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VOID FRACTION MEASUREMENTS IN VERTICAL SLUG FLOW: APPLICATIONS TO SLUG CHARACTERISTICS AND TRANSITION

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Abstract—A conductance probe is used to detect the instantaneous void fraction at the centerline of a vertical tube in upward gas–liquid flow for a wide range of gas flow rates, so that various flow patterns and the transitions between them could be studied. The information was digitized and recorded for further processing, which included short-time-averaging and histograms. The results obtained were used for flow pattern recognition and for the estimation of the liquid slug holdup and its length. Certain conclusions regarding the existing two-phase flow models were drawn.

Key Words: slug flow, void fraction, flow patterns

1. INTRODUCTION

Vertical two-phase flow is usually classified into four basic flow regimes: bubbly, slug, churn and annular flows. The slug flow occurs over a wide range of gas and liquid flow rates and is often encountered in important industrial processes.

Mechanistic models for the hydrodynamics of slug flow usually require input data on the void fraction of the liquid slug in order to initiate the calculations (Dukler & Hubbard 1975; Gregory *et al.* 1978). In addition, the voidage within the liquid slug plays a major role in theoretical models describing the transition from bubbly to slug flow (Taitel *et al.* 1980) and then to the churn flow regime (Brauner & Barnea 1986). However, relatively few works were published on the experimental results dealing with the voidage within the liquid slug. Dukler & Hubbard (1975) measured the gas holdup in horizontal liquid slugs by using an impact probe system. This method proved to be difficult in realization and did not provide reasonable repeatability of the results. Gregory *et al.* (1978) obtained experimental values of the gas holdup in liquid slugs with a capacitance-type probe. They have proposed a frequently used simple empirical correlation. Fernandes (1981) measured the void fraction of the liquid slug in air–water vertical flow by employing quick-closing valves. He found that in a 5 cm dia pipe the voidage within the liquid slug is essentially independent of both the gas and the liquid flow rates and its average value equals 27.5%.

Additional experimental techniques for the measurements of void fractions were used and reported. Local void fractions or interface passage frequencies were obtained by microthermocouples, conductance probes, hot-film anemometry or fiber optic probes. Information regarding the cross-sectional averaged void fraction was extracted by photon attenuation techniques and by conductance measurements. An excellent review of the earlier works which used the abovementioned techniques is given by Jones & Delhaye (1976). The instantaneous fluctuations of the local and spatially averaged void fractions were used by several investigators to construct flow pattern identificators (Jones & Zuber 1975; Barnea *et al.* 1980; van der Welle 1985; Annunziato & Girardi 1987; Sekoguchi *et al.* 1987; Matuszkiewicz *et al.* 1987).

The purpose of the present investigation is to develop a reliable and simple method for the estimation of the slug length, the average holdup within the liquid slug and the voidage in the near wake of the Taylor bubble. Tools for quantitative identification of the transition from bubbly to slug flow and from slug to churn flow are suggested. The results of these measurements are employed in order to check the validity of phenomenological models.

2. EXPERIMENTAL FACILITY AND PROCEDURE

Experiments were carried out in a vertical air–water system using a Plexiglas pipe, 10 m long with a 5 cm i.d. Air and water were supplied separately and the appropriate flow rates were controlled by rotameters. A detailed description of the experimental facility is given in Shoham (1982). The local instantaneous void fraction was detected by measuring the electrical conductance between a tip probe and a flat large electrode, as a function of time. The probe consisted of Teflon-coated 0.2 mm dia stainless steel wire, which was accurately cut under a microscope at the tip. The probe has sufficient mechanical stiffness, while having a sufficiently small measuring area to provide adequate spatial resolution for the flow conditions examined in the present investigation. Moreover, the use of a relatively thick wire allow us to reduce substantially the total size of the probe, which was about 0.3 mm, as compared to the glass-covered probes which exceed 1 mm in the outer diameter. As was shown recently (Fearn 1988), the introduction of wires exceeding about 0.3 mm dia can cause a significant effect on the bubble motion in the pipe. The tip electrode was located at the centerline of the pipe at a distance of 6 m from the entrance. The second electrode of the d.c. circuit has an area which is by orders of magnitude larger than that of the tip electrode and was glued to the pipe wall in order to eliminate disturbances to the flow. The probe output during the experiments was also monitored by a scope. Due to the low voltages employed, usually < 2 V, a sufficiently stable signal could be obtained. The probe was replaced when the output signal became unstable, due to impurities that stick to the probe.

