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Flow Patterns of Gas-Liquid Two-phase Flow through an Abrupt Expansion in Millimeter-Scale Rectangular Channel

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Abstract

The effect of an abrupt expansion on the flow pattern of air-water two-phase flow in a millimeter-scale rectangular channel was investigated. The channel height was fixed as 0.19 mm, 0.50 mm, 1.00 mm and 2.00 mm. The expansion ratio was 5, 2.5, 1.67 and 1.25 for every channel height. The superficial velocity of air was varied from 5.0 cm/s to 80.0 cm/s and that of water was varied from 10.0 cm/s to 80.0 cm/s. As a result, a flow pattern with recirculation zone was observed in the channel height of 2.00 mm and 1.00 mm. This is the same pattern as that in the conventional scale pipes and ducts with an abrupt expansion. Furthermore, there was no effect of an abrupt expansion on the flow pattern when the expansion ratio was close to unity. On the other hand, in the channel height of 0.19 mm, each bubble spread in the lateral direction after it passed through the abrupt expansion. This is an interesting phenomenon in the small channel height.

Key words

Gas-Liquid Two-Phase Flow, Flow Pattern, Abrupt Expansion, Rectangular Channel, Millimeter-Scale Channel

1. Introduction

Gas-liquid two-phase flows are widely observed in chemical plants, atomic power plants and so on for the use in heat exchangers. The diameter of pipes used in the plants ranges from several centimeters to a few meters. In these pipes, the volumetric forces such as the inertial forces of gas and liquid, the gravitational force acting on the liquid, and the buoyancy forces acting on the gas govern the behavior of the gas-liquid two-phase flow [1].

Recently, demands of gas-liquid two-phase flow in microreacter, microelectronic devices and compact heat exchangers have been increasing. In the microscale channels, the surface force, interfacial force, and viscous force would be dominant in place of the volumetric forces. Accordingly, the flow pattern and the basic characteristics of the gas-liquid two-phase flows in microscale channels would be different from those in the conventional scale pipes [2-4]. Also, the channels used in the compact heat exchangers would be rectangular in shape due to high-specific surface area. In addition, there must be a change in the cross-sectional area in the channel passage, such as an abrupt expansion [5-7], an abrupt contraction [8], and so on. In this study we focused on a millimeter-scale rectangular channel with an abrupt expansion, and investigated the effect of the abrupt expansion on the flow pattern of gas-liquid two-phase flow.

2. Experimental Apparatus

A schematic diagram of the experimental apparatus is shown in Fig. 1. Air and de-ionized water were used as the working fluids. Water was supplied from a reservoir tank into the flow channel by a pump. The flow rate was measured by a flow meter and controlled by the pump equipped with a power inverter. Air was supplied from an air compressor and the flow rate was controlled by a mass flow controller. The water inlet pipe was 5.0 mm in diameter, and the air inlet pipe was mounted concentrically on the water inlet pipe. The superficial velocities of air, j_g, and water, j_w, were calculated using the channel height h and the channel width downstream of the abrupt expansion. They were varied up to 80.0 cm/s. The flow pattern of air-water two-phase flow across the abrupt expansion was observed with a high-speed camera at a flame rate of 500 fps.

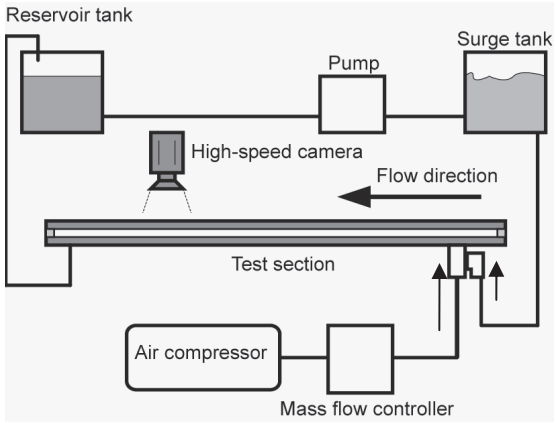

Fig. 1 Schematic diagram of experimental apparatus

The details of the test section are shown in Fig. 2. The test section was constructed by clipping a thin sheet of fluororesin paper by two transparent glass plates. The wide face of the test section was horizontally placed. The length of the two glass plates were 465 mm, and the distance between the inlet of air and water and the outlet was 420 mm. The width upstream of the abrupt expansion was W_1 = 10, 20, 30 and 40 mm. The abrupt expansion was placed 170 mm downstream of the inlet of air and water and the

