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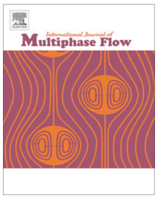

Bubble characterization in horizontal air–water intermittent flow

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ABSTRACT

Elongated bubbles were characterized experimentally for air–water flow in a horizontal pipe at nearly atmospheric conditions. The range of flow rates employed covered regimes at the transition from elongated bubble to slug. Ensemble-averaged digital image processing techniques were applied for detection of the liquid–gas interface with aid of a set of photo gates to synchronize bubble passage with image acquisition. Quantitative data of front and tail parts of the bubbles were analysed for different mixture velocities and the results confirmed visual observations frequently reported in the literature. Close to transition, a linear tendency of the bubble nose to move towards the pipe centerline position, for increasingly higher values of the Froude numbers, was observed and quantified. Bubble tail shapes were quantified and the hydraulic jumps were shown to be dependent of Froude number, while the liquid film thicknesses were governed by the liquid volume fraction. Changes on the bubbles characteristics are apparently linked to variations in the bubble velocities and seem to reflect a competition between viscous and inertia effects.

Introduction

The transport of gas and liquid simultaneously in horizontal pipelines is present in many engineering applications. During the last decades, an intense effort has been devoted to the study and modelling of the flow characteristics in order to increase safety and profit margins in pipeline operations (see Havre et al., 2000, for a review).

An important characteristic of two phase flows is the existence of a variety of flow regimes, depending, among other variables, on the flow rates of each phase. These regimes are defined based on the geometrical distribution of phases in the pipe cross section (see Mandhane et al., 1974; Taitel and Dukler, 1976). The present work is devoted to investigating the horizontal intermittent flow regime that is characterized by the passage of a succession of liquid slugs followed by elongated bubbles travelling above a thin liquid film. Intermittent flows can be subdivided into two sub-regimes: (i) plug or elongated bubble flow and (ii) slug flow. The plug flow regime is found at low flow rates. It is usually composed of liquid slugs with a low concentration of dispersed gas bubbles followed by elongated bubbles that move along the top of the pipe. According to Kadri et al. (2009), in this regime the liquid slugs can extend for more than 100 pipe diameters. The slug flow regime is characterized by the intermittent appearance of aerated liquid slugs, separated from one another by gas bubbles, travelling near the centre of the pipe. In this last regime, the frequency of flow intermittence is higher when compared to plug flow. Also, the typical lengths of liquid slugs and bubbles are much shorter when compared to plug flow.

In the oil and gas industry, significant capital losses can occur when long liquid slugs are present due to the elevated pressure levels generated by their passage that can, for safety reasons, require production shut down. Also, intermittent flows can induce severe transient loads on the structures with potentially catastrophic consequences. Although the slug and the plug flow regimes are both considered intermittent, the typical loads, lengths of slugs and bubbles and frequencies associated with each regime can be remarkably different (see Nydal et al., 1992; Hurlburt and Hanratty, 2002; Kadri et al., 2009). Thus, it is very important to distinguish between these regimes for a proper design of pipelines and damping devices, such as the slug catchers.

According to the flow maps of Mandhane et al. (1974), Taitel and Dukler (1976), Barnea (1987), Lin and Hanratty (1987a), among others, for a given liquid superficial velocity, the transition from plug to slug regime is expected to occur above a threshold of gas velocities. However, at transition, these two regimes are not clearly distinguishable, especially for the case of horizontal pipes. The absence of dispersed gas bubbles was suggested by Barnea et al. (1980), as a criterion to distinguish plug from slug regime. Lin and Hanratty (1987b), used pressure measurements to define the transition threshold. Based on a photographic study, Ruder

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et al. (1989), described plug flows as being an unaerated liquid slug followed by a gas bubble with characteristics similar to a "Benjamin bubble" (Benjamin, 1968). Later, this definition was extended by Ruder and Hanratty (1990), with the aid of pressure pulsation and void fraction measurements, and photographic visualization, to include qualitative characteristics of the front and rear part of the bubbles. They suggested that the transition from plug to slug regimes occurs when the tail of the bubble approximates the form of a single-stage hydraulic jump. Although they have measured different parameters of the flow, the major contribution to define plug flows was derived from qualitative analysis of a restricted number of images. Based on observations of different behaviours for the two regimes, Fagundes Netto et al. (1999) also suggested the use of the characteristic shapes of the front and rear of elongated bubbles as a means of accessing transition. They suggested the angle of the hydraulic jump at the rear of the bubble as a possible criterion to define this threshold.

The goal of the present study is to apply quantitative visualization techniques to investigate the shape of the rear and front parts of the bubbles in the transition from plug to slug regimes. This work was motivated by the recent availability of high frame rate cameras that, combined with techniques for image analysis, added new possibilities to address the problem. The combination of these techniques have been used to investigate two-phase flows in several works, such as (Polonsky et al., 1999; Nogueira et al., 2003; Ursenbacher, 2004; Shemer et al., 2007; Mayor et al., 2007; Guo et al., 2010). The non-intrusive nature of these techniques make them suitable for studying flow regimes sensitive to disturbances, such as plug, slug and annular flows. The main drawback of the technique is the requirement of optical access to the flow.

