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BRIEF COMMUNICATION

AXIAL DEVELOPMENT OF VOID FRACTION PROFILES IN VERTICAL TWO-PHASE FLOW

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1. INTRODUCTION

Recent developments in the study of two-phase flow phenomena have yielded a better understanding of the physical mechanisms involved and the formulation of more reliable theoretical models. This, in turn, has raised new requirements regarding more detailed experimental information about the flow structures upon which theoretical models can be constructed.

There are numerous experimental studies of void fraction distributions for different geometries reported in the literature (Chexal *et al.* 1991). The radial void fraction distribution in pipes is a topic which currently attracts considerable interest among researchers (St Pierre & Bankoff 1967; Lee 1986; Serizawa & Kataoka 1987). Moreover, a clear knowledge of the spatio-temporal behaviour of the void fraction is important for the understanding of flow pattern structures and transitions. The most intriguing transition is that from a bubbly to a slug flow pattern. Among the numerous studies that have dealt with the topic, one worthy of mention is the systematic experimental program carried out by Bouré and co-workers (Mercadier 1981; Micaelli 1982; Matuszkiewicz *et al.* 1987), wherein void fraction waves in bubbly flows were measured. They conjectured that the bubbly-to-slug flow pattern transition was due to instability of the kinematic waves. This was supported recently by further studies on this issue (Biesheuvel & Gorissen 1990; Kytömaa & Brennen 1991; Lahey *et al.* 1992).

Generally, studies of two-phase flows in pipes and channels are performed over fully-developed flows in order to avoid the interference of entrance effects. Consequently, very little is known about the entrance region—although there is some evidence that the void structure development plays an important role in pattern transitions (Lahey *et al.* 1992).

The subject of the present study is the relationship between the flow pattern transition and flow development. The entrance region of a bubble column was investigated by measuring the axial void fraction distribution for different operating conditions. In addition, visual observations of the flow structure were performed and correlated with the void fraction data trends.

2. EXPERIMENTAL SETUP AND METHOD

A schematic diagram of the experimental rig is shown in figure 1. The rig consists basically of a vertical transparent test section, filled with an initial height of 102 cm of bi-distilled water (conductivity $\simeq 10\mu S/cm$), where an upward oxygen flow is introduced from the bottom. The test section was made out of a 2.3 cm i.d. cylindrical lucite tube, 200 cm in length. For this diameter the bubbly flow pattern is unstable for every gas flow rate according to the currently accepted criteria (Taitel *et al.* 1980). The bottom of the tube was flanged to fit over a bronze porous plate (grain size 5 μm), through which the gas was injected into the test section. A thermal-type transducer with a sensitivity and accuracy of 0.08 and 0.4 cm/s, respectively, was used for

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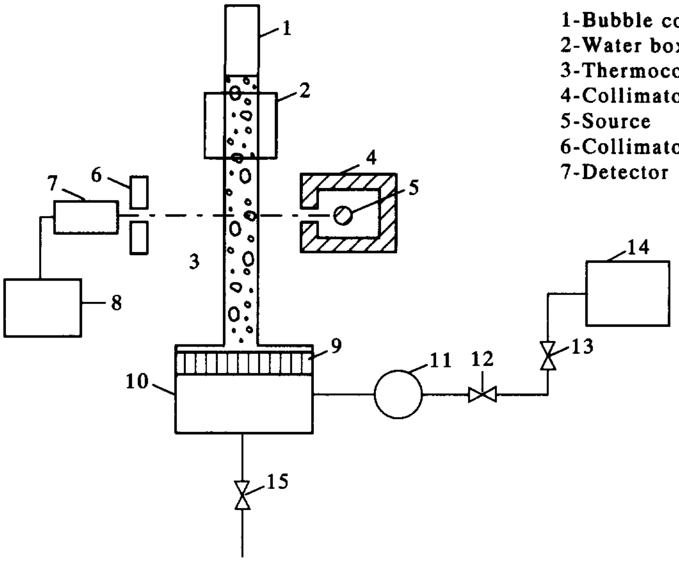

Figure 1. Schematic diagram of the experimental facility.

measurement of the gas flow rate. This kind of transducer, which senses the skewness caused by the gas flow rate in a symmetrically heated tube, is suitable because it is independent of the gas pressure.