The probe output was sampled continuously by a computer using a 12-bit A/D converter. The sampling rate was usually 6 kHz, while a rate of 8 kHz was used at higher flow rates. This sampling frequency was quite adequate for the purpose of the present investigation. All the information digitized by the computer was recorded on a magnetic tape for further processing. The total duration of the continuous sampling for any given experimental conditions varied from 10 to about 30 min. For each set of experimental conditions, the total number of data points acquired exceeded 10^6. Due to the finite response time of the probe, voltages which differed from the extreme values, corresponding to the continuous presence of either gas or liquid phases in the vicinity of the tip electrode, are obtained [figure 1(a)]. In order to overcome this difficulty, the signal processing in the present investigation was somewhat different from the usually employed TTL hardware (e.g. van der Welle 1985). Software which used adjustable thresholds was employed in order to obtain the binary signal from the raw data [figure 1(b)]. These thresholds account not only for the absolute values of the instantaneous voltage, but also for the time derivative. The transition between the

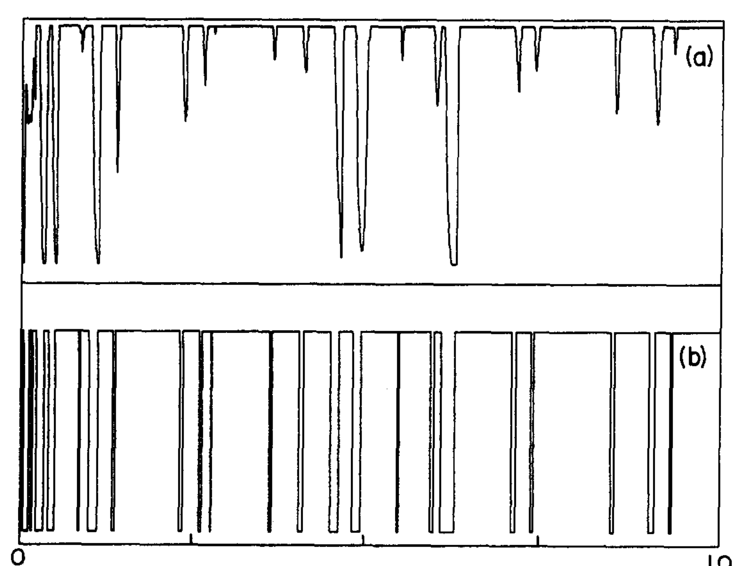

Figure 1. (a) The tip probe output; (b) the computer-processed binary signal. Bubbly flow ($U_{GS} = 0.10$ m/s).

gas and the liquid phases was determined by comparing the instantaneous slopes of the probe voltage with the selected thresholds. The validity of the procedure was checked by comparing the raw signal with its binary counterpart on the screen.

3. RESULTS AND DISCUSSION

The experiments were carried out at a constant velocity, $U_{LS} = 0.01$ m/s, and at a wide range of air flow rates, which covered void fractions from 0.1 to 0.8 and thus included bubbly, slug and churn flow patterns. The raw signals obtained for the various patterns were processed to give binary signals [figures 1(a,b)] which represent the instantaneous void fraction at the centerline of the pipe $\epsilon_i(t)$.

