.



(a) (b)

Figure 6. (a) Location of bubble nose according to the mixture Froude number and (b) the changes of bubble nose shape with increasing gas superficial velocity and mixture Froude number.

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