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Some Observations on the Structural Developments of Bubbly Flow : Channel Size Effect

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Abstract

The present study provides some experimental observations on the structural developments of bubbly flow and the void wave damping in vertical, circular channel with a large diameter, and discusses the channel size effect on them. It is observed that the developing mode of bubbly flow structures and its transition mechanism are influenced by the channel size as well as the bubble size, and that they are well revealed in the behavior of wave damping.

1. Introduction

From the statistical processing of void fluctuations, the void waves, that is, the propagations of void disturbances could be related to the essential features of developing flow structures. Some recent works on void waves covered the bubble-to-slug flow regime transition (BSFRT) region. They include Matuszkiewicz *et al.* [1], Saiz-Jabardo & Bouré [2], Park *et al.* [3], and Kytömaa & Brennen [4]. In previous works, however, no detailed measurements of the wave damping were taken to link it with BSFRT. And most of them were performed in a channel with small diameter. The discrepancies between different investigations might be attributed to unidentified effects of the parameters which could affect the flow phenomena and regime transition mechanism.

From recent measurements [5], it was observed that the bubble size has much influence on the structural developments of bubbly flow and found that they are well revealed in the propagation parameters of void waves.

The main objectives of this work are to experimentally investigate the developments of bubbly flow structures and their relation to the void wave propagations in a pipe with a large diameter (*D* = 80 *mm*). The present study is a continuation of the previous experimental work [5] in a small diameter pipe (D = 25 *mm*).

2. Experimental Method

The experimental setup and signal processing method are described in detail in Song *et al.* [5]. The height of the test section is about 3 *m* and its inner diameter is 80 *mm*. An impedance void meter is used to measure the void fraction. In this study, the void sensors are installed at 2.5 *m* downstream of the bubble generator. The distance between two main sensors is chosen to be 70 *mm*. A high-speed video motion analyzer is used with a light sheet projector for flow visualization and bubble sizing. The light sheet is used to avoid the overlapping of bubbles at different planes in video images and to observe the radial void profiles easily.

A series of tests are performed at 4 *bars*, 18~20°C under the following test conditions: liquid superficial velocity, J_f = 0.12, 0.18 *m/s*; void fraction, α = 0.03 ~ 0.4; volume-equivalent bubble diameter, D_b = 2.8, 4.2, 6.2, 7.9, 10.2 *mm*.

The void signals simultaneously measured from three void sensors are statistically processed, via FFT techniques [5], to estimate several statistical parameters, from which bubbly flow structures and the void wave parameters are investigated. They include PDF and the Signal-to-Noise Ratio (SNR) of the void signals, which is defined as the normalized standard deviation of instantaneous void signals, and the propagation properties of void waves such as a flow time scale, a wave speed and a wave damping factor. Especially, the degree of the spatial damping of void waves is quantified in terms of the "spatial gain factor" which is indicative of a measure of the spatial wave damping.

The spatial gain factor (SGF) is defined as:

$$\beta = \exp[\ (\kappa_I)_{\min}\ \Delta z\ ] \tag{1}$$

in terms of the minimum value of κ_I in the frequency domain since it can be treated as the most unstable one which will dominantly propagate and be easily amplified than those with other frequency components. SGF is a parameter which can be predicted from the two-fluid model [6]. Here, the imaginary part of the wave number, $\kappa_I(f)$, can be determined by

$$\kappa_I(f) = -\frac{1}{\Delta z} \ln[\ |H_{ij}(f)|\ ] \tag{2}$$

where $|H_{ij}(f)|$ is the magnitude of the transfer function and Δz is the distance between two void sensors, i, j.

3. Experimental Results

The flow regimes which appear in the transitional process of bubbly flow can be objectively characterized based upon SNR and PDF of void signals, and it can be classified into *discrete* bubbly flow, *clustered* bubbly *flow*, and *slug* flow [5].

Observed Flow Developments

From statistical analysis of void signals, two modes of flow structural developments in bubbly flow were observed, depending on the bubble size.

(1) Gradual transition

In case of large bubble size, the bubble shape is ellipsoidal and the radial void profile shows the core peaking at low void fraction as previously observed [5]. The gradual flow developments are represented by SNR in Fig. 1 for D_b = 7.9, 10.2 *mm* at J_f = 0.12 *m/s*, and they are also well represented by the variation of the time scale, T_f, as shown in Fig. 2 for different bubble sizes at J_f = 0.12 *m/s*.