3.1. Short-time-averaged void fraction

The resulting binary signals were further processed to extract meaningful statistical information. The time-averaged local void fraction was calculated first. The fast sampling rate accepted in the experiments made it possible to perform this averaging over relatively short time "windows", so that the variance of the resulting short-time-averaged void fraction with time could be studied. The width of the "windows" was adjusted in each case so that it was long enough to give statistically meaningful information, and on the other hand, short enough to allow the possibility of detecting the intermittency of slug and churn flow regimes. The selected length of the "window" corresponds to a passage of a column of length equal to twice the pipe diameter, $2D$, at the characteristic translation velocity of the Taylor bubbles. The value of $2D$ is assumed to be the minimum length of a Taylor bubble and hence serves as a criterion to distinguish between the dispersed and the elongated bubbles. In the bubble flow regime this short-time-averaged void fraction ϵ_{2D} was expected to fluctuate around its mean value. In the slug flow regime, this kind of data processing enables one to distinguish between the large Taylor bubbles, where ϵ_{2D} obviously attains the value of unity, and the body of the liquid slugs, where the void fraction fluctuates around its mean value. The variation of ϵ_{2D} with time could thus serve as one of the possible detectors of the flow pattern.

Figures 2 (a–f) show the short-time-averaged ϵ_{2D} vs time for a constant liquid flow rate and for various gas flow rates. In each case the data shown represents 200 averaging windows, thus corresponding to a passage of a column which is $400D$ long. The consecutive figures demonstrate the gradual transition from the bubbly flow to slug and churn flow regimes with increasing gas flow rates. Figure 2(a) is a typical example of the bubbly flow pattern, with fluctuating short-time-averaged void fraction. At higher gas flow rates, the general pattern remains the same, but the mean value gradually increases. Eventually a transition to the slug flow regime occurs. Figure 2(b) represents the bubbly flow regime for the highest possible gas flow rate (superficial velocity $U_{GS} \simeq 10$ cm/s), on the verge of the transition to slug flow. Note that the average void fraction in this case is 24%, in good agreement with the 25% value which is the criterion suggested by Taitel *et al.* (1980) for the bubbly–slug transition.

At higher gas flow rates, the slug flow regime is observed. Representative patterns of the slug flow at progressive values of U_{GS} are shown in figures 2(c–e). In all cases the typical structure of the intermittent flow is observed. Taylor bubbles with a local void fraction equal to unity, separated by aerated liquid bridges, can be clearly distinguished in this presentation. The adopted data processing allows one to estimate the average void fraction within the liquid slugs. Moreover, it makes it possible to estimate the dependence of the ensemble-averaged void fraction as a function of the distance from the Taylor bubble. The well-defined pattern of aerated bridges and Taylor bubbles disappears when the gas flow rate is further increased [figure 2(e)] and the transition to the churn flow regime occurs [figure 2(f)]. The plot of the short-time-averaged void fraction ϵ_{2D} vs time seems to be quite a practical tool for flow pattern identification, since it is directly related to the typical structure for each flow pattern and thus makes it possible to define boundaries between them.

3.2. Histograms representing the bubble size distribution

The binary signal allows one also to obtain information regarding the bubble size distribution in the two-phase flow. It was assumed in this work that the chord length detected by the probe

