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Effects of Channel Gap and Channel Attitude on Flow Pattern of Air-water Two-phase Flow in Rectangular Millimeter-scale Channels

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Abstract

Effects of channel gap and channel attitude on the flow pattern of gas-liquid two-phase flow in rectangular millimeter-scale gap channels are investigated. The channel gap is varied from 0.5mm to 10.0mm. The observed flow patterns in horizontally placed channels are classified into three categories: bubbly flow, slug flow and annular flow. As the gap becomes small, the bubbly flow regime shifts to the slug flow regime. The boundary between the slug flow regime and the annular flow regime is hardly dependent on the gap. In the bubbly flow regime, the so-called channeling phenomenon of bubbles takes place.

Concerning the effects of channel attitude on the flow pattern, a channel with a gap of 1.0mm is mainly used. The inclination angle of the channel is varied from 0° to 90°. The observed flow patterns for a vertically wide channel with an inclination angle of 0° are classified into three categories: bubbly flow, slug flow and stratified wavy flow. Those for an inclination angle of 90° are classified into bubbly flow, slug flow and annular flow. As the inclination angle increases from 0° to about 30°, the bubbly flow regime becomes wide. With a further increase in the inclination angle from about 30° to 90°, it becomes narrow. The slug flow regime changes with an increase in the inclination angle in a complicated manner.

Key words

Micro Reactor, Gas-Liquid Two-Phase Flow, Flow Pattern, Rectangular Millimeter-Scale Channel, Channel Attitude

1. Introduction

Reduction of process scale has attracted much interest of many researchers and engineers especially in chemical and materials engineering. This is because precise control of the reaction temperature, reaction time, materials volume ratio, and so on is possible.

In general, the conventional process scale range is "cm" to "m", while the target of the reduced scale range is "sub-mm" to "μm". Concerning chemical, analytical processes as well as micro reactors, the reduction of process scale is promoted drastically. The small process called "labo on chip" allows precise analysis with very small amount of samples. Although these reduced scale processes should be more popular, there are many fundamental difficulties.

One is the handling of fluids. Even for liquids, pumping, sending, mixing of them in micro channels and vessels are rather difficult [1-4]. These difficulties become more serious when gas is introduced into the

channels and vessels. In case of gas-liquid two-phase flow, there are few reports about applications.

These difficulties arise from a change in the governing forces. The force due to surface tension becomes dominant as the scale of the reactor decreases. To solve these problems in "μm" scale reactors, it is important to understand the transition phenomena during a change in the dominant forces. In a "mm" scale channel, such transition phenomena of gas-liquid two-phase flow can be observed[5-11], but the detailed information on them is not available.

The objective of this study is to find out new transition phenomena and to clarify the effects of the inclination angle and gap of the channel on flow pattern of a gas-liquid two-phase flow in a "mm" scale rectangular channel.

2. Experimental Apparatus and Method

Figure 1 shows a schematic of the experimental apparatus. The millimeter-scale rectangular flow channels were placed horizontally for channel gap experiment. De-ionized water and air were used as the working fluids. The water was supplied into the test channel through a degassing vessel by a pump. The water flow rate was regulated by a power controller equipped with the pump and a valve. Air was introduced from the same side of the liquid inlet to the test channel. The air flow rate was regulated by a mass flow controller. Both the superficial velocities of air and water were varied from 5.0cm/s to 120cm/s. A gas-liquid two-phase flow was formed in the channel and it developed fully in the first half of the channel. A mixture of water and air was lead to the reservoir where the air was separated and the water was circulated with the pump. The fully developed flow patterns were observed with a still camera and by eye inspection from the upper side of the channel.

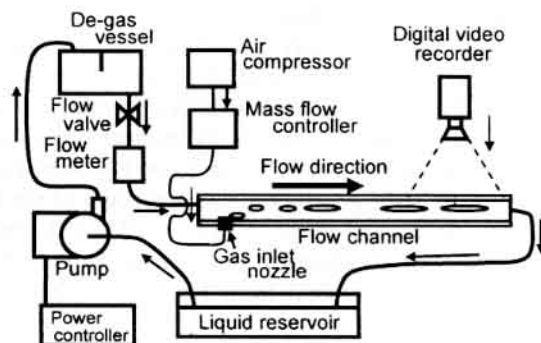


Fig. 1 Schematic diagram of experimental apparatus

Figure 2 shows the details of the test channel. The width of the channel was 50 mm and the length was 1,100 mm. The height of the channel(gap) was 0.5, 1.0, 2.0, 5.0 and 10.0 mm. The flow channel was made of transparent acrylic resin to observe the flow pattern through the channel walls. The contact angle of a water droplet on the acrylic resin was 71°. Consequently, the test channel is wetted by water. The gas was supplied into the test section from a single-hole metal nozzle. The diameter of the hole was 1mm. U-shaped manometers were used for measuring the static pressure.

