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BUBBLE-TO-SLUG TRANSITION FOR LOW-RE TWO-PHASE FLOWS

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ABSTRACT

A critical review on the mechanism and models on the bubble-to-slug transition of two-phase gas-liquid flows are presented in the present paper. It is shown that the most possible mechanism controlled the bubble-to-slug transition is the bubble coalescence. Focusing on the bubble-to-slug transition for the low-Re two-phase flow, a simple Monte Carlo method is used to simulate the influence of the initial bubble size on the bubble-to-slug transition. Some secondary factors, such as the liquid viscosity, the surface tension, and the relative slip between the two phases, are ignored in the present study. It is found that the locus of the dimensionless rate of collision is a universal curve. Based on this curve, it is determined that the bubble initial size can affect the phase distribution and flow pattern when its dimensionless value is in the range from 0.03 to 0.4. A simple relationship between the critical void fraction and the initial bubble size is proposed, which agrees very well with the experimental data.

Keywords: bubble-to-slug transition, two-phase gas-liquid flow, Low Reynolds number, influence of bubble size.

INTRODUCTION

When two phases flow co-currently in a channel, they can arrange themselves in a number of different configurations, called flow patterns or flow regimes. Each flow pattern is characterized by a relatively similar distribution of the two phases and of their interfaces. Transition from one flow pattern to another takes place whenever a major change occurs in geometry of the gas-liquid interface. Among the typical flow patterns, bubble flow and slug flow are usually observed when the gas void fraction is small. Bubble flow is characterized by discrete small bubbles approximately uniformly distributed in a continuous liquid phase. The bubble size is smaller than the pipe diameter. On the contrariety, slug flow is characterized by Taylor bubbles which have a diameter almost equal to the pipe diameter and a length larger than the pipe diameter. These Taylor bubbles move uniformly forward, and are separated by slugs of continuous liquid, which bridge the pipe and may or may not contain small gas bubbles. Accurately predicting the transition of bubble to slug is critical and important due to the fact that slug flow may cause undesirable pressure fluctuations, even hammer in pipeline flows; especially severe slugging may pose a threat to safety or undermine the reliability of the system.

Presently, two-phase gas-liquid flows in mini- and/or micro-channels attract more and more attentions due to the increasingly more modern industrial applications[1]. In these cases, the liquid Reynolds number based on the liquid superficial velocity is low. Liquid turbulence is absent or does not play an important role for the bubble size determination. No bubble break-up because of turbulent eddies occurs. Therefore, the initial bubble size can be expected to be an important parameter. The transition condition of the bubble-to-slug transition for these low-Re two-phase flow will be different with respect to that for the high-Re two-phase flow and is not understood as well as that for high.

In this paper the focus is on the bubble-to-slug transition for low-Re two-phase flows. The mechanisms and models on the bubble-to-slug transition proposed in the open literature are critically reviewed firstly. The major attention is paid on some factors which aren't taken into account in the common models, such as the influence of the bubble initial size. A simple Monte Carlo method is used to simulate the influence of the initial bubble size on the bubble-to-slug transition, in which some secondary factors, such as relative slip between the two phases, are ignored. A simple relationship between the critical void fraction and the initial bubble size is proposed, which is compared with some experimental data.

MECHANISM AND MODELS ON BUBBLE-TO-SLUG TRANSITION

The classical picture of the bubble-to-slug transition is following the early work of Radovicich & Moissis[2]. They observed that for gas void fraction less than 10%, the rate of bubble agglomeration is usually slow, and bubble flow persists as long as the bubble diameter is not large. When the gas void fraction is between 10% and 30%, agglomeration starts to occur more frequently and the amount of coalescence increases with the gas void fraction, purity of the liquid, and its surface tension. When the gas void fraction is greater than 30%, the collision between bubbles is so frequent that transition to slug flow always taken place. Therefore, the bubble-to-slug transition is controlled by the bubble coalescence. In fact, they suggested a critical void fraction, which is between 0.1 and 0.3, for the transition. They also found that large initial bubble sizes and small pipes favored an early transition to slug flow. This fact, however, as well as the influences of the liquid purity and surface tension, is not received enough recognition in the literature.

