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EFFECTS OF PIPE INCLINATION ON THE INTERNAL STRUCTURE OF THE LIQUID SLUG BODY

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ABSTRACT

In this work, the internal structure of the liquid slug body has been investigated at different pipe inclination angles, from horizontal to vertical. The structure of the liquid slug body section has been characterised by several parameters, namely, void fraction, void fraction distribution and bubble size distribution.

A wire mesh sensors (WMS) was used to take measurements in an inclinable facility. Air and water were employed as the working fluids. The pipe diameter is 67 mm. Liquid superficial velocities of 0.2 and 0.7 m/s have been used with different gas superficial velocities.

The results reveal that the void fraction distribution is strongly affected by the inclination angle. However, the inclination angle does not have such a strong effect on the bubble size distribution. In addition, a relationship between the void fraction and bubble size distribution in the liquid slug is observed.

INTRODUCTION

One of the most common flow patterns found in gas-liquid flows is the slug flow regime. It is commonly described in terms of the slug unit concept, as in Dukler and Hubbard [1]. In this concept, a slug unit is made up of two main alternating parts, namely the liquid slug body and the large bubble or gas pocket. The liquid slug body consists of continuous liquid with bubbles entrained within it, whereas the large bubble is surrounded by a thin film (vertical) or with a thicker layer underneath (inclined or horizontal). Traditionally the liquid slug body has only been considered as a continuous liquid section or a homogeneous bubbly flow, and most hydrodynamic models of pressure drop for slug have relied on this assumption. Not surprisingly, most of the time, the data available in the literature on inclined gas-liquid flows is limited to average values. For instance, the works of Mattar and Gregory [2], Nydal and Andreussi [3] and Hernandez-Perez and Azzopardi [4] have reported overall values of liquid holdup in the pipe obtained from time traces of cross sectional averaged liquid holdup. They also reported other parameters of the two-phase mixture, particularly for slug flow regime, such as structure frequency and flow pattern prediction from the probability density function of the time series of liquid holdup. However, in reality the phase distribution changes within a particular cross sectional plane as well as along the liquid slug. Furthermore, as reported by Hernandez-Perez and Azzopardi [4], pipe inclination angle will make a difference in the flow patterns observed in inclined flow. They observed that as the gas superficial velocity and inclination angle increase from the horizontal, the flow is characterised by a higher gas volume fraction, as a result of the increasing concentration of dispersed bubbles in the liquid slug body, but no description of the liquid slug body was achieved.

In reality the body of the liquid slug is rather complex, Mori and Miwa [5], and its structure can be affected by different parameters such as pipe diameter, fluid properties and pipe inclination. The behaviour of liquid slug will affect in turn other parameters such as pressure drop and the overall volume fraction occupied by the phases.

In general, the liquid slug body can be described by several parameters, such as velocity, frequency, and length of gas and liquid slugs, void fraction, void fraction distribution and bubble size distribution. In the literature nothing has been reported on the effect of pipe inclination on the structure of the liquid slug body (to the best of our knowledge). Most of the studies have been concerned with the hydrodynamic parameters, for instance Nicklin et al. [6] established a correlation for translational velocity of Taylor bubbles in moving liquid, while Van Hout et al. [7] measured the translational velocity of elongated bubbles in continuous slug flow. Later, a few studies have been presented on numerical simulation of Taylor bubble motion; usually they are limited by the sort of assumptions that need to be made, such as flow symmetry and stagnant liquid. For example Clarke and Issa [8] modelled the motion of a periodic train of Taylor bubbles in vertical flow by imposing cyclic conditions at the inlet and outlet of the slug unit based on the assumption that the flow pattern repeats itself over consecutive slug units. Taha and Cui [9] among others have highlighted the use of dimensionless groups in the study of Taylor bubbles along with the numerical approach.

More recent developments in instrumentation have allowed researchers to look further at the two-phase flow; Winterton and Munaweera [10] reported average bubble diameters in bubbly flow for different gas–liquid systems.

In this work, a study of the effect of pipe inclination on the liquid slug body is performed based on experimental data obtained at different pipe inclination angles. Particular emphasis is put bubble size distribution, determined with the use of advanced instrumentation known as wire mesh sensor (WMS). The main advantage of the wire mesh sensor over conventional flush-mounted capacitance and conductance probes is that it gives detailed information about phase distribution over the full cross sectional area of the pipe, and from there bubble size distributions can be obtained by proper data processing.

EXPERIMENTAL FACILITY

In this research, a systematic study of the behaviour of gas-liquid mixtures in inclined pipes has been carried out. An acrylic pipe with a 67 mm diameter was used. This relatively large pipe diameter, for which few data are available, has been utilized in support of the fact that as the flow demand in the multiphase systems has grown, so do pipeline sizes required. Stationary flow rates of air and water were used at room temperature and atmospheric pressure; in multiphase flow research it is common to use air-water as the two-phase mixture due to its availability, low cost and safety reasons. Figure 1 illustrates the experimental setup, which is similar to that used by Hernandez-Perez et al. [11].