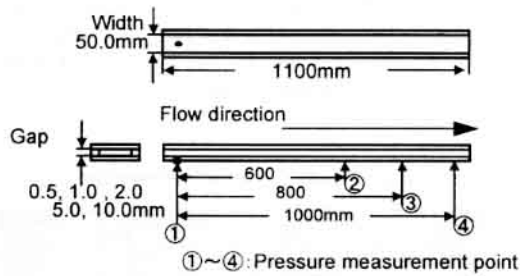


Fig.2 Details of flow channels

All tested attitudes of the flow channel are shown in Fig.3. The inclination angle of attitude-3 was 30°.

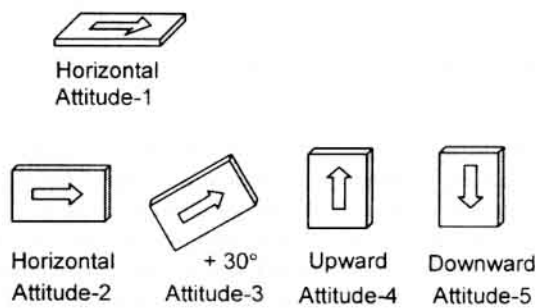


Fig.3 Attitude of the flow channels

3. Results and Discussion

3.1 Effects of channel gap

All flow patterns were observed at attitude-1. The main flow patterns were categorized into three types: bubbly flow, slug flow and annular flow. The typical three flow patterns of gas-liquid two-phase flow in the 2mm gap channel are shown in Fig.4.

- (1) Bubbly flow (B): Small bubbles flow in the continuous liquid phase.
- (2) Slug flow (S): Large two-dimensional slug-shaped bubbles flow in the continuous liquid phase. The length of each bubble is greater than the width of the channel of 50mm. The liquid contains isolated gas bubbles.
- (3) Annular flow (A): Both gas and liquid phases flow as continuous phases. The gas phase exists near the center of the channel. In addition, two transition flow patterns, slug-bubbly flow (S-B) and annular-slug flow (A-S), were observed.

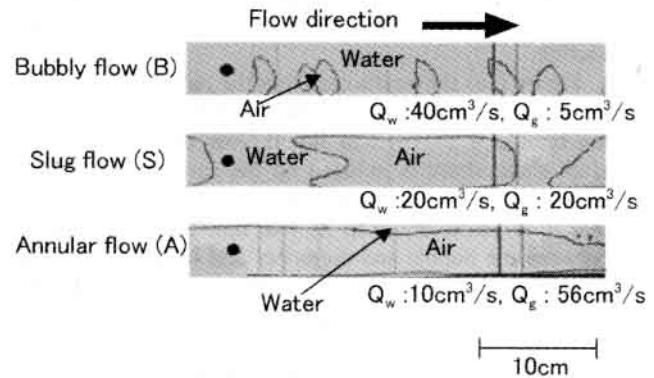


Fig. 4 Typical flow patterns in 2mm gap channel

The flow pattern map for the 2.0mm gap channel is shown in Fig.5. The vertical axis is the superficial gas velocity, j_g , and the horizontal axis is the superficial water velocity, j_w . The flow regime consisted mainly of bubbly flow, slug flow and annular flow under the experimental conditions considered. Figure 5 also shows the comparison of the flow pattern transition lines for the channels with the gaps of 2.0mm and 5.0mm. The annular-slug boundary lines for the two channels agreed with each other. Meanwhile, the bubbly-slug boundary line for the 2.0mm gap channel shifted to the lower right side of that for the 5.0mm gap channel. In other words, bubbles in the channel with a gap of 2.0mm are more likely to coalesce with one another than those in the channel of a gap of 5.0mm in a lower j_w region. Concerning the bubbly-slug boundary lines of 2mm and 5mm gap channels, the boundary lines observed here agreed satisfactorily with those observed by Ali et.al [10] for a superficial water velocity ranging from 80cm/s to 120cm/s. However, the bubbly-slug boundary lines for j_w from 10cm/s to 80cm/s cannot be extrapolated from the results of Ali et.al.

