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Postprint: Determination Method for Bubbly-to-Slug Flow Transition Boundary in Rectangular Channels

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Date: 2018-01-05T00:00:00+00:00

Abstract

In two-phase flow systems, flow patterns directly affect system characteristics such as frictional resistance and heat transfer, while flow pattern transitions are influenced by channel geometry and dimensions. Under ambient temperature and pressure conditions, using air and water as working fluids, the vertical upward transition from bubbly 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. In the narrow channel regime, 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; the method proposed by Zhao Jianfu is adopted to calculate the critical void fraction, yielding 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 determined using the approach proposed by Ishii (1977), whereas for conventional rectangular channels, the distribution coefficient is 1.2.

Full Text

Preamble

Research on flow regime transition criteria in rectangular channels has been conducted for many years. Hibiki et al. [4] performed a comprehensive study of flow patterns in rectangular channels with gaps ranging from 0.3 to 17 mm, developing new criteria for flow regime transitions. Their work included validation against bubbly-to-slug transition models proposed by Ishii [5] and Taitel [6], and they introduced a novel distribution coefficient C0 for calculations. However, despite extensive research, conclusions in this field—particularly regarding criteria for the bubbly-to-slug flow transition—remain inconsistent across different literature sources. This study addresses these discrepancies through systematic experimentation with rectangular channels of different geometric dimensions, focusing on the transition boundary from bubbly to slug flow in vertical upward orientation.

Experimental Setup

Experiments were conducted under ambient temperature and pressure conditions. The solid and dashed lines in Figure 1 [Figure 1: see original paper] represent the water and air loops, respectively. The test sections comprised 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. All channels had a length of 2000 mm. Following Kandlikar' s definition [7], Channel 1 was classified as a narrow rectangular channel, while Channels 2 and 3 were considered conventional rectangular channels.

Deionized water was driven by a centrifugal pump through a filter, control valve, and mixing chamber before entering the test section and returning to the water tank to form a closed loop. Compressed air was stored in a gas tank and, during operation, passed through a pressure regulator and check valve into the mixing chamber and test section, after which it was discharged to the atmosphere through a gas-water separation device at the top of the test section. The mixing chamber contained uniformly distributed capillaries with a diameter of 1 mm to ensure uniform bubble generation and consistent bubble sizes at the test section inlet. Water and gas flow rates were measured using separate mass flow meters with accuracies of 0.1 grade and 0.2 grade, respectively. Pressure sensors with an accuracy of 0.2 grade were installed at 500 mm and 1500 mm from the test section inlet. A high-speed camera was positioned opposite the center of the two pressure measurement points to capture detailed bubble behavior.

[Figure 1: see original paper]

Flow Pattern Identification of Bubbly and Slug Flows

High-speed photography was employed to observe gas-liquid configurations, overcoming the limitations of human visual perception in identifying high-speed flow phenomena. Literature [1-4] indicates that descriptions of bubbly and slug flows differ between conventional and narrow rectangular channels. Figure 2 [Figure 2: see original paper] presents schematic diagrams of these flow patterns observed in different rectangular channels during the experiments.

In conventional channels, bubbly flow is characterized by small, separated bubbles dispersed within the liquid phase. In channels with smaller gaps, bubbles tend to adopt cylindrical shapes, while in larger-gap channels they appear more spherical. Slug flow features gas slugs with rounded heads and relatively flat bodies, alternating with liquid slugs that typically contain numerous dispersed small bubbles.

In narrow rectangular channels, the constraining effect of the small gap makes bubbly flow difficult to observe even at low gas velocities, as bubbles prematurely coalesce to form cap flow patterns. These bubbles exhibit semi-circular heads with approximately flat lower surfaces. Slug flow in narrow channels is similar to that in conventional channels, but the liquid phase in narrow-channel slug flow generally contains only a small number of bubbles, and liquid droplets occasionally appear within the gas slugs.

[Figure 2: see original paper]

Comparison of Bubbly-to-Slug Flow Transition Boundaries

Transition boundaries for bubbly-to-slug flow in rectangular channels obtained from literature [2, 11] were compared with experimental results, as illustrated in Figure 3 [Figure 3: see original paper] (where s represents channel gap, w represents width, and D represents equivalent diameter, all in mm). The comparison reveals that the bubbly-to-slug flow transition primarily depends on the channel gap. For gaps smaller than 2 mm, the transition boundaries for gaps of 0.3 mm, 1.0 mm, and 1.6 mm nearly coincide. For gaps larger than 2 mm, the transition boundary shifts leftward as the hydraulic diameter increases. This behavior occurs because the confinement effect diminishes with increasing gap size, reducing wall shear effects and facilitating bubble collision and coalescence, which causes slug flow to appear earlier.