Due to the electrical properties of the water and air, an instrument such as the conductivity wire mesh sensor is suitable for this work. The wire mesh sensor was specially design to fit the test pipe and located at a distance of 75 pipe diameters from the inlet section.

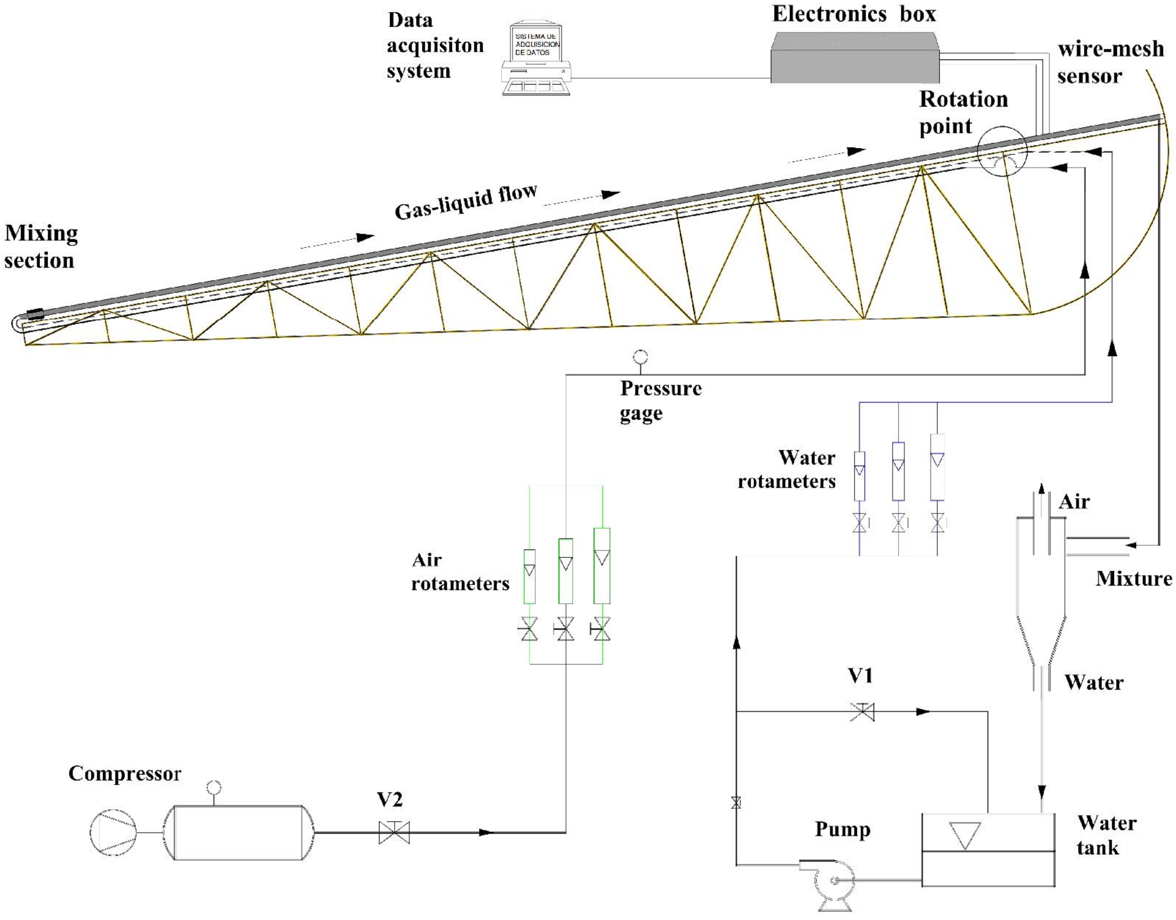

Figure 1 Experimental facility employed in this work

The sensor consists of two electrode grids with 24 electrodes each, placed at an axial distance of 1.5 mm. Its function is based on the measurement of the local instantaneous conductivity of the two-phase mixture. The conductivity is measured at the crossing points of the wires of the two grids. This results in a 24x24 sensitive points, which are equally distributed over the cross section (Figure 3), the wires have a diameter of 20 microns. For the conductivity measurement, one plane of electrode wires is used as transmitter, the other as receiver plane. A complete description of the wire-mesh sensor is given by Prasser at al. [12]. Before running the experiments, a calibration was undertaken. The data acquisition was performed at 1000 Hz and the data were taken for time intervals of 40s.