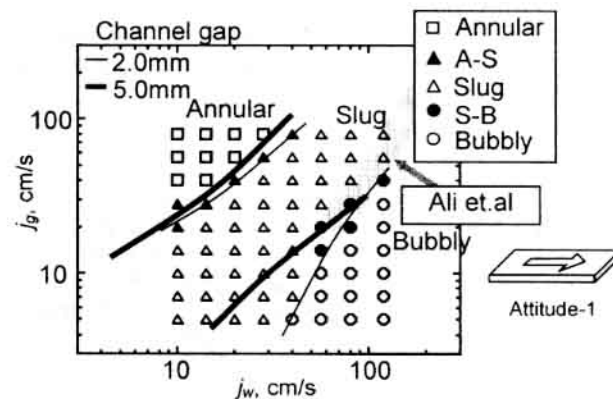


Fig. 5 Comparison of flow pattern regimes for different gaps (Channel gap, $H=2.0, 5.0$ mm)

The relationship between the bubble thickness, h , and the channel gap, H , will be discussed in the following section.

Figure 6(a) shows the case that the bubble thickness, h , is smaller than the channel gap, H , the lower surface of the bubble is exposed to liquid flow of high velocity. High shear stress is induced on the surface and, hence, the surface becomes unstable. Figure 6(b) shows the case that h is nearly equal to H , two thin liquid films exist between the bubble and the upper and lower walls. The liquid velocity in each film is not high. Accordingly, the bubble surface is kept stable.

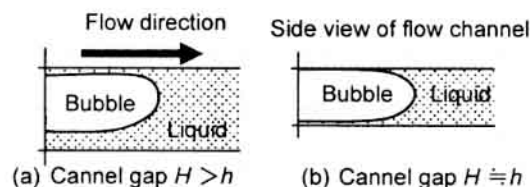


Fig. 6 Schematics of cross-sectional bubble shape

Cotter [11] gave the curvature radius of a bubble placed in stagnant liquid below a flat plate as a function of the horizontal curvature radius and vertical curvature radius. The vertical curvature radius of a bubble, which is a half of the bubble thickness, h , is estimated to be from 0.9mm to 1.9mm under the experimental conditions considered in this study. Accordingly, this result means that the bubble thickness ranges from 1.8mm to 3.8mm. The channel gap, H , of 2.0mm is included in this bubble thickness range.

A comparison of flow pattern transition lines for the 2.0mm gap channel and 1.0mm gap channel are shown in Fig.7. The annular-slug boundary lines for 1.0 and 2.0mm gaps are in good agreement with each other. The slug-bubbly boundary line for the 1.0mm gap channel shifted to the upper left side of that for the 2.0mm gap channel under a low superficial water velocity condition. In other words, bubbles in the 1.0mm gap channel tend to break up more frequently than bubbles in the 2.0mm gap channel.

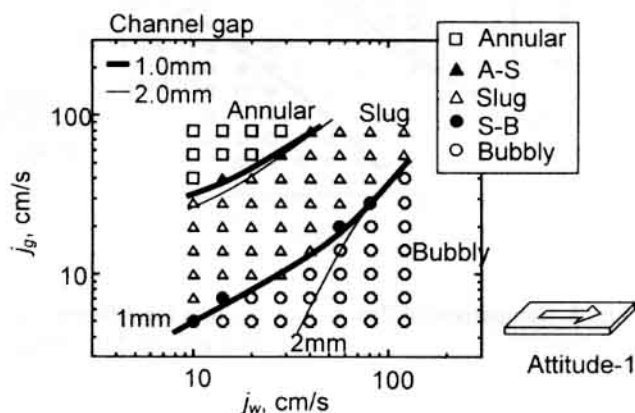


Fig.7 Comparison of flow pattern regimes
(Channel gap, $H=1.0, 2.0$ mm)

To understand the difference more in detail, the flow patterns in the 1.0mm and 2.0mm gap channels were observed and compared under the same superficial velocities. Figure 8(a) shows a typical slug flow pattern in the 2.0mm gap channel. Meanwhile, Fig.8(b) shows many small bubbles dispersed in the 1.0mm gap channel. From Fig.8(b), it is difficult to understand the motion of small bubbles. Photographs therefore were recorded successively on a digital camera at a constant time interval. Analysis of the photographs revealed that some bubbles move through the clearance of stagnant bubbles like a "channeling flow". It was clarified that thin water films between a stagnant bubble and the upper and lower walls break down. As a result, gas-liquid-solid three-phase interfaces were formed on the walls.