As gas flow increases, the bubble number density is increased and the bubbles located in the channel center gradually form bubble clusters. Bubbly flow with large bubble size becomes the clustered bubbly flow with intermittent bubble clusters as bubbles flow downstream or the gas flow rate is increased.

(2) Abrupt transition

In bubbly flow with small bubble size, there shows the near-wall peaking of radial void profile in low void fraction range, and it is observed that the bubbles tend to be uniformly distributed as gas flow rate and void fraction increase.

The flow structural developments for small bubble size, characterized by the abrupt changes of flow structures, are well represented by the variation of SNR in Fig. 1 and also represented by the variation of the flow time scale, T_f, as shown in Fig. 2. The gas phase flows as discrete bubbles along the flow channel without forming a bubble clustering, while the bubble number density gradually increases as J_g is increased. With a further increase of J_g, highly packed bubble flow is formed. In the transitional process, rather abrupt coalescences of the packed bubbles appear to form large and distorted structures of gas phase which are developed into Taylor bubbles to form slug flow only by an addition of gas flow.

For small bubble sizes, the time scale shows small values with slightly increasing trends over the entire bubbly flow region. Once the large structures of gas phase appear, however, it increases abruptly.

It is observed that the transitional process in small bubble case goes on over a relatively larger range of gas flow when compared to the case of small diameter channel, where an abrupt formation of slug flow was observed [5]. One of the reason for the difference between the flows in small and large diameter pipes could be attributed to the ratio of the relative magnitude of interfacial forces and wall shear force. As the pipe diameter is increased, the interfacial forces will become more dominant than the wall force.

While well-established flow regimes are easy to discriminate either visually or from PDF diagram, the transitional flow between bubbly and slug flow is not easy to distinguish only by visual observations in some cases such as large bubble size or large channel size. More objective tools, such as SNR and the flow time scale (T_f), will be useful for flow regime identification and the discrimination of its transition.

Spatial Wave Damping

The spatial damping of void waves is quantified in terms of the spatial gain factor (SGF) defined by eqn. (1). The variation of SGF with void fraction is shown in Fig. 3 for J_f = 0.12 m/s with various bubble sizes.

For the large bubble case, the clustered bubbly flow indicates nearly unity of SGF, where the bubble clusters are formed and then grow. Then, the gradual growth of bubble clusters to form cap bubbles is indicated by SGF > 1, which means the wave amplification. This tendency is the same as observed by Song *et al.* [5] over a wide range of flow conditions in a small diameter pipe.

For the small bubble sizes, the void waves are attenuated over a range of void fraction in the bubbly flow region, and the attenuation tends to increase as the bubbles become packed, as shown in Fig. 3 for J_f = 0.12 m/s. SGF increases sharply near a certain void fraction, and it goes to the unity which corresponds to the transition flow. As J_g increases beyond this critical value, the transition flow grows quickly to form slug flow where SGF goes beyond the unity and the propagating waves are amplified.

In case of large channel flow, the bubbly flow tends to be more unstable even at low void fraction than the case of small size channel because of the dominance of interfacial interactions.

Channel Size Effect on BSFRT

The critical void fraction, α_c, which indicates BSFRT, is much dependent on the bubble size even under the fixed liquid flow rate. In Fig. 4, the critical void fraction is plotted vs. the bubble size. Also, compared are the data for the case of small channel (D = 25 *mm*) with the bubble sizes of D_b = 2.7, 3.2, 3.8, 4.2, 4.8 *mm* at various liquid velocity conditions [5]. Two cases show different trends of the bubble size effect on the transitional void fraction.

All previous BSFRT criteria were obtained based upon the assumption that the critical void fraction is in the range of α_c = 0.25~0.3. As shown in this work, however, it is evident that the bubble size effect on the phasic interactions could cause the variation of local flow structures and eventually affect the appearance of global flow structures, that is, BSFRT.

4. Conclusions

The structural developments of bubbly flow and the void wave propagations are experimentally investigated in a vertical air-water flow in a large diameter channel, and they are compared with the small diameter case.