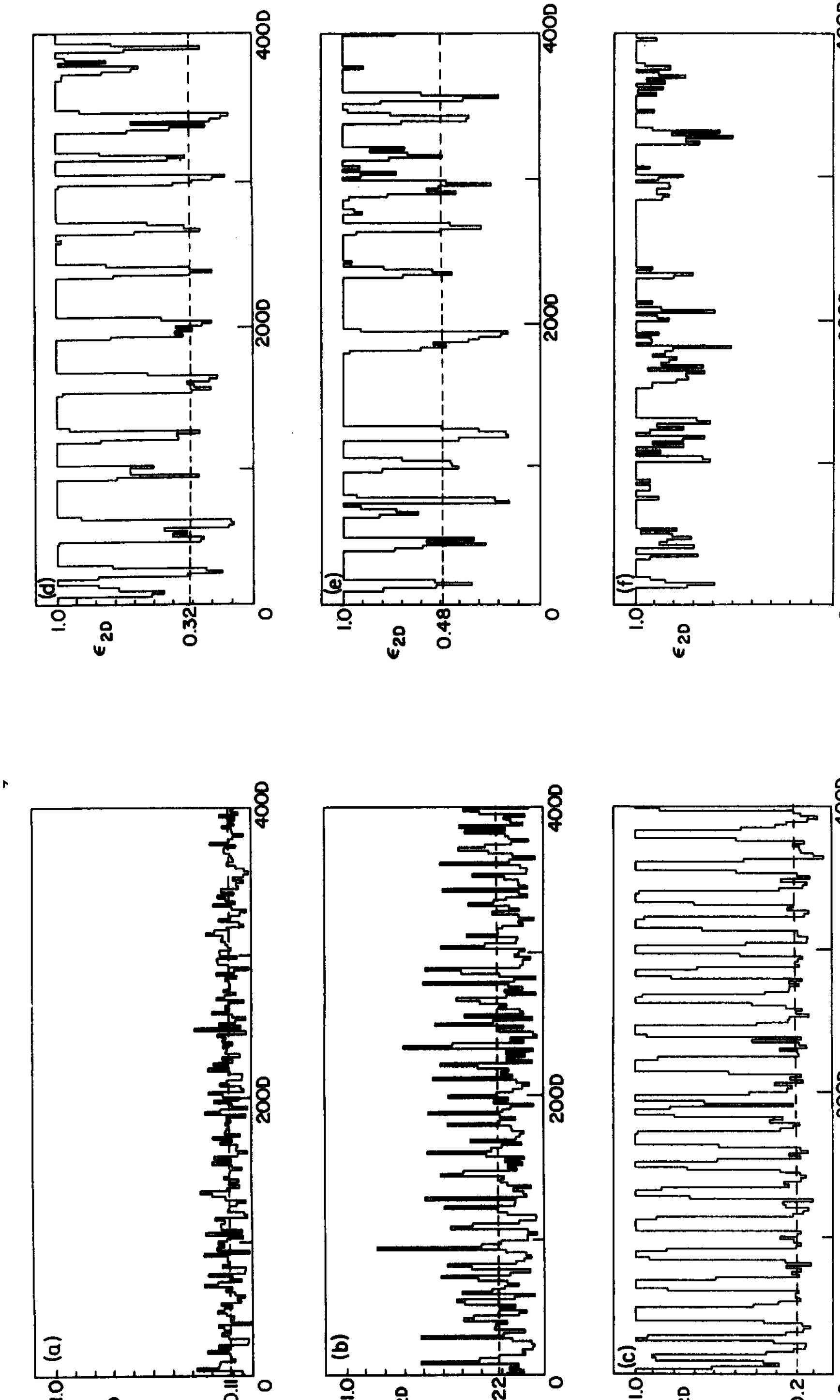

Figure 2. Time variation of the short-time-averaged void fraction ϵ_{2D}: (a) $U_{GS} = 0.03$ m/s; (b) $U_{GS} = 0.10$ m/s; (c) $U_{GS} = 0.25$ m/s; (d) $U_{GS} = 1.0$ m/s; (e) $U_{GS} = 1.6$ m/s; (f) $U_{GS} = 6.0$ m/s. - - - Denotes the mean void fraction within the liquid slug.

represents the characteristic length-scale of the bubbles. Herringe & Davis (1976) and van der Welle (1985) have shown that in the case of spherical bubbles, this length-scale is quite close to the bubble diameter. For elongated bubbles, the detected chord length obviously represents the length of the bubble in the axial direction. Since the main goal of the present investigation is to use the measured characteristic length-scale of the bubbles in order to discriminate between the elongated Taylor bubbles and the dispersed bubbles within the liquid slug, the exact shape of the dispersed bubbles is essentially irrelevant.