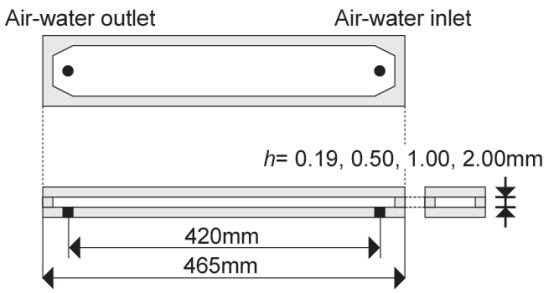

Fig. 2 Details of test section

channel width downstream of the abrupt expansion W_2 was 50mm. The expansion ratio A_s is defined as the ratio of W_2 to W_1. Configurations of an abrupt expansion are shown schematically in Fig. 3. The thickness of the thin sheet of paper was changed as 2.00 mm, 1.00 mm, 0.50 mm and 0.20mm. The actual channel height was 2.00 mm, 1.00 mm, 0.50 mm, and 0.19 mm. Gas-liquid two-phase flows were fully developed before the abrupt expansion.

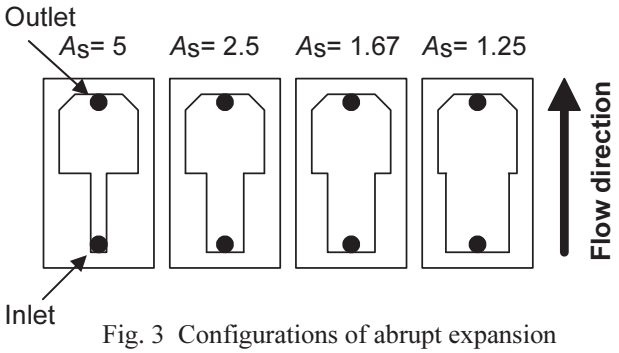

Fig. 3 Configurations of abrupt expansion

3. Results and Discussion

3.1 Flow pattern in a channel without abrupt expansion

The flow pattern observed in a channel without an abrupt expansion was categorized into three. The photographs of them are shown in Fig.4 (a) through Fig.4 (c).

(1) Bubbly flow (B): Small bubbles move in the continuous liquid phase (Fig.4 (a)).

(2) Slug flow (S): Large slug-shaped bubbles move in the continuous liquid phase (Fig.4 (b)). The length of the bubble is larger than the width of the channel.

(3) Annular flow (A): Gas and liquid phases are both in continuous phases. The gas phase exists near the center of the channel (Fig.4 (c)).

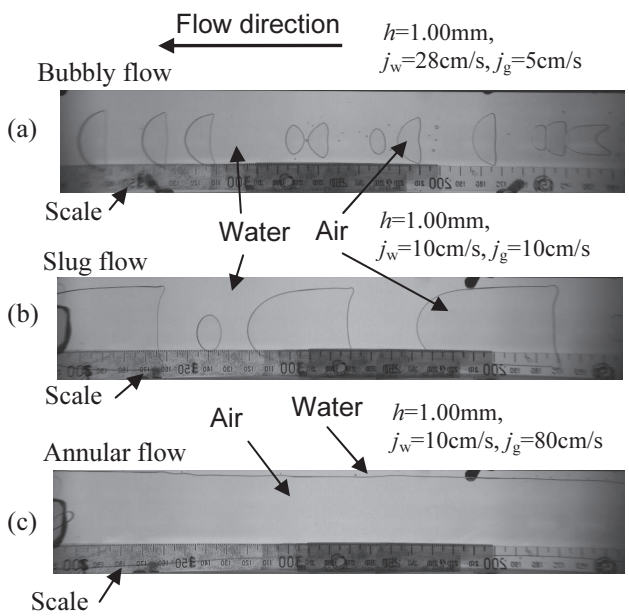

Fig.4 Typical flow patterns observed in the rectangular channel

The flow pattern maps for the channel without an abrupt expansion are shown in Fig. 5 through Fig. 8. The vertical axis is the superficial air velocity, j_g, and the horizontal axis is the superficial water velocity, j_w. The pressure in the test section was elevated above the atmospheric pressure especially for the height of 0.19mm. Accordingly, the superficial air velocity was evaluated at a mean pressure in the test section. The transitional flow pattern from bubbly to slug flows is denoted by B-S and that from slug to annular flows is denoted by S-A. The shaded area indicates the boundary area between bubbly and slug flows obtained by Ali *et al.* [9], and the solid line denotes the boundary line between the two kinds of flows by Moriyama *et al.* [10]. The height, h, and width, W, of the test section of Ali *et al.* were 0.778 mm and 80 mm, respectively, and those of Moriyama *et al.* were 0.096 mm and 30 mm, respectively. The sizes of these channels are comparable to those chosen in this study.