It is shown that the developing mode of bubble flow structures is dependent on the channel size as well as the bubble size and the characteristics of wave damping are closely related to the flow structural developments. The initiation of the instability of void waves basically means that the coalescences of bubbles begin to form the large structures of gas phase. It is also confirmed that the spatial gain factor can be used to discriminate the transition from bubbly to slug flow.

The channel diameter effect should be investigated along with the bubble size effect for completeness of physical modelling of the transition criteria.

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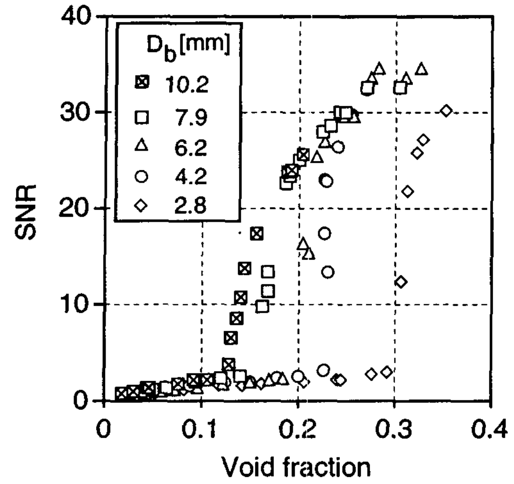

Fig. 1 Variation of the signal-to-noise ratio : J_f = 0.12 m/s

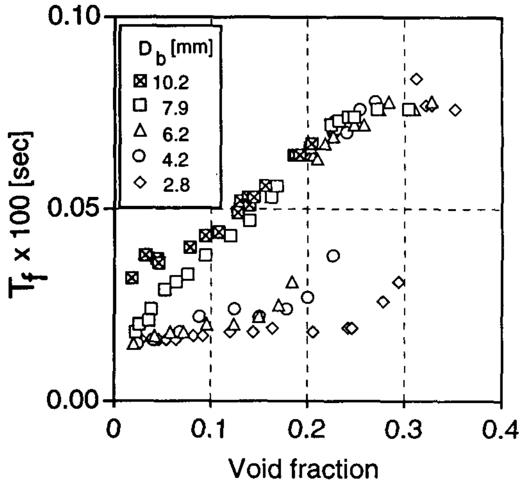

Fig. 2 Variation of the flow time scale : J_f = 0.12 m/s

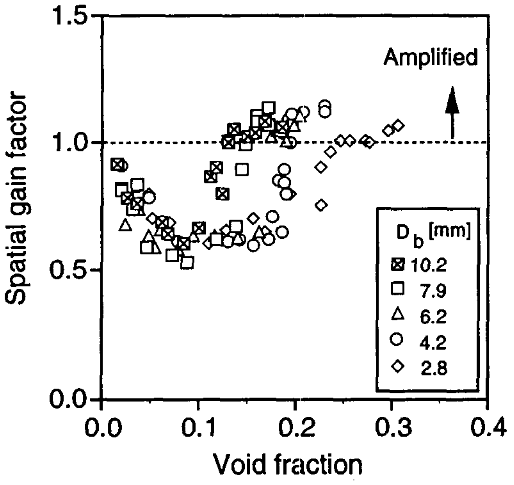

Fig. 3 Variation of the spatial gain factor : J_f = 0.12 m/s

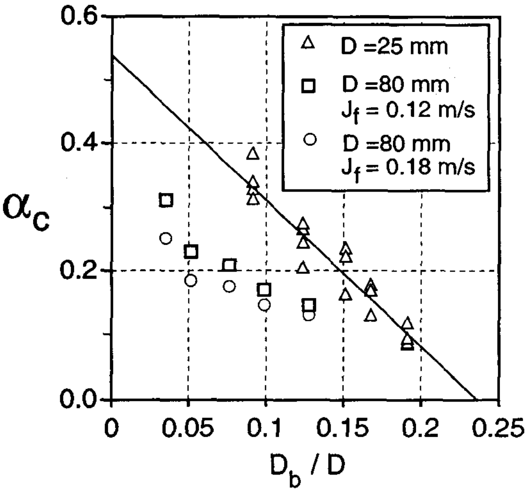

Fig. 4 Comparison of the critical void fraction : channel size effect