In our case, an effort was made to cover various flow patterns and thus to detect bubbles of sizes that differ by orders of magnitude. It was decided that a convenient way to represent the recorded distributions is by histograms, which can also serve as an alternative flow pattern identificator. In order to construct these histograms, the duration of the voids obtained from the binary signal were translated into the corresponding bubble size using the translation velocity of the Taylor bubbles. Note that the translation velocity of the small dispersed bubbles in the 5 cm dia air–water pipe flow is almost identical to that of the Taylor bubbles (Taitel *et al.* 1980). The translational velocity of the Taylor bubbles was calculated using the Nicklin *et al.* (1962) correlation, which was also verified experimentally in the present investigation. In this way the bubble size distributions obtained at various flow rates could be compared. The whole range of bubble sizes was divided into 50 bins, where the ratio between the widths of two consecutive bins was kept constant, so that in the logarithmic presentation equal bin sizes are obtained.

The resulting histograms representing various flow patterns are given in figures 3(a–e). The bubbly flow regime is characterized by a single maximum in the histogram and relatively narrow range of bubble sizes, covering a single decade [figure 3(a)]. At a higher gas flow rate [figure 3(b)], bubbly flow on the verge of transition to the slug regime is shown. In this figure sporadic appearance of longer bubbles, up to the scale approaching the pipe diameter, can be distinguished. It is consistent with the assumption adopted in the present investigation that the bubble length of $2D$ represents the minimum size of the Taylor bubble in slug flow. When the gas flow rate is further increased, the transition to the slug flow pattern occurs, and a typical histogram with two distinct maxima is obtained [figure 3(c)]. These two maxima, which represent the liquid aerated slugs and the Taylor bubbles, respectively, are separated by a deep "valley" region showing that the bubble sizes around $1D$ are practically absent in the flow. This distribution thus supports the adopted criterion for the inception of slug flow and the corresponding minimum size of the Taylor bubbles.

It is instructive to mention here that the bubble size distribution within the liquid slugs in figure 3(c) strongly resembles that obtained in the dispersed bubble, as shown in figures 3(a,b). This corroborates the conjecture by Barnea & Brauner (1985) that the liquid bridge domain can be considered as a bubbly flow.

The two peaks in the histogram becomes less pronounced with increasing flow rates. When the flow conditions approach the slug–churn boundary [figure 3(d)], the amount of bubbles around the $1D$ sizes increases substantially, and the distribution becomes more uniform. At this flow rate, the average voidage within the liquid slug is 0.48 [cf. figure 2(e)]. This value is very close to the maximum cubic volumetric packing ($\epsilon = 0.52$). The enhanced coalescence of the bubbles under these conditions (Brauner & Barnea 1986) is the most probable reason for the observed distribution. Note also that the experimental technique is not always capable of distinguishing between large continuous bubbles and a cluster structure composed of smaller bubbles. When the average void fraction in the liquid slug approaches the critical value of 0.52, the liquid bridge can not sustain itself anymore (Brauner & Barnea 1986), so that the typical structure of the developed slug flow, as shown in figures 2(c) and 3(c), is destroyed and the transition to the churn flow regime occurs. In this case all bubble sizes are present in the flow [figure 3(e)].

The comparison between the histograms clearly leads to the conclusion that they can serve as an additional instrument for flow pattern identification. By gradually increasing a single flow parameter in the system, e.g. the gas flow rate, the general shape of the histograms varies from a single well-defined peak in the case of the dispersed bubbles, to two separated peaks in a developed slug flow, which then gradually disappear, until the distribution becomes nearly flat in the churn flow regime.