As shown in Figs. 5 through 8, the flow pattern maps consist mainly of bubbly and slug flows. The annular flow was observed only in the region of high superficial air

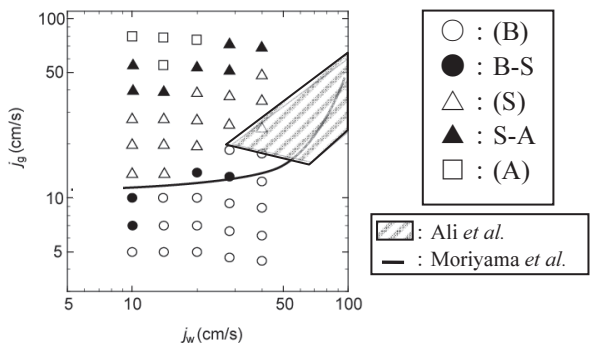

Fig. 5 Flow pattern map (h=2.00 mm)

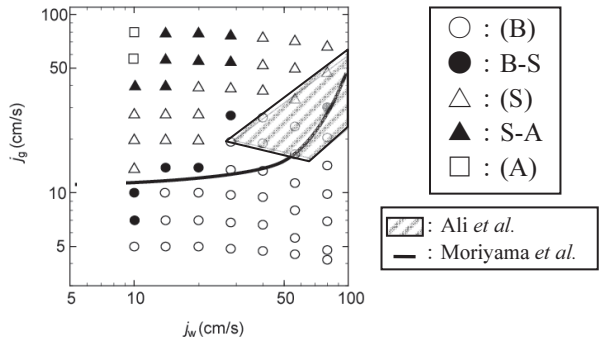

Fig. 6 Flow pattern map (h=1.00 mm)

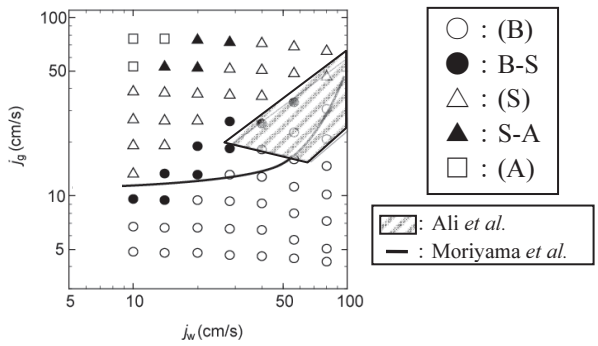

Fig. 7 Flow pattern map (h=0.50 mm)

velocity and low superficial water velocity in every figure. The boundary between the bubbly and slug flows in Figs. 5 through 7 was in good agreement with those reported by Ali *et al.* and Moriyama *et al.* This boundary however shifted upward in Fig. 8.

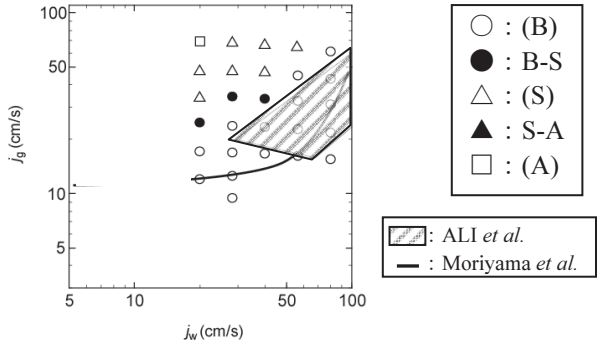

Fig. 8 Flow pattern map (h=0.19 mm)

3.2 Effect of expansion ratio on flow pattern

The flow patterns presently observed in air-water two-phase flows through an abrupt expansion can be categorized into four types. The photographs of them are shown in Fig.9 (a) through Fig. 9 (d). They are named the types (1), (2), (3), and (4).