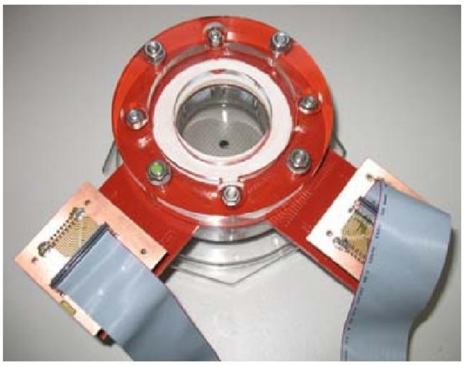

Figure 2 Wire mesh sensor (24x24 wires)

RESULTS AND DISCUSSION

Void fraction and void fraction distribution in the liquid slug body

Data for the void fraction in the liquid slug body are needed as a closure relationship in slug pressure drop models. The mean void fraction in the liquid slug body has been calculated from the PDF of the time series of cross sectional average void fraction, as indicated in figure 3.

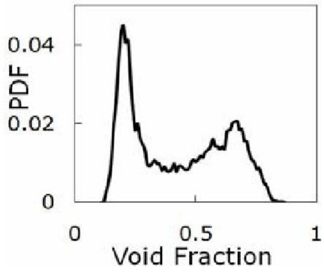

Figure 3 Probability Density Function of cross sectional average void fraction. The location of the peak in the low void fraction region represents the average void fraction in liquid slug body.

The void fraction in the liquid slug body for several inclination angles are plotted in figure 4. It can be observed that it increases with the inclination angle from the horizontal in such a way that, there seems to be a maximum between 60 degrees and the vertical position.

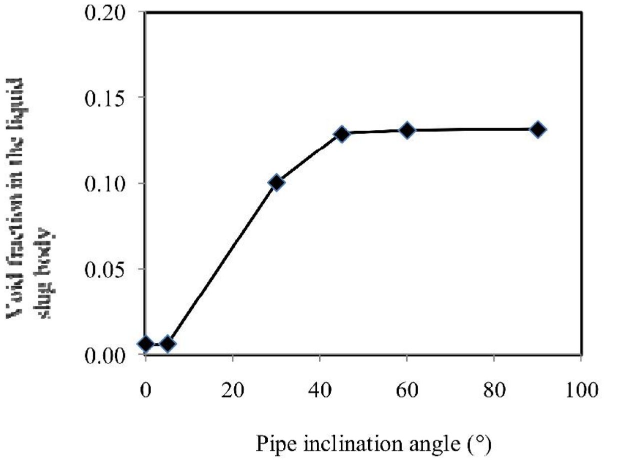

Figure 4 Average void fraction in the liquid slug body at different inclination angles, liquid superficial velocity 0.2 m/s and gas superficial velocity 0.94 m/s

The way in which the gas is distributed inside the liquid slug body is affected by the pipe inclination angle is shown in figure 5. The contours show a higher void fraction at the upper part of the cross sectional area, which is even higher for the horizontal case.

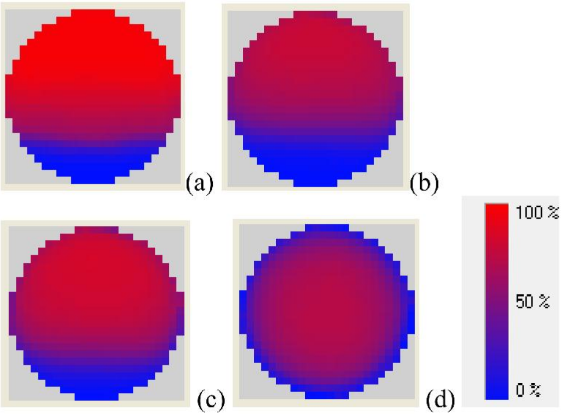

Figure 5 Contours of void fraction in the pipe cross sectional area at different inclination angles, liquid superficial velocity 0.2 m/s and gas superficial velocity 1.4 m/s. (a) 0 °, (b) 30 °, (c) 60 °, (d) 90 °.

Bubble size and bubble size distribution

The void fraction in the liquid slug described above is related to the bubble entrainment, which is enhanced by the action of the gravity component in the flow direction. Knowledge of the bubble size is important to characterise the internal structure of the liquid slug body. In a two-fluid model, the bubble size is one of the parameters required for estimating the interfacial transport of mass, momentum, and energy. The bubbles entrained are not necessarily distributed homogeneously and nor do they have the same size.

In order to determine the bubble size distribution, bubbles are identified and quantified as connected gas-filled regions by means of 3D image processing algorithms, and the bubble size is accounted for in terms of the volume equivalent bubble diameter. The details of the data processing technique are explained elsewhere [13]. The contribution of the bubbles in a bubble class (equivalent bubble diameter) is used to plot the bubble size distribution.