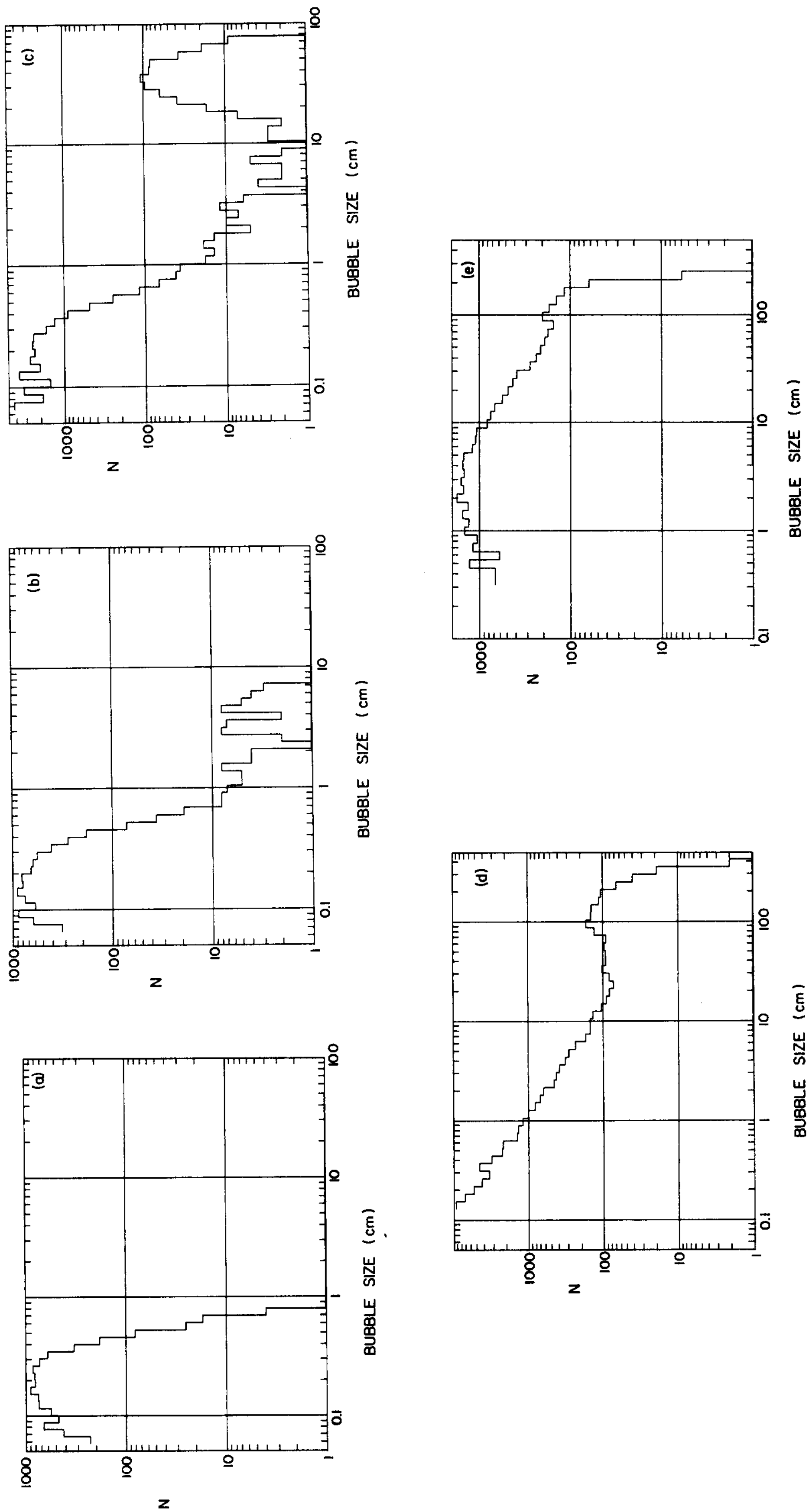

Figure 3. Histograms of the bubble size distribution: (a) $U_{GS} = 0.03$ m/s; (b) $U_{GS} = 0.10$ m/s; (c) $U_{GS} = 0.25$ m/s; (d) $U_{GS} = 1.6$ m/s; (e) $U_{GS} = 4.0$ m/s.

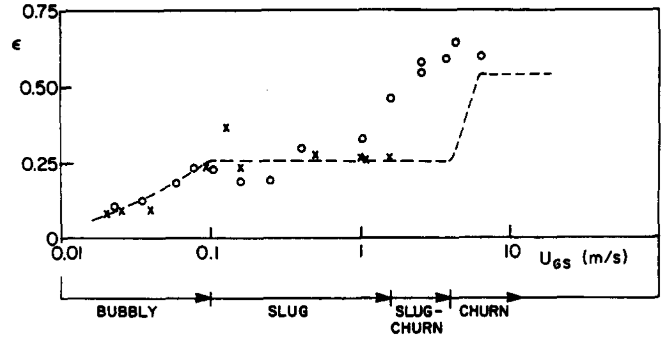

Figure 4. Average void fraction within the liquid slug: O, present results; ×, Fernandes (1981); ----, model (Barnea & Brauner 1985).