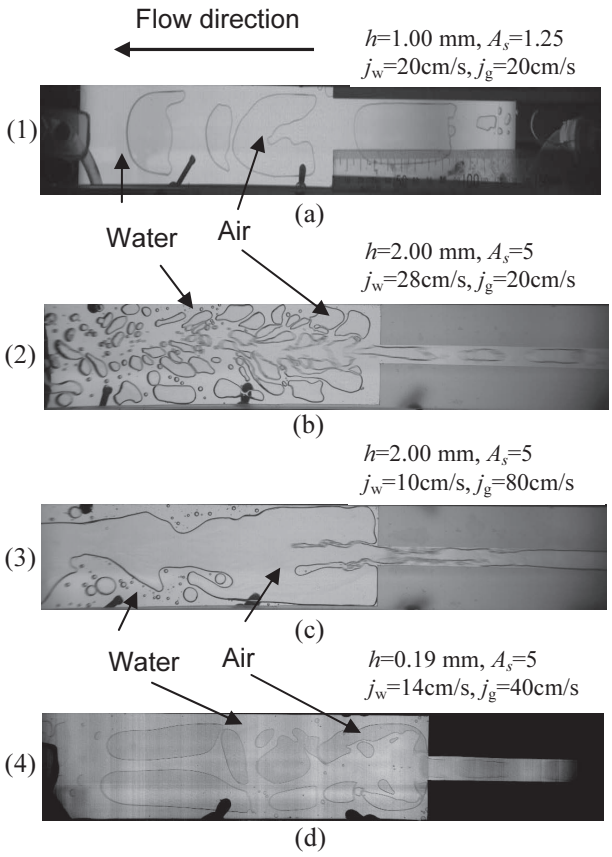

Fig. 9 Typical flow patterns through the abrupt expansion

(1) The flow pattern is not influenced by an abrupt expansion. Bubbly, slug, annular flows are included in this type. This situation was often seen in the small expansion ratios.

(2) A recirculation zone was observed right after the abrupt expansion. This flow pattern was observed in the conditions of high water flow rate (high j_w) and high expansion ratio.

(3) An air cavity was formed after the abrupt expansion and a water jet penetrated into it. This pattern was observed in high air flow rate (high j_g), low water flow rate (low j_w) and high expansion ratio.

(4) Each bubble splits in the lateral direction just after the abrupt expansion.

The flow pattern maps for A_s=5, 2.5, 1.67 and 1.25 are shown in Figs. 10 through 13 to reveal the effect of expansion ratio. The height of the channel was fixed to be 2.00 mm. As shown in Fig. 10, when both the superficial air velocity and superficial water velocity were low, the type (1) was observed. As the superficial water velocity was increased, the type (2) became to be observed. The type (3) appeared in the high j_g and low j_w region. As the expansion ratio, A_s, was decreased from 5 to 2.5, the type (3) disappeared. With a further decrease in A_s, type (1) became dominant under the experimental conditions chosen in this study. The flow pattern was hardly affected by j_g and j_w for A_s=1.25.

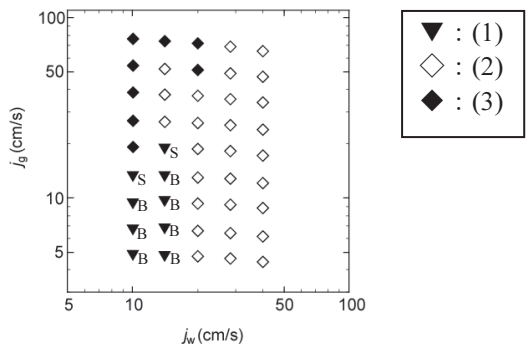

Fig. 10 Flow pattern map for h=2.00 mm and A_s=5
(B and S denote bubbly and slug flows, respectively)

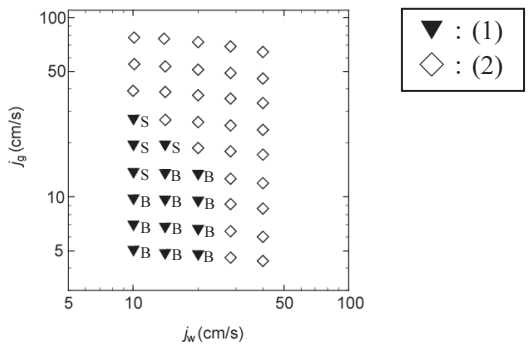

Fig. 11 Flow pattern map for h=2.00 mm and A_s=2.5
(B and S denote bubbly and slug flows, respectively)