Examples of bubble size distributions for four different gas superficial velocities are presented in figure 6. Similar to the probability density function of cross sectional average void fraction, the distribution of the bubble shows two peaks in slug flow regime. This is in agreement with the profile of bubble size distribution in slug flow regime reported by Da Silva et al. [14]. For the lowest gas flow rate, the two peaks have a similar height. However, it can be observed that there is a gradual change in the shape of the curve as the gas superficial velocity increases, this happens in the height of the peaks, and the location of these peaks remains fairly constant, with a slight displacement of the second peak to the right. This is expected, since bubble coalescence will take place, and indicates that as the gas superficial velocity increases, the bigger bubbles have major contribution to the void fraction in the liquid slug body.

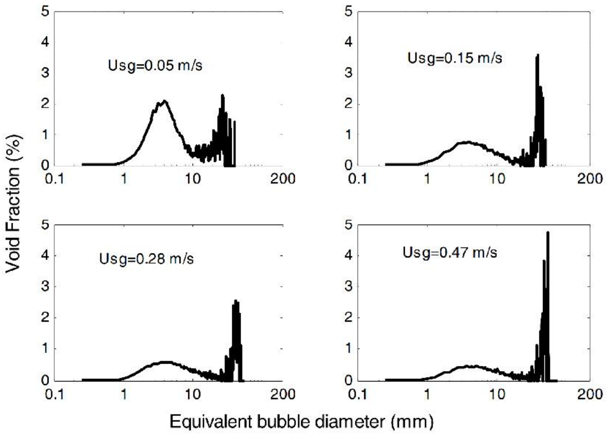

Figure 6 Bubble size distribution at different gas superficial velocities (Usg), liquid superficial velocity 0.7 m/s and vertical up flow

In figure 7 the effect of the pipe inclination angle on the bubble size distribution is presented. The cases presented in figure 8 were selected for a particular flow condition of liquid superficial velocity 0.7 m/s and gas superficial velocity 1.4 m/s. Different bubble size distributions can be observed as the pipe inclination angle changes from horizontal to vertical. This is related to the change in flow pattern. However, in general a bimodal distribution seems to dominate, particularly for steep inclinations. A remarkable peak can be observed at 50 mm in all cases. The first peak in the bubble size distribution, which occurs at about 5 mm, corresponds to the liquid slug body. From this, it can be recognised that in the liquid slug body, the bubbles sizes are lower than 67 mm, which is the pipe diameter.

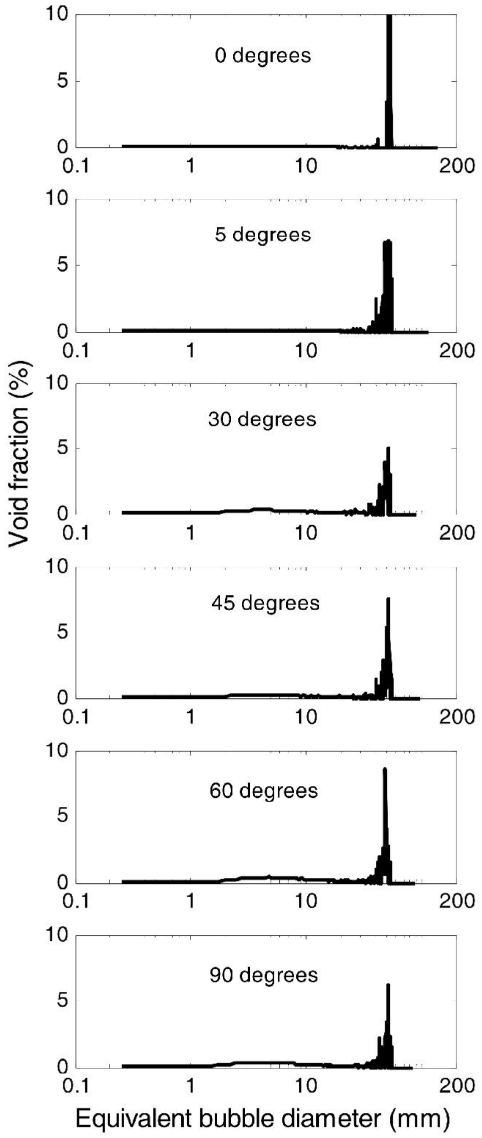

Figure 7 Bubble size distribution at different inclination angles, liquid superficial velocity 0.7 m/s and gas superficial velocity 1.4 m/s

CONCLUSION

A study of the effect of the change of pipe inclination on the structure of the liquid slug body has been carried out with the use of advanced instrumentation, and the following conclusions can be drawn:

The void fraction distribution is strongly affected by the inclination angle.

However, the inclination angle does not have such a strong effect on the bubble size distribution.

A relationship between the void fraction and bubble size distribution in the liquid slug is observed. This is observed by means of a bimodal bubble size distribution curve.

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