3.3. *Liquid slug length and its voidage*

As has been mentioned above, bubbles longer than $2D$ were considered as Taylor bubbles. The duration of the regions separating the two consecutive Taylor bubbles, multiplied by the appropriate translational velocity, gives the length of the liquid slugs. Averaging the liquid slug lengths encountered over the whole duration of sampling gives the average liquid slug length. In the whole range of gas flow rates considered here the mean slug length appeared to be practically independent of U_{GS} and varied in the range $10D$–$15D$. This value can also be easily obtained from examining figures 2(c–e), where each step represents a length of $2D$. This result is in agreement with the experimental observations by Moissis & Griffith (1962) and Fernandes *et al.* (1983) and supports the conclusions by Shemer & Barnea (1987) regarding the stable slug length. The model predictions for stable slug length by Dukler *et al.* (1985) and Barnea & Brauner (1985) gave similar estimates.

As shown by Serizawa *et al.* (1975), Inoue *et al.* (1976), Herringe & Davis (1976) and Drew & Lahey (1982), among others, the holdup distribution in bubbly flow is close to being uniform in the radial direction, with certain deviations in the vicinity of the wall. The exact character of these deviations appears to be a function of the inlet conditions, as well as the flow rates of both fluids (Herringe & Davis 1976). Hence, in a bubbly flow regime, the time-averaged local void fraction at the centerline does not differ significantly from the cross-sectional average void fraction. Averaging the binary signals $\epsilon_i(t)$ over time may give therefore a reasonable estimate of the mean cross-sectional void fraction. Figure 4 presents this average void fraction in the liquid slugs. The boundaries between different flow patterns are also given in this figure. These transitional values of U_{GS} were obtained from the analysis of the time variation of the short-time-averaged void fractions [figures 2(a–f)] and the histograms presented in figures 3(a–e). The pattern transitions based on these figures were also in agreement with the visual observations. For $U_{GS} < 0.1$ m/s, the bubbly flow regime was obtained, and the mean void fraction was computed therefore by averaging the whole sampling duration. At higher gas flow rates, Taylor bubbles appear, and the data in figure 4 reflects the mean gas holdup within the liquid bridges between these large bubbles. The data by Fernandes (1981) for similar experimental conditions, but obtained by a quite different technique, is also plotted in this figure and is in good agreement with the present results up to $U_{GS} = 1$ m/s.

Barnea & Brauner (1985) suggested a method to predict the gas holdup within the liquid slug. This method is based on the assumption that the gas in the liquid bridge behaves as dispersed bubbles. The liquid slug at any flow rate is able therefore to accommodate the maximum gas holdup of the fully-developed bubble flow with the same mixture velocity. These conditions correspond to the transition boundary between the bubble and slug flows. This transition boundary may be estimated either by a predictive model or from the experimental data. The results based on the model by Barnea & Brauner (1985) are also shown in figure 4 for comparison.

The transition between the bubbly and the slug flow regime occurs at mean void fraction of about 25%, as has been suggested by Taitel *et al.* (1980), Mishima & Ishii (1984) and Bilicki & Kestin (1987). For most of the gas flow rate range where the slug flow regime exists, the void fraction within the liquid slug retains approximately the same value of 25% and is nearly constant, in agreement with Barnea & Brauner (1985). At $U_{GS} > 1$ m/s, the void fraction within the liquid slug increases substantially, until an upper limit of approx. 60% is obtained. This limit value was also associated by Brauner & Barnea (1986) with the maximum possible volumetric packing of the dispersed bubbles within the liquid slug and thus represents the value where the transition to the churn flow regime occurs.