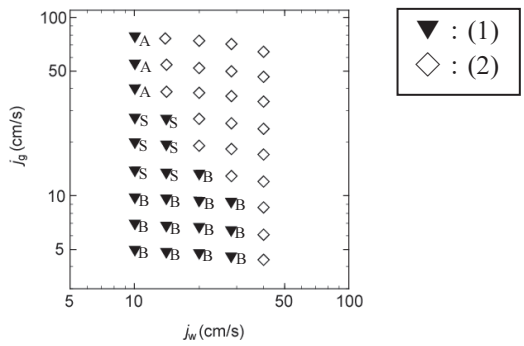

Fig. 12 Flow pattern map for h=2.00 mm and A_s=1.67
(B, S and A denote bubbly, slug, and annular flows, respectively)

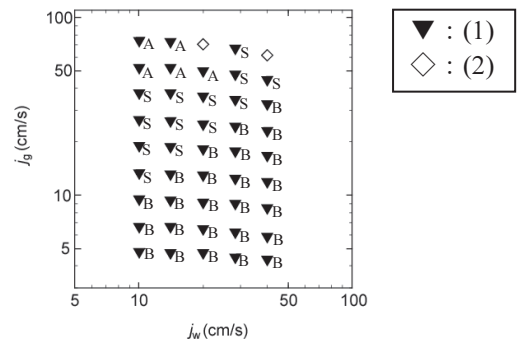

Fig. 13 Flow pattern map for h=2.00 mm and A_s=1.25
(B, S and A denote bubbly, slug, and annular flows, respectively)

3.3 Effect of channel height on flow pattern

The flow pattern maps for h=1.00, 0.50 and 0.19 mm are shown in Figs. 14 through 16 to reveal the effect of channel height on the flow pattern at the same expansion ratio. The expansion ratio was A_s=5. The flow pattern map for h=1.00mm was almost the same for h=2.00 mm shown in Fig.10. The type (1) and type (3) disappeared for h=0.50mm and the type (4) first appeared in the region where both j_g and j_w were low. The type (2) typical of the flow pattern in the conventional scale pipes and ducts disappeared completely for h=0.19 mm in Fig. 16. Consequently, the effects of volumetric forces on the flow pattern became small compared to that of the surface force under this condition.

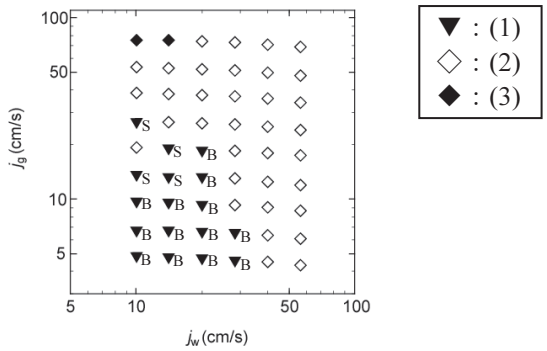

Fig. 14 Flow pattern map for h=1.00 mm and A_s=5
(B and S denote bubbly and slug flows, respectively)

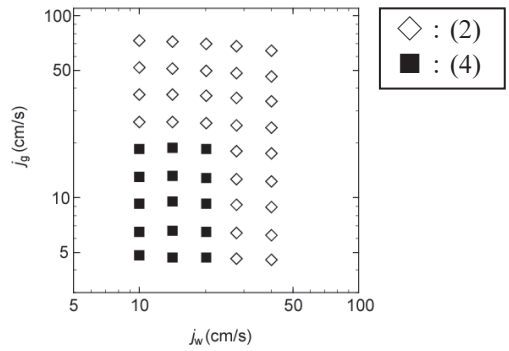

Fig. 15 Flow pattern map for h=0.50 mm and A_s=5

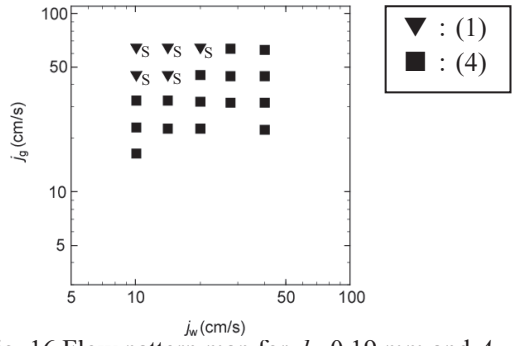

Fig. 16 Flow pattern map for h=0.19 mm and A_s=5
(S denotes slug flow)