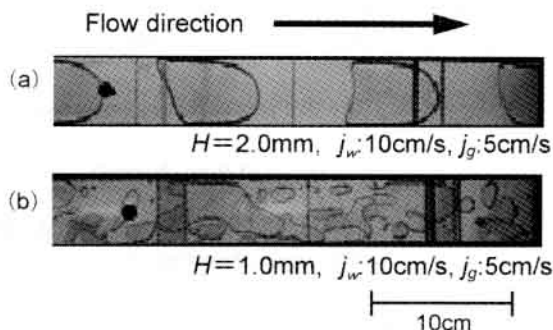


Fig.8 Comparison of flow pattern (Channel gap, $H=1.0, 2.0$ mm)

The vertical cross-section of the two channels are schematically shown in Fig.9. In case of the 2.0mm gap channel, thin liquid films exist between a bubble and the upper and lower walls. Accordingly, the bubble can move smoothly, as shown in Fig.9(a). On the other hand, for the 1.0mm gap channel, thin liquid films on the two walls break down and gas-liquid-solid three-phase interface are formed, as shown in Fig.9(b). In order to move the bubble, it is necessary to move the three-phase interface. The flow resistance therefore becomes high when the channeling occurs.

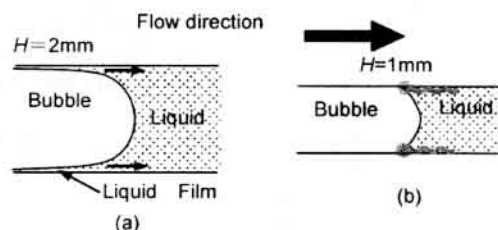


Fig.9 Schematic diagrams of cross-sections of gas-liquid

This result suggests that bubbles are more likely to break up as the channel gap decreases. In order to clarify the presumption, a channel with a gap of 0.5mm was chosen. The flow pattern map is plotted in Fig.10.

Compared to the slug-bubbly boundary lines for the 2.0mm and 1.0mm gap channels, the boundary line for the 0.5mm gap channel shifted toward the slug flow regime. Extension of the bubbly flow regime suggests that a bubble is more likely to break up in the 0.5mm gap channel than that in the 1.0mm gap channel.

The effects of the gap can be summarized as follows: The mechanism of bubble break up seems to change at around a gap of 2mm. When the gap was increased over 2mm, bubbles tend to break up due to the influence of turbulence of the liquid flow. On the other hand, when the gap was decreased below 2mm, bubbles tend to break up due to the restriction effect of the channel walls.

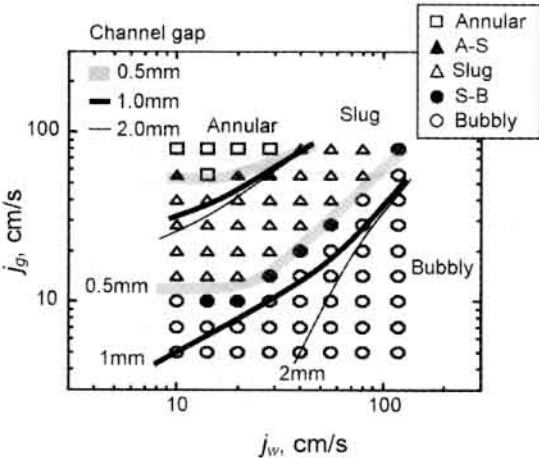


Fig. 10 Comparison of flow pattern regimes ($H=0.5, 1.0, 2.0\text{mm}$)

3.2 Effects of channel attitude

Figure 11 shows the flow pattern map in 1mm gap channel for attitude-1. The flow patterns consisted mainly of the bubbly flow, slug flow and annular flow.