Note that in the range of gas flow rates where the voidage in the liquid slug, $\epsilon = 0.5$–0.6, a gradual transition from the slug to churn flow regime indeed occurs, as follows from the analysis of figures 2(e,f) and 3(d,e), as well as from the visual observations. It can be seen from figure 4 that at relatively high gas flow rates, $1 < U_{GS} < 4$ m/s, the void fractions within the liquid slug detected in the present work, exceed those reported by Fernandes and predicted by the model of Barnea & Brauner (1985). This discrepancy may be attributed to the growing non-uniformity in the void fraction distribution across the pipe with increasing velocity (van der Welle 1985). The assumption that the void fraction at the centerline represents the cross-sectional mean value, obviously becomes less accurate when the transition to churn flow is approached.

An alternative criterion for the slug–churn transition was given by Mishima & Ishii (1984) in terms of the overall mean void fraction. Applying the criterion to the present experimental conditions yields the slug–churn transition boundary at $U_{GS} \simeq 2$ m/s. This value is in agreement with our observations, where a gradual transition to churn flow occurs at $U_{GS} > 1$ m/s (figure 4).

In the present work an effort was made to examine the assertion by Fernandes *et al.* (1983) that the voidage in the near-wake region behind the Taylor bubble is larger than the mean value in the liquid slug. The experimental technique and processing adopted in this investigation make it possible to obtain the ensemble-averaged void fraction as a function of the distance from the Taylor bubble. Such near-wake void fractions ϵ_{NW} were calculated from the experimental data for the regions of $1D$, $2D$ and $4D$ behind the Taylor bubble. The results averaged over a large amount of Taylor bubbles and normalized by the appropriate mean ϵ in the liquid slug, are presented in figure 5. In all cases considered, the void fraction in the near-wake region was higher than the averaged void fraction in the liquid slug. The ratio ϵ_{NW}/ϵ decreases with increasing U_{GS} and nearly attains the value of unity when the churn flow regime is approached. This phenomena can be partially attributed to the flow conditions in the near-wake region. As was noticed in flow visualization experiments by Shemer & Barnea (1987), up to a distance of about $2D$ behind the Taylor bubble, there is a region with enhanced turbulent activity, due to strong mixing of flows with two different velocities. One can speculate therefore that close to the bottom of the Taylor bubble this high turbulence level will cause an increase in the amount of trapped air. This effect becomes less pronounced at higher gas flow rates, where the relative contribution of mixing in the wake region is less noticeable.

4. SUMMARY AND CONCLUSIONS

The present work reports on the measurement of the local instantaneous void fraction at the centerline of a pipe in air–liquid vertical upward flow. By using a relatively simple technique,

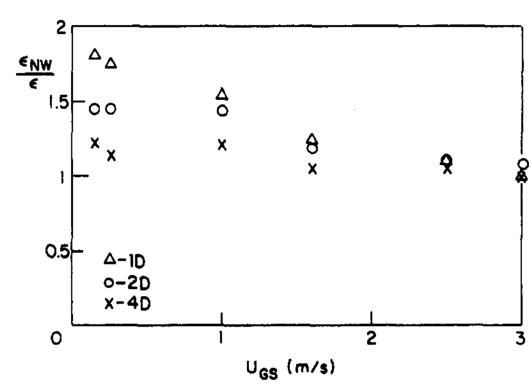

Figure 5. The ratio between the void fraction in the near wake of the Taylor bubble and the mean void fraction in the liquid slug.

a substantial amount of information regarding the hydrodynamics of two-phase flows was obtained.

Two different flow pattern identificators were suggested. The first is based on the behavior of the short-time-averaged void fraction as a function of time, while the second one employs the histograms representing the bubble size distribution in the flow under investigation. Quantitative hydrodynamic parameters of the slug flow, like the mean slug length, the average voidage within the liquid slug and the voidage in the near-wake region of the Taylor bubble, were also obtained. The measured values of the voidage in the liquid slug were related to the boundaries of transition from the dispersed bubbles to the slug flow regime, and then to the churn flow. The experimental results obtained support the phenomenological models which used the prescribed values of holdup as a criterion of transition between various flow patterns.

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