3.4 Bubble splitting mechanism in type (4)

The type (4) is a unique phenomenon observed only in small channel heights as in h=0.50 and 0.19mm. This phenomenon is considered to occur due to the pressure drop associated with an abrupt expansion. The pressure loss is expressed as follows.

$$\Delta P_E = \zeta \frac{\rho}{2} v^2 \tag{1}$$

where ζ is the loss coefficient of an abrupt expansion, ρ is the mean density of a mixture of gas and liquid, the mean velocity v is assumed to be the sum of the superficial gas and liquid velocities upstream of the expansion. In this study ζ, ρ, and v are represented as follows.

$$\zeta = (1-m)^2 \tag{2}$$

$$\rho = \frac{j_w}{j_w + j_g}\rho_w + \frac{j_g}{j_w + j_g}\rho_g \tag{3}$$

$$v = \frac{(j_w + j_g)}{m} \tag{4}$$

The area ratio m is the inverse of A_s. In Eq. (3), ρ_g is much smaller than ρ_w, and, hence, the second term on the right-hand side of Eq. (3) is neglected. By substituting Eqs. (2)

through (4) for ζ, ρ, and v into Eq. (1), the following equation was derived.

$$\Delta P_E = \frac{(1-m)^2 (j_g + j_w) j_w \rho_w}{2m^2} \tag{5}$$

On the other hand, the difference between the pressure inside a bubble and that outside the bubble is given by the Laplace-Young equation as follows.

$$\Delta P_{LY} = (P_{in} - P_{out}) = \sigma(\frac{1}{R_1} + \frac{1}{R_2}) \tag{6}$$

where σ is the surface tension, R_1 and R_2 are the principle radii of curvature of a bubble. In this study the bubble is ellipsoidal in shape and, hence, $(1/R_1 + 1/R_2)$ is represented by

$$\frac{1}{R_1} + \frac{1}{R_2} = \frac{2}{h} + \frac{2}{W_1} \tag{7a}$$

The width W_1 is much greater than h, and hence the term $2/W_1$ is negligible compared to $2/h$. Eq.(7a) is transformed as

$$\frac{1}{R_1} + \frac{1}{R_2} = \frac{2}{h} \tag{7b}$$

Substituting Eq. (7b) for $(1/R_1 + 1/R_2)$ into Eq. (6) gives the following equation.

$$\Delta P_{LY} = \frac{2\sigma}{h} \tag{8}$$

Here, we assume that a bubble is split in the lateral direction when ΔP_E exceeds ΔP_{LY}. By equating Eq. (5) and Eq. (8), the following equation is obtained for the boundary among the type (4) and the remaining three types.

$$j_g = k \frac{4\sigma m^2}{h(1-m)^2 \rho_w} \frac{1}{j_w} - j_w \tag{9}$$

where k is a fitting parameter. In Figs. 17 through 19 a solid line denotes Eq. (9) for k=2. The line shown in Fig. 17 approximately fits the boundary between type (2) and type (4). In Fig.18 the solid line is located near the bottom of the left-hand side and type (4) was not observed in this figure. This fact partly supports the adequacy of Eq.(9). On the other hand, Eq.(9) cannot predict the boundary of type (4) region. The fitting parameter k therefore must be changed from 2 in this case. It is difficult at present to determine k because information on the flow pattern map around an abrupt expansion is limited. Further experiments should be carried out to make clear the adequacy of Eq. (9).

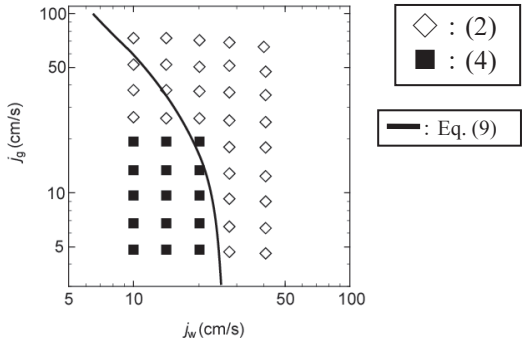

Fig. 17 Flow pattern map for h=0.50 mm and A_s=5

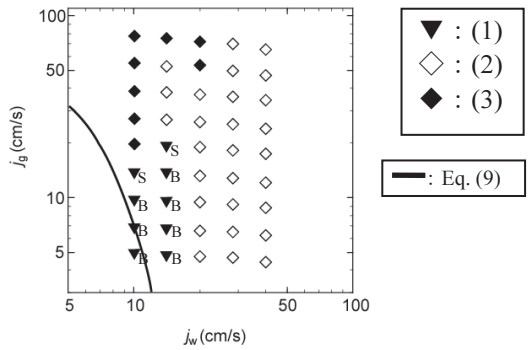

Fig. 18 Flow pattern map for h=2.00 mm and A_s=5
(B and S denote bubbly and slug flows, respectively)

