A Method for Determining the Bubbly-to-Slug Flow Transition Boundary in Rectangular Channels (Postprint)

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Abstract

In two-phase flow systems, flow patterns directly affect system characteristics such as frictional resistance and heat transfer, while the flow pattern transition process is influenced by channel geometry and dimensions. Under ambient temperature and pressure conditions, using air and water as the working media, the vertical upward transition from bubbly flow to slug flow was investigated in eight rectangular channels of different sizes. The results indicate that when the rectangular channel gap exceeds 2 mm, the bubbly-to-slug flow transition boundary shifts leftward with increasing channel hydraulic diameter. Within the narrow channel range, the transition criterion based on the drift-flux model proposed by Ishii (1977) can be employed to calculate the flow pattern transition boundary; in conventional rectangular channels, the critical void fraction in the transition criterion is related to the initial bubble size, and the method proposed by Zhao Jianfu was adopted to calculate the critical void fraction, yielding good agreement between predicted transition boundaries and experimental results. When calculating the cross-sectional gas holdup using the drift-flux method, for narrow rectangular channels, the distribution coefficient can be calculated using the method proposed by Ishii (1977), whereas for conventional rectangular channels, the distribution coefficient is 1.2.

Full Text

Criterion for Predicting Transition Boundary from Bubbly Flow to Slug Flow in Rectangular Channels

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Abstract

In two-phase flow systems, flow patterns directly affect frictional resistance and heat transfer characteristics, while the transition process itself is influenced by channel geometry and dimensions. This study investigates the vertical upward transition from bubbly to slug flow in eight rectangular channels of various sizes, using air and water at ambient temperature and pressure. The results demonstrate that when the channel gap exceeds 2 mm, the transition boundary from bubbly to slug flow shifts leftward as the hydraulic diameter increases. In narrow channels, the transition criterion based on the drift-flux model proposed by Ishii (1977) can be employed to predict the flow pattern transition boundary. For conventional rectangular channels, the critical void fraction in the transition criterion is related to the initial bubble size; using the method proposed by Zhao Jianfu to calculate the critical void fraction yields good agreement between predicted transition boundaries and experimental results. When calculating the cross-sectional void fraction using the drift-flux method, the distribution coefficient for narrow rectangular channels can be computed using Ishii' s (1977) approach, whereas for conventional rectangular channels, the distribution coefficient equals 1.2.

Key words: Flow pattern transition; Bubbly flow; Slug flow; Void fraction; Initial size

Introduction

In two-phase flow systems, flow pattern transitions directly affect the mechanisms of flow resistance and heat transfer, causing corresponding changes in empirical or semi-empirical correlations based on flow patterns. Therefore, precise flow pattern identification serves as the foundation for investigating thermal-hydraulic characteristics of two-phase flow in various channels. Research on flow patterns in rectangular channels has been conducted primarily abroad, as documented in references [1-4]. Sadatomi et al. [1] studied flow patterns in vertical upward rectangular channels with hydraulic diameters exceeding 10 mm, identifying bubbly, slug, and annular flows, and found that channel geometry has minimal influence on flow patterns when the diameter exceeds 10 mm. Mishima et al. [2] investigated flow patterns in narrow rectangular channels using X-ray photography, observing that churn flow did not appear in a narrow rectangular channel with a 1.0 mm gap. Wilmarth and Ishii [3] examined horizontal narrow rectangular channels with gaps of 1 mm and 2 mm, validated models for bubbly-to-slug flow transition from Ishii [5] and Taitel [6], and proposed a new correlation for calculating the distribution coefficient C_0. Hibiki et al. [4] derived new flow pattern transition criteria through studies of rectangular channels with gaps ranging from 0.3 to 17 mm.

Research on flow pattern transition criteria in rectangular channels has been ongoing for many years; however, conclusions in this field, particularly regarding criteria for bubbly-to-slug flow transition, remain inconsistent across different literature sources. This study selects rectangular channels of different geometries to investigate the vertical upward bubbly-to-slug flow transition boundary.