[Figure 3: see original paper]

Determination Methods for Bubbly-to-Slug Flow Transition Boundaries

Drift-Flux Based Transition Criteria

Many researchers have adopted the drift-flux formulation as a criterion for bubbly-to-slug flow transition. Jones and Zuber [8] (1975) proposed a transition boundary criterion for rectangular channels. Most transition criteria based on the drift-flux model incorporate the distribution coefficient C0, necessitating accurate determination of C0 values for different rectangular channels.

Distribution Parameter Calculation in Rectangular Channels

The general form of the drift-flux model is:

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

where $\langle j_g \rangle$ is the average superficial gas velocity, $\langle \alpha \rangle$ is the average void fraction, $\langle j \rangle$ is the mixture superficial velocity, and V_{gj} is the average drift velocity.

Zuber and Findlay [9] were among the first to propose a correlation for the distribution parameter. Subsequently, Jones and Zuber [8] and Ishii [5] developed specific forms for circular pipes and narrow channels, respectively: $C_0 = 1.2$ (Jones and Zuber) and a gap-dependent correlation (Ishii).

The total pressure drop ΔP measured in the experiments comprises gravitational, frictional, and accelerational components. Since the channels have constant cross-section and operate under adiabatic conditions, the accelerational pressure drop is negligible. The frictional pressure drop ΔP_f was calculated using the Chisholm C method [10], allowing the gravitational pressure drop ΔP_g to be determined from:

$$\Delta P_g = \Delta P - \Delta P_f$$

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. When the cross-sectional void fraction is known, the gravitational pressure drop can be expressed as:

$$\Delta P_g = \rho_l g L \langle \alpha \rangle$$

Taitel (1980) [6] and Sadatomi (1982) [1] subsequently proposed more broadly applicable transition correlations. The average cross-sectional void fraction calculated using the pressure drop method is therefore:

$$\langle \alpha \rangle = \frac{\Delta P_g}{\rho_l g L}$$

Evaluation of Bubbly-to-Slug Flow Transition Criteria

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

[Figure 4: see original paper]

Based on the calculated distribution coefficients, four transition criteria were evaluated. The error analysis results are presented in Table 1 . Among the calculations for bubbly-to-slug flow transition criteria in eight rectangular channels, Ishii' s 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.

Ishii' s model determines the critical void fraction by comparing bubble size with the rectangular channel gap, while the other models assume a constant critical void fraction. Therefore, accurate calculation of the critical void fraction is the key to successful bubbly-to-slug flow transition prediction.

Correction of Bubbly-to-Slug Flow Transition Criteria

Classical theory attributes the bubbly-to-slug flow transition to bubble collision and coalescence, which increases bubble size until it exceeds the channel characteristic dimension and forms gas slugs. Consequently, the initial bubble size significantly influences the critical void fraction for flow regime transition [12]. Ishii' s model demonstrates good applicability in narrow rectangular channels primarily because experimental studies in such channels typically employ consistent initial bubble sizes, facilitating consensus on flow transition conditions. In contrast, for channels with larger gaps, inconsistent gas-liquid mixing methods result in widely varying initial bubble sizes. Since existing models assume the critical void fraction varies only between 0.2-0.3, modification of Ishii' s critical void fraction correlation becomes necessary for rectangular channels with larger gaps.

Zhao Jianfu [12] conducted numerical calculations on bubble collision effects on the bubbly-to-slug transition and obtained a universal curve describing the influence of initial bubble size on collision frequency. The study revealed 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:

$$\alpha_c = 1.18[(0.664 + 0.876\eta)]$$

By applying the bubble initial sizes captured through high-speed photography in Channels 2 and 3 to equation (9) and calculating with Ishii' s transition criterion, a new bubbly-to-slug flow transition boundary was obtained. As shown in Figure 5 [Figure 5: see original paper], the comparison between experimental and predicted values shows minimal error, demonstrating that equation (9) can be used to calculate the critical void fraction in rectangular channels with larger gaps.

[Figure 5: see original paper]

Conclusions

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

(2) For rectangular channel gaps larger than 2 mm, the transition boundary shifts leftward as the hydraulic diameter increases.

(3) In the narrow channel range, Ishii’ s drift-flux correlation can be adopted as the flow regime transition boundary.

(4) In conventional rectangular channels, the critical void fraction in transition criteria depends on the initial bubble size. By using Zhao Jianfu’ s correlation for critical void fraction to modify Ishii’ s void fraction calculation, the predicted transition boundaries show good agreement with experimental results.

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