A standard γ-ray attenuation technique was utilized for the measurement of the void fraction in the test section. For this purpose a 100 mCi, ^{137}Cs source was used in conjunction with a NaI(Tl) detector. Chordal void fraction measurements were obtained which do not differ significantly from the cross-sectional-averaged void fraction for the present conditions. The static error in the void fraction (i.e. the one due to the statistical nature of the γ-ray technique) had a typical value of 1.5%, and a maximum of 2.5% at very low void fractions. It has been shown (Jones 1973) that an additional error, namely the dynamic error, is introduced when an intermittent flow pattern, such as slug flow, is present. Assuming that the void fraction oscillates between a minimum and a maximum value (Qazi *et al.* 1992) this error can be calculated. In our case the dynamic error had a maximum possible value of 2.5%.

The void fraction measurements were carried out in successive runs, increasing and decreasing the gas flow rate up to a maximum value of 110 cm^3/s (corresponding to a volumetric flux of 27 cm/s).

Visual and photographic observation also played an important role in this experimental study. To diminish the optical distortion caused by the curvature of the test section, a movable transparent box, full of water, with flat faces was placed over the test section.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Local void fraction

Figure 2 shows typical plots of the void fraction as a function of the volumetric flux measured at different distances from the gas injection point. For fully-developed flow (observed at $Z/D > 22$) the void fraction increases smoothly with the volumetric flux, as can be seen in figure 2(A). At intermediate positions [figure 2(B)], the void fraction first increases somewhat rapidly, but at a volumetric flux of about 5 cm/s its rate of increase decreases significantly.

Close to the injection point [figure 2(C)], as the gas flow rate increases, the void fraction increases up to a maximum value at about $j_G = 14$ cm/s. A further increase in the gas flow rate leads to a gradual decrease of the void fraction. Interestingly, no such peak is observed during a decrease in the gas flow rate: the void fraction evolution follows a different path which merges with the flow-increasing path at a volumetric flux of about 5 cm/s. To test the stability of this hysteresis, the volumetric flux was maintained constant at 14 cm/s (where the peak in the void fraction was observed) for 2.5 h, while increasing the volumetric flux and while decreasing it. No significant change was observed, showing a rather robust stability of both steady states.

3.2. *Axial void fraction distribution*

The void fraction variations along the axis of the test section are shown in figure 3 for different values of the gas volumetric flux. Large deviations from the asymptotic values are observed for the non-developed conditions. For the larger volumetric fluxes, the void fraction has a high value near the injection point, which decreases to a minimum at around 30 cm from the entrance. The void fraction then recovers progressively to an asymptotic value. The fully-developed void fraction values [figure 2(A)] agree with the void fractions obtained from the well known Zuber–Findlay correlation (Zuber & Findlay 1965).

From figure 3, it can be seen that the flow can be considered fully-developed at about 50 cm from the injection point, corresponding to $Z/D = 22$.

3.3. *Flow structure visualization*

Visual and photographic observations of the bubbly-to-slug flow pattern transition were performed. The observations showed that the bubbles do not coalesce progressively to form bullet-shaped bubbles. Bubbles were seen to group in clusters, which become more dense along the axis of the test section and at some location the simultaneous coalescence of many small bubbles produces Taylor–Dimitrescu bubbles. The position at which this occurred was measured for different volumetric fluxes and is shown in figure 4. The plot is the result of different observations and, with an estimated error of 4 cm, it shows clearly a hysteresis loop. This effect could be a consequence of pressure fluctuations introduced by the intermittent flow pattern which is known to occur in vertical two-phase flows (Tutu 1984). Once plugs are formed they produce a pressure oscillation which promotes the production of more plugs.

It has been pointed out already that the void fraction presents a minimum at a certain position (figure 3). Suggestively, the location of the minimum corresponds approximately to the formation of the bullet-shaped bubbles. From these observations, the variation of the void fraction along the