As pointed out by Schwartzbeck & Kocamustafaogullari[3], a constant value of the gas void fraction, α_{cr}, may be the best way to describe the bubble-to-slug transition. For example, Taitel et al.[4] used $\alpha_{cr} = 0.25$, while Mishima & Ishii[5] recommended a value of $\alpha_{cr} = 0.3$. Recently, based on the experimental data obtained from the experiments of two-phase flows at microgravity, Colin et al.[6] and Jayawaderna et al.[7] proposed separately empirical correlations to predict the transition quality $X_c = C_0\alpha_{cr}$, where C_0 denotes the gas distribution parameter in the drift-flux model. But a general accepted expression for the critical void fraction is still absent.

In the literature, there is also a popular viewpoint, which is also following the work of Radovicich & Moissis[2]. It is believed that bubble flow is a transient flow in which bubble coalescence gradually occurs along the channel leading to larger and larger bubbles, and ultimately to slug flow. Given a sufficiently long residence time in a pipe, a swarm of bubbles will develop into slug flow. However, Hewitt[8] found that there was no effect of channel length on the transition condition in their studies of the bubble-to-slug transition in a 31.8 mm pipe for different channel length. Similar conclusion can also be found in the work of Kapteyn[9].

A challenge of the above picture of the bubble-to-slug transition comes from the studies on the void fraction waves[10, 11]. Following their works, the hypothesis, first made by Wallis[12], that the bubble-to-slug transition can be attributed to the instability of the void fraction waves which result from wave amplification becomes more popular in the literature. Further examining the original publications, however, shows that the sole conclusion can be proved by these studies is that the instability of the void fraction wave serves as an indictor of the bubble-to-slug transition, not a cause of it. Very recently, Cheng et al.[13] studied the bubble-to-slug transition in a 28.9 mm diameter column at a constant water velocity for different bubble initial sizes, and found that the instabilities of the void fraction waves determined by the system gain factor and the wave velocity gradient are not coincident with each other, nor do they agree with the visual observations of the bubble-to-slug transition in the column except for one case. It is confirmed that the instability of the void fraction wave is not the factor that causes the bubble-to-slug transition in two-phase flow.

It is easy to understand the fact that the change of the stability of the void fraction wave occurs near the bubble-to-slug transition if we consider the stability of the void fraction wave as a kinetic parameter of two-phase flow. When the flow pattern transition occurs, the flow structure changes necessarily, and its kinematic parameter also changes. Based on this knowledge, many researchers studied the stabilities in the two-phase bubble flow equation systems and their relation to the flow pattern transition[14-18]. The equstion systems are developed based on the two-fluid continuum method. Different constitutive relations for mathematical description of the mechanical and thermal interactions inside and between two phases, namely closure laws, are used by different researchers. Characteristic analysis of the equation systems is commonly used to analyze void fraction wave propagation. For real characteristic roots, small disturbances are stabilized, so the initial-value problem is correctly posed. Complex characteristics may not necessarily indicate an incorrect formation, but may be attributed to a physical instability of the assumed flow configuration, whereby transition to a different flow pattern, usual slug flow, may take place. Due to strong influence of the selection of closure laws, a great decentralization of the predicted values of the critical void fraction is witnessed.

Based on the same consideration, Lu & Zhang[19] suggested that the transition from bubble to slug flow will happen when the interfacial area reaches a maximum. Similar method is also used in Levy[20], where the maximum of the group P_iC_D/A indicates the transition. In the above group, P_i, C_D and A denote the interfacial perimeter, the interfacial drag coefficient and the cross-section area of the channel, respectively. The demerit due to strong influence of the selection of closure laws also exists in this kind of models.