In the present work, procedures based on back-illuminated bubble images were combined with a high frame rate digital camera to enable the extraction of the bubble-slug interfaces at the transition from plug to slug flow. Back-illuminated bubble images have been widely used in the literature as a two-phase flow visualization technique (e.g. Bendiksen, 1984; Ruder and Hanratty, 1990). Also, the acquisition of images triggered by the passage of bubbles has been extensively applied to investigate bubble behaviour in two-phase pipe flow (e.g. Gopal and Jepson, 1998; Polonsky et al., 1999; van Hout et al., 2002; Nogueira et al., 2003; Ursenbacher, 2004; Mayor et al., 2007; Guo et al., 2010; Shemer et al., 2007). In the works of Polonsky et al. (1999), Pinto et al. (2001), Shemer et al. (2007), Mayor et al. (2007), the techniques for extraction of instantaneous and averaged bubble contours, as well as for quantitative measurements of the velocity field around the bubbles, were developed and validated.

An improvement introduced here is the estimation of individual bubble velocity in real time, what allows for the utilization of an automatic adaptive adjustment of time delays used to synchronize each bubble passage with image acquisitions. By this technique, bubbles travelling at different velocities could still be captured within the field of view of the camera. This feature can aid in the study of plug and slug flows in horizontal pipes, since in these flows instantaneous bubbles can display variations in their velocities under the same nominal flow conditions. By the procedure used in the present work, hundreds of bubble contours could be ensemble averaged with increased efficiency, providing useful statistical information about the bubble characteristics.

Experiments

The experiments were performed in a horizontal pipe with internal diameter (D) of 0.0508 m and length (L) of 23 m, yielding a length-to-diameter ratio of approximately 450. A schematic view of the apparatus is shown in Fig. 1. The test rig was built from Fluorinated Ethylene Propylene (FEP) pipes, in order to reduce optical distortions during image acquisition. This material was previously used in the work of Hewitt et al. (1990), and it proved to reduce light scattering at the wall due to the matching of its refractive index with that of water.

Air and water were injected into the section by a "Y" junction located at the inlet of the test pipe. A split plate was mounted inside the junction to reduce the level of flow fluctuations at the inlet. Water was pumped in closed loop at superficial liquid velocities up to 0.5 m/s. A centrifugal compressor provided air to the test section with velocities up to 40 m/s. The flow rates of air and water were measured using calibrated turbines, CONTECH® models SVTG G19 and SVTL L19, with experimental uncertainties estimated to be within 1% and 0.5%, respectively. At the end of the line, the air–water mixture was separated into two vessels from where the water was returned to the pump inlet, while the air was vented out of the laboratory space.

The measurement section was located at a distance of approximately 400 pipe diameters from the inlet. It was composed of three infrared gate sensors, PASCO® model ME-9204B, a CMOS high frame rate camera (Motion Pro X3TM with 1.3MPixels), an illuminating panel of LEDs, and a visualization box. As will be described shortly, the infrared gates had a dual role in the experiments. They were used to measure slug statistics, such as slug length, velocity and frequency, as well as to provide a trigger signal for the image acquisition system. Downstream of the photo gates, the FEP tube was encased in a visualization box filled with water in order to reduce refractive indexes mismatches. On the opposite side of the camera, the panel of high power white LEDs was installed to provide background illumination for image acquisition with proper contrast.

Measurement of bubble and slug statistics

The three infrared photo gate sensors mentioned before are presented in more detail in Fig. 2. They were employed to measure the bubble and slug statistics of interest, namely, bubble front and rear velocities, slug length and slug frequency. These parameters were estimated as suggested in the work of Polonsky et al. (1999). The three infrared gates were installed orthogonally to the pipe, and spaced 0.3 m from each other (Δd_{gates}). According to preliminary experiments, a sensible noise reduction in the signals from the photo gates was observed when the sensors were placed close to the centerline of the pipe. The reason for this behaviour is the high concentration of dispersed bubbles travelling close to the top of the pipe. However, for low Froude numbers the elongated bubbles also travel close to the top of the pipe. Therefore, the sensor is not sensitive to their passage when positioned at the centerline of the pipe. Thus, a good compromise between the detection of elongated bubbles and the noise reduction was found when the sensor was positioned at a height of 2/3 of the pipe diameter, as shown in Fig. 2.

The first two photo gates were used to measure the front and rear velocities of the bubbles, while a third gate provided a trigger signal to start a quartz based clock, properly adjusted according to measured front or rear velocity. The clock was used to output signals for synchronization for image acquisitions. For fast measurements of the bubble front and rear velocities the output signals of gates 1 and 2 were fed to an external XOR logic circuit, which produced a single pulse of finite duration. The circuit provided a high state logical level during the passage of the front or the rear of the bubble through photo gates 1 and 2. This pulse width could be quickly and accurately measured at a rate of 20 MHz, using a built-in function of a multifunction *D*/*A* board model AT-MIO-16X and Labview™ routines. The bubble front or rear velocity was then calculated as the ratio of the distance between the photo