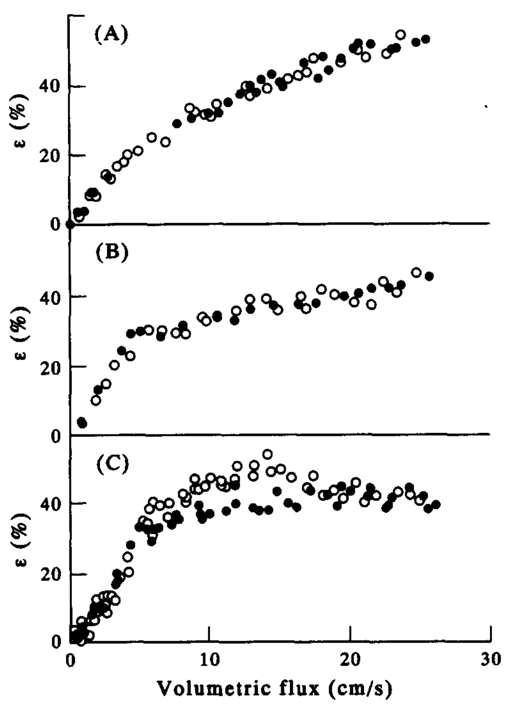

Figure 2. Void fraction vs volumetric flux measured at different distances from the injection point: (A) 49 cm, (B) 13 cm and (C) 6 cm. Open and solid symbols represent increasing and decreasing volumetric flux, respectively.

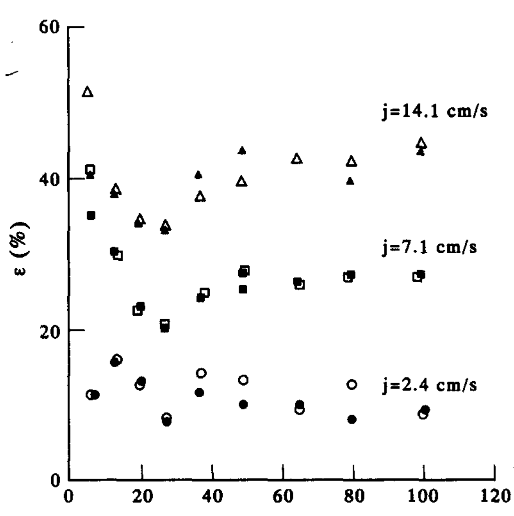

Figure 3. Void fraction variations with axial position for different volumetric fluxes. Open and solid symbols represent increasing and decreasing volumetric flux, respectively.

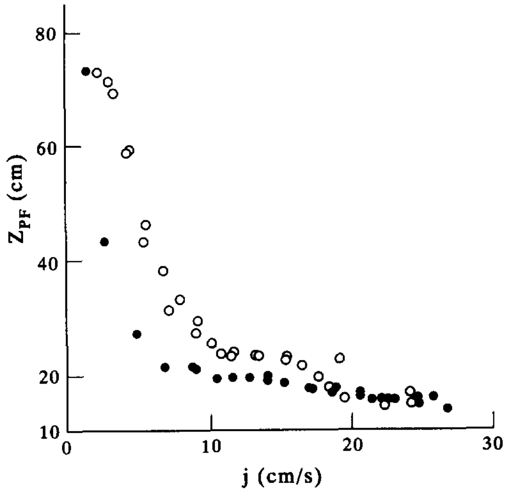

Figure 4. Location of plug formation vs volumetric flux. Open and solid symbols represent increasing and decreasing flux, respectively.

flow direction could be explained. The formation of clusters in the first part of the tube leads to higher gas velocities (Bilicki & Kestin 1987), which in turn causes a decrease in the void fraction. The lower velocities of the plugs (Nicklin *et al.* 1962; Fabre & Liné 1992) are responsible for the recovery of void fraction observed downstream.

4. CONCLUSIONS

A systematic experimental study was performed in order to determine the axial void fraction distributions in a bubble column. The development of the flow pattern was investigated for different operating conditions. Near the injection point a void fraction peak is observed when the gas flow rate is increased. For decreasing injection rates no such behaviour is observed, resulting in a hysteresis phenomenon. At intermediate positions no hysteresis is observed, but the curve still has a change of slope. Far from the injection point smooth curves are obtained.

This hysteresis loop has been observed before (Wallis 1969), but only with low-quality water and in overall void fraction measurements. The results presented here indicate that the hysteresis always exists but it is restricted to the entrance region of the tube. Impure water has a lower bubble coalescence rate and, thus, the transition zone is longer and observable from overall void fraction measurements.

Development lengths of about 20 diameters were measured and with little influence of the gas volumetric flux. Finally, it was observed that the mean volume of the bubbles does not increase progressively to form Taylor–Dimitrescu bubbles. In the first part of the tube the bubbles tend to group together in clusters. These clusters become more dense, with tens of bubbles, which suddenly coalesce leading to Taylor–Dimitrescu bubble formation.

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