In the most of the models on the bubble-to-slug transition, a constant critical void fraction is used or predicted, although the mechanism and/or the method underlying them are different. A great decentralization of the values of the critical void fraction exists in the different models and among those obtained from different experiments. The reason may be attributed to the influence of the initial bubble size, which is usually not taken into account. There are many experimental evidences[2, 13, 21-23] that the initial bubble size might be the key factor, especially for the low-Re two-phase flows. It may cause discrepancies in the phase distribution and flow pattern under similar experimental conditions. Therefore, any theoretical model, which was used to predict the bubble-to-slug transition without considering the bubble initial size, would be unreliable.

NUMERICAL RESULTS AND DISCUSSIONS

As discussed above, the correct mechanism controlling the bubble-to-slug transition is the bubble coalescence. For the low-Re two-phase flows where liquid turbulence is absent or does not play an important role for the bubble size determination, the rate of coalescence is dependent on the number of collisions and other secondary factors, such as the liquid viscosity and the surface tension. In the present study, these secondary factors are ignored for the sake of concision. Then calculation on the rate of collision between bubbles can give some prompts about the transition. Here, we adopt a simple Monte Carlo method to calculate the rate of collision between mono-size bubbles distributed uniformly in a channel. The major objective is to reveal the influence of the bubble initial size on the rate of collision. Furthermore, in order to give prominence to the influence of the bubble initial size, the relative slip between the two phases is also ignored.

Let X_1, X_2, and X_3 represent three independent random variables distributed uniformly in the range of [0, 1]. The location of the center of bubbles (R, Φ, Z) can be expressed as

$$R = X_1^{1/2}(1-\eta)/2 \tag{1}$$

$$\Phi = 2\pi X_2 \tag{2}$$

$$Z = (2/3)N\eta^3X_3/\alpha \tag{3}$$

where $\eta = D_b/D$ is the dimensionless bubble initial size, N and α denote the number of bubbles and the void fraction, respectively. If the distance between any pair of bubbles is less than the bubble diameter, collision occurs. The rate of the collision is the rate between the number of collision and the number of bubble pair.

Table 1. The maximum of the rate of collision

α	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
$\eta_{\max}$	0.38	0.35	0.35	0.42	0.38	0.36	0.38	0.37	0.34
$P_{\max}$	0.312	0.617	0.910	1.163	1.505	1.780	2.074	2.370	2.617

Fig. 1 shows the variations of the dimensionless rate of collision, P_R, with the bubble initial size for nine different gas void fraction from 0.05 to 0.45 with $\Delta\alpha$ = 0.05. Here the characteristic factor of the rate of collision is the maximum, $P_{\max}$, for each void fraction, which is shown in table 1. denotes the locations of the maximum, η_{max}, are also shown in the table. The discrepancies reflect the intrinsic fluctuation of the method.

It is shown that the locus of the dimensionless rate of collision is a universal curve with two characteristic points. The first one locates approximately at $\eta = 0.03$, while the second at $\eta = 0.4$. Between these two points, the curve can be expressed as

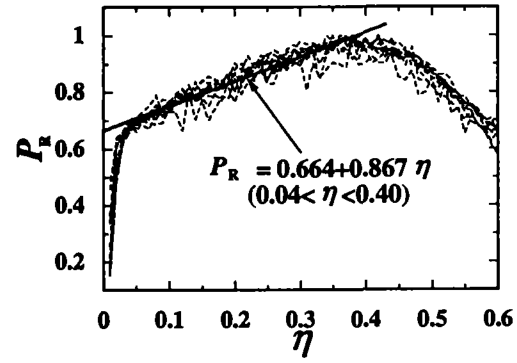

Fig. 1 Variations of the rate of collision with the bubble size for α from 0.05 to 0.45 with $\Delta\alpha = 0.05$.

$$P_R = 0.664+0.867\eta \qquad (4)$$

When $\eta < 0.03$, the dimensionless rate of collision decreases acutely with the decrease of the bubble initial size. It may be indicted that the collision between bubbles rarely occurs under this condition. Then the bubble coalescence will mainly be attributed to the bubble parking. It is reasonable to suggest that the bubble-to-slug transition cannot occur unless the maximum packing $\alpha = 0.53$ is reached.