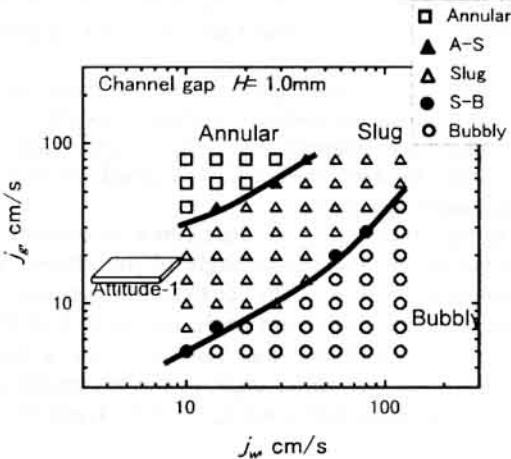


Fig.11 Flow pattern map for attitude-1

Figure 12 shows the comparison of the flow pattern transition lines for the attitude-1 and attitude-2. The bubbly-slug boundary line for attitude-2 shifted to the lower right side of that for attitude-1. In other words,

bubbles in the channel with attitude-2 are more likely to coalesce with one another than those in the channel with attitude-1. This tendency was caused by a top wall surface area difference between the two types of channels. In case of attitude-1, the upper wall spread wide in the horizontal direction and, hence, bubbles can be scattered on the surface of the upper wall. On the other hand, in case of attitude-2, as the surface area of the upper wall is very small, bubbles are lifted up by the buoyancy forces acting on them, gather near the upper wall, and coalesce with one another. For the continuous gas phase in attitude-2, the wavy flow pattern was observed and plotted in Fig.12 with open squares. The wavy flow pattern regime agreed favorably with the annular flow pattern regime of attitude-1.

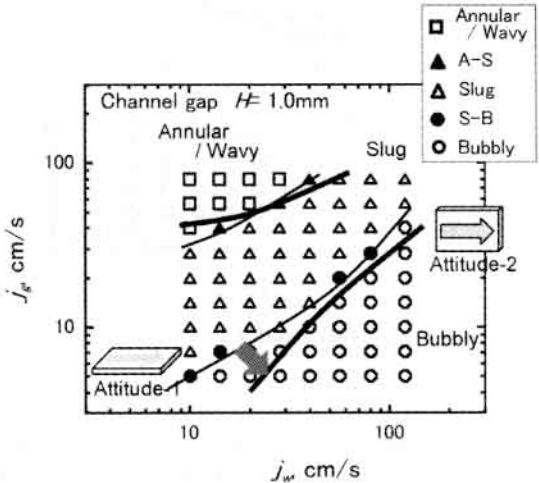


Fig.12 Flow pattern map for attitude-1 and attitude-2

Figure 13 shows a comparison of the annular flow pattern and the wavy flow pattern. In the two photographs, both the gas and liquid phases were continuous phase. The gas phase in the annular flow existed near the center of the channel, as seen in the upper figure. On the other hand, the gas phase in the wavy flow moved along the upper wall by buoyancy. In the stratified flow regime, when the velocity difference between the gas and liquid phases was large, a wave motion was caused on the surface. This pattern was named the stratified wavy flow.

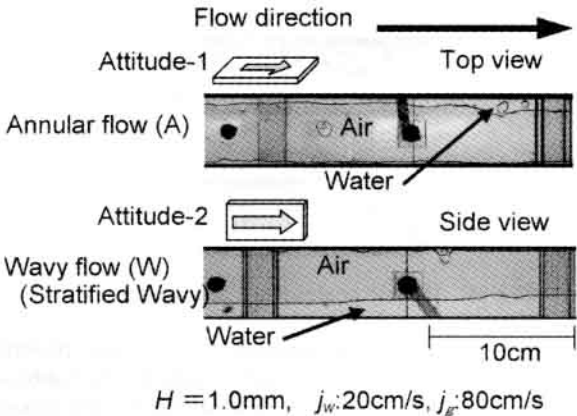


Fig.13 Comparison of annular flow pattern and wavy flow

Figure 14 shows a comparison of the flow pattern transition lines between the attitude-2 and attitude-3. The bubbly-slug and annular-slug boundary lines for attitude-3 shifted to the upper left side of that for attitude-2. In other words, bubbles in the channel with attitude-2 are more likely to coalesce than those in the channel with attitude-3.