Experimental Setup

The experiments were conducted at ambient temperature and pressure. In Figure 1, solid and dashed lines represent the water and gas loops, respectively. The test sections consisted of three rectangular channels with cross-sections of 43$×1.6*mm*^{2}$ (Channel 1), 43$×3*mm*^{2}$ (Channel 2), and 43$×10*mm*^{2}$ (Channel 3), corresponding to hydraulic diameters of 3 mm, 5.6 mm, and 16.2 mm, respectively. All channels had a length of 2000 mm. Based on Kandlikar’ s definition [7], Channel 1 is classified as a narrow rectangular channel, while Channels 2 and 3 are conventional rectangular channels.

Deionized water was driven by a centrifugal pump, passing through a filter, control valve, and mixing chamber before entering the test section and returning to the water tank to form a closed loop. Air was compressed by a gas pump and stored in a reservoir; during operation, it passed through a pressure regulator and check valve into the mixing chamber and test section, then discharged to the atmosphere via a gas-liquid separator located above the test section. The mixing chamber contained uniformly distributed capillaries with a diameter of 1 mm to ensure uniform bubble generation and consistent bubble size at the test section inlet. Water and gas flow rates were measured using separate mass flow meters with accuracies of 0.1 and 0.2 class, respectively. Pressure sensors with 0.2 class accuracy were installed at 500 mm and 1500 mm from the test section inlet. A high-speed camera was fixed opposite the center position between the two pressure measurement points to capture bubble behavior.

[Figure 1: see original paper]

Flow Pattern Identification

This experiment employed high-speed photography to observe gas-water configurations, overcoming the limitations of human visual perception for high-speed fluid phenomena. References [1-4] describe bubbly and slug flows differently for conventional versus narrow rectangular channels. Figure 2 [Figure 2: see original paper] presents schematic diagrams of bubbly and slug flows observed in various rectangular channels during the experiments.

In conventional channels, bubbly flow consists of discrete small bubbles dispersed within the liquid phase. In channels with smaller gaps, bubbles tend to be cylindrical, whereas they become spherical in larger-gap channels. In slug flow, gas slugs typically feature rounded heads and flat bodies, alternating with liquid phases that often contain numerous dispersed small bubbles.

In narrow rectangular channels, due to gap constraints, bubbly flow is difficult to observe even at low gas velocities, as bubbles prematurely coalesce to form cap flows with semi-circular heads and approximately flat lower portions.

Slug flow in narrow channels resembles that in conventional rectangular channels, though the liquid phase generally contains only a few bubbles, and liquid droplets occasionally appear within the gas slugs.

Results and Discussion

3.1 Comparison of Bubbly-to-Slug Flow Transition Boundaries Transition boundaries for bubbly-to-slug flow in rectangular channels obtained from references [2] and [11] were selected for comparison with experimental results, as shown in Figure 3 [Figure 3: see original paper] (where s denotes channel gap, w denotes width, and D denotes equivalent diameter, all in mm). The comparison reveals that the bubbly-to-slug flow transition in rectangular channels depends primarily on the channel gap. When the gap is smaller than 2 mm, transition boundaries for gaps of 0.3, 1.0, and 1.6 mm nearly coincide. For gaps larger than 2 mm, the transition boundary shifts leftward as the hydraulic diameter increases. With reduced gap confinement, wall shear effects diminish accordingly, facilitating bubble collision and coalescence, which causes slug flow to appear earlier.

3.2.1 Criteria for Bubbly-to-Slug Flow Transition Boundary Many researchers have adopted drift-flux formulations as discriminants for bubbly-to-slug flow transitions. Jones and Zuber [8] (1975) proposed a transition boundary criterion for rectangular channels. Ishii [5] (1977) developed a bubbly-to-slug flow transition criterion for rectangular channels, demonstrating that bubble diameter D_b influences the critical void fraction value.

3.2.2 Calculation of Distribution Coefficient in Rectangular Channels The general drift-flux formulation is typically expressed as:

$$\langle j_g \rangle = C_0 \langle \alpha \rangle \langle j \rangle + \langle \alpha \rangle V_{gj}$$

where $\langle j_g \rangle$ represents the average superficial gas velocity, $\langle \alpha \rangle$ the average void fraction, $\langle j \rangle$ the superficial velocity, and V_{gj} the average drift velocity. Zuber and Findlay [9] were among the first to propose a correlation for the distribution coefficient. Subsequently, Jones and Zuber [8] and Ishii [5] developed specific expressions for the distribution coefficient in circular pipes and narrow channels: $C_0 = 1.2$ (Jones and Zuber) and Ishii’ s correlation.