On the other hand, when $\eta > 0.4$, the dimensionless rate of collision decreases gradually with the increase of the bubble initial size. But in this case, a small amount of collision can cause the transition due to the relative larger bubble initial size. Therefore, no steady bubble flow can exist under this condition.

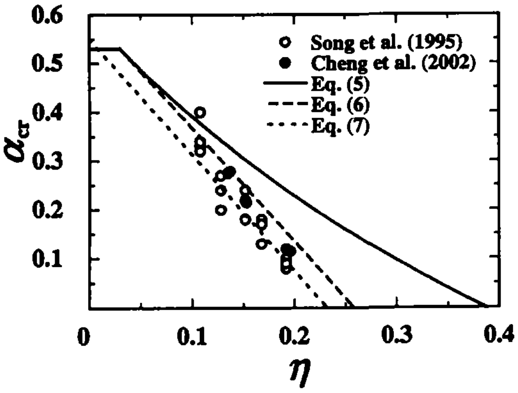

Fig. 2 The influence of bubble initial size on the critical void fraction for the bubble-to-slug transition.

Thus, the range in which the bubble initial size can affect the phase distribution and flow pattern will be that from 0.03 to 0.4. The influence will be depended on the dimensionless rate of collision, and can be expressed as a linear function of $(P_R^{-1}-1)$:

$$\alpha_{cr} = 1.18[(0.664+0.867\eta)^{-1}-1], \text{ for } 0.03<\eta<0.4 \qquad (5)$$

Eq. (5) can also be linearized with regard to η:

$$\alpha_{cr} = 0.60-2.32\eta \qquad (6)$$

which is very close to the following empirical relation proposed by Song et al.[23]:

$$\alpha_{cr} = 0.55-2.37\eta \qquad (7)$$

However, the first group of the data in Fig. 16(b) in Song et al.[23] was shifted incorrectly from $\eta = 0.108$ to 0.08, which can cause a increase of the parameters in Eq. (7).

Fig. 2 shows the predictions of the influence of the bubble initial size on the critical void fraction for the bubble-to-slug transition by Eq. (5) – (7). The experimental data by Song et al.[23] and Cheng et al.[13] are also shown. A satisfied agreement can be obtained.

CONCLUSIONS

A critical review on the mechanism and models on the bubble-to-slug transition of two-phase gas-liquid flows are presented in the present paper. It is shown that the most possible mechanism controlled the bubble-to-slug transition is the bubble coalescence. Focusing on the bubble-to-slug transition for the low-Re two-phase flow, a simple Monte Carlo method is used to calculate the rate of collision between mono-size bubbles distributed uniformly in a channel. The major objective of the simulation is to reveal the influence of the initial bubble size on the bubble-to-slug transition. Some secondary factors, such as the liquid viscosity, the surface tension, and the relative slip between the two phases, are ignored in the present study. It is found that the locus of the dimensionless rate of collision is a universal curve. When $\eta < 0.03$, the dimensionless rate of collision decreases acutely with the decrease of the bubble initial size, and the collision between bubbles may rarely occur. On the other hand, when $\eta > 0.4$, a small amount of collision can cause the transition due to the relative larger bubble initial size, and then no steady bubble flow can exist under this condition. Thus, the range in which the bubble initial size can affect the phase distribution and flow pattern will be that from 0.03 to 0.4. A simple relationship between the critical void fraction and the initial bubble size is proposed, which agrees very well with the experimental data.

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