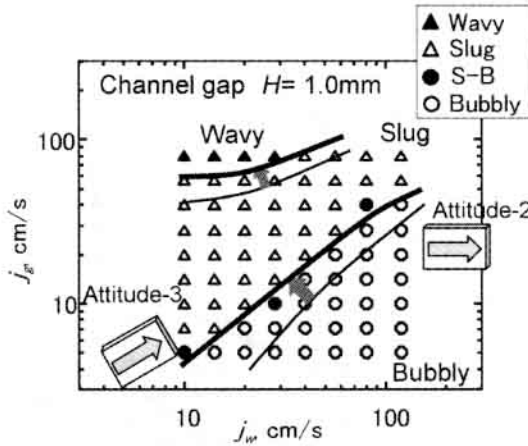


Fig. 14 Flow pattern map for attitude-2 and attitude-3

Figure 15 shows the coalescence mechanism of bubbles in the channel with attitude-2. Bubbles ascended towards the upper wall by buoyancy, spread along the upper wall, finally coalesce with one another. Bubbles in the channel with attitude-3 ascended towards the upper wall by buoyancy, but accelerated in the flow direction due to channel inclination. Bubbles do not spread along the top wall and, as a result, it is hard for them to coalesce with one another. The shape and motion of a bubble were significantly affected by the surface tension force and buoyancy force in the channel with attitude-3.

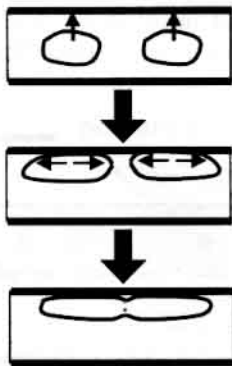


Fig. 15 Bubble coalescence at attitude-2

Figure 16 shows a comparison of the flow pattern transition lines for attitude-3 and attitude-4. The bubbly-slug boundary line for attitude-4 shifted to the lower

right side of that for attitude-3 in the lower superficial gas velocity, but in the higher superficial gas velocity, the boundary line shifted to the upper left side. In other words, bubbles in the channel with attitude-4 are more likely to coalesce than those in the channel with attitude-3 in the lower superficial gas velocity.

In the lower superficial gas velocity, the shape and motion of a bubble were affected by the buoyancy force and surface tension force, and hence, ascending bubbles coalesced with one another. Meanwhile, in the higher superficial gas velocity, the shape and motion of a bubble were affected mainly by the inertial force. Accordingly, ascending bubbles did not coalesce so often.

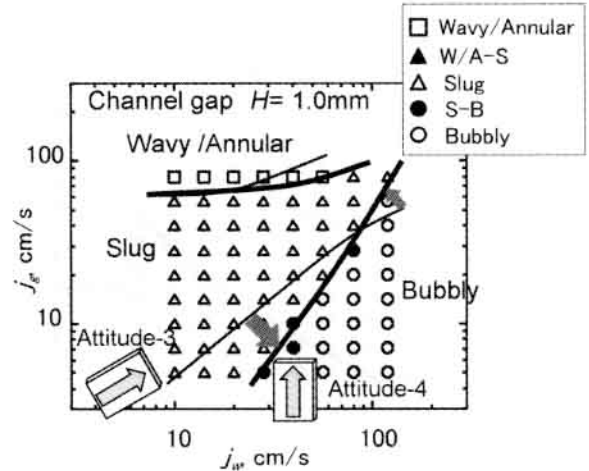


Fig. 16 Flow pattern map Flow direction: 30°

4. Conclusions

In milli-scale horizontally placed rectangular channels, the effect of the plate gap on the flow pattern was clarified as follows.

- (1) When the channel gap was greater than the estimated bubble thickness, the bubble was likely to disintegrate due to a hydrodynamic instability appearing on the bubble surface.
- (2) When the channel gap was nearly equal to the estimated bubble thickness, the bubble was stable.
- (3) When the channel gap was smaller than the estimated bubble thickness, so-called channeling phenomenon appeared.

On the other hand, the coalescence of bubbles was affected by the inclination angle of the channel in a complicated manner. The coalescence became less frequent as the inclination angle increased from 0° to 30° but the tendency was reversed with a further increase in the inclination angle, as can be seen from the flow pattern maps shown in Figs. 11, 12, 14, and 16.

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