The total pressure drop ΔP measured in the test section comprises gravitational, frictional, and accelerational components. Since the channel has a constant cross-section and operates under adiabatic conditions, the accelerational pressure drop can be neglected. The frictional pressure drop ΔP_f was calculated using the method of Chisholm [10]. The gravitational pressure drop can be expressed as:

$$\Delta P_g = \rho_l g L(1 - \langle\alpha\rangle) + \rho_g g L\langle\alpha\rangle$$

where $\langle\alpha\rangle$ is the average void fraction between the two pressure measurement points and L is the distance between them. Consequently, the average cross-sectional void fraction calculated using the pressure drop method is:

$$\langle\alpha\rangle = \frac{\Delta P_g - \rho_l g L}{(\rho_g - \rho_l) g L}$$

Experimental results shown in Figure 4 [Figure 4: see original paper] indicate that the distribution coefficient in the drift-flux model tends to increase as the rectangular channel gap decreases. In the narrow channel range, Ishii' s correlation can be selected for calculating the distribution coefficient, while for channel gaps exceeding 5 mm, the distribution coefficient can be approximated as 1.2.

3.2.3 Evaluation of Bubbly-to-Slug Flow Transition Criteria Based on the obtained distribution coefficient calculation methods, four transition criteria were evaluated. The error analysis results are presented in Table 1 . For calculations of bubbly-to-slug flow transition criteria across eight rectangular channels, the Ishii model exhibits relatively small average errors for smaller channels, making it suitable for narrow rectangular channels. However, for larger rectangular channels, all four models show substantial errors and limited applicability.

The Ishii model derives a variable void fraction by comparing bubble size with rectangular channel gap, whereas the other four models assume a constant critical void fraction. Consequently, accurate calculation of the critical void fraction represents the key to successful bubbly-to-slug flow transition criteria.

3.3 Modification of Bubbly-to-Slug Flow Transition Criteria Classical theory attributes bubbly-to-slug flow transition to bubble collision and coalescence, which increase bubble size until exceeding the channel diameter to form gas slugs. Consequently, initial bubble size significantly influences the critical void fraction for flow pattern transition [12]. The Ishii model demonstrates good applicability in narrow rectangular channels primarily because experimental studies in these channels exhibit consistent initial bubble sizes, facilitating consensus on flow transition. In contrast, larger-gap channels show inconsistent gas-liquid mixing, resulting in substantial variations in initial bubble size. Since some models assume the critical void fraction only varies between 0.2 and 0.3, modifying the critical void fraction calculation in Ishii' s model becomes necessary for larger-gap rectangular channels.

Reference [12] conducted numerical calculations of bubble collision effects on bubbly-to-slug flow transition, deriving a universal curve describing how initial bubble size affects collision frequency. The study indicates that when η ($\eta =$

D_b/D) ranges from 0.04 to 0.4, the relationship between critical void fraction and initial bubble size follows:

$$\alpha_c = 1.18[(0.664\eta^{-0.876} + 1)^{-1}]$$

Applying the initial bubble sizes captured by high-speed photography in Channels 2 and 3 to Equation (9) and calculating with Ishii' s transition criterion yields a new bubbly-to-slug flow transition boundary. Comparison with experimental values, shown in Figure 5 [Figure 5: see original paper], reveals minimal error between predictions and measurements, confirming that Equation (9) can be used to calculate the critical void fraction in larger-gap rectangular channels.

[Figure 5: see original paper]

Conclusions

(1) Based on drift-flux methodology, distribution coefficients for the three test sections were calculated. The results indicate that Ishii' s correlation for the distribution coefficient is applicable in narrow rectangular channels, while a constant value of 1.2 is appropriate for conventional rectangular channels.

(2) When the rectangular channel gap exceeds 2 mm, the transition boundary shifts leftward as the hydraulic diameter increases.

(3) In narrow channels, Ishii' s drift-flux formulation can be adopted as the flow pattern transition boundary criterion.

(4) In conventional rectangular channels, the critical void fraction in transition criteria depends on initial bubble size. Modifying Ishii' s void fraction calculation using Zhao Jianfu' s correlation for critical void fraction yields good agreement between predicted transition boundaries and experimental results.

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