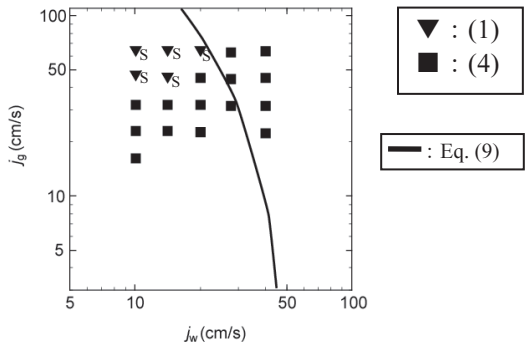

Fig. 19 Flow pattern map for h=0.19 mm and A_s=5
(S denotes slug flow)

4. Conclusions

The effect of an abrupt expansion on the flow pattern of gas-liquid two-phase flows in millimeter-scale rectangular channels was investigated. The flow patterns were categorized mainly into the following four types:

(1) The flow pattern is not influenced by the abrupt expansion.

(2) A recirculation zone appears right after the abrupt expansion.

(3) An air cavity is formed after the abrupt expansion and a water jet penetrates into it.

(4) Each bubble splits in the lateral direction just after the abrupt expansion.

The recirculation zone was observed for h=2.00 mm, 1.00 mm and 0.50 mm at high expansion ratios. This is the same tendency as in the conventional size pipes. By contrast, in the low channel height as h=0.19 mm, an interesting phenomenon was observed instead of the formation of recirculation zone. In this flow pattern, each bubble splits in the lateral direction. The effects of the volumetric forces disappeared and the surface force became dominant in this flow pattern.

The boundary between type (4) and type (2) for h=0.50 mm and A_s=5 in Fig.17 was approximately predicted by the following equation.

$$j_g = k \frac{4\sigma m^2}{h(1-m)^2 \rho_w} \frac{1}{j_w} - j_w$$

Nomenclature

A_s expansion ratio ($=W_2/W_1$)
h channel height
j_g superficial air velocity
j_w superficial water velocity
W_1 channel width before abrupt expansion
W_2 channel width after abrupt expansion
ρ_w density of water
ρ_g density of gas
σ surface tension
m $=1/A_s$

References

[1] Attou, A., Bolle, L. and Seynhaeve, J.M.: Experimental study of the critical flashing flow through a relief line: evidence of the double-choked flow phenomenon, *Int. J. Multiphase Flow*, **26**(2000), 921-947.

[2] Kumagai, T. and Iguchi, M.: Wettability Effect on Flow Pattern in Horizontal Air-Water Two-Phase Flow in Rectangular Small Channels (in Japanese), *J. JSEM*, **7**-1(2007), 50-55

[3] Xu, J.L., Cheng, P. and Zhao, T.S.: Gas-liquid two-phase flow regimes in rectangular channels with mini/micro gaps, *Int. J. Multiphase Flow*, **33**(2007), 575-594.

[4] Waelchli, S. and Rohr, R.P.: Two-Phase flow characteristics in gas-liquid microreactors, *Int. J. Multiphase Flow*, **32**(2006), 791-806.

[5] Wael, H.A., Chan, Y.C. and Mamdouh, S.: Pressure recovery of two-phase flow across sudden expansions, *Int. J. Multiphase Flow*, **33**(2007), 575-594.

[6] Wael, H.A., Chan, Y.C. and Mamdouh, S.: Development of two phase flow downstream of a horizontal sudden expansion, *Int. J. Heat and Fluid Flow*, **29**(2008), 194-206.

[7] Chen, I.Y., Liu, C.-C., Chien, K.-H. and Wang, C.-C.: Two-phase flow characteristics across sudden expansion in small rectangular channels, *Exp. Therm. Fluid Sci.*, **32**(2007), 696-706.

[8] Chen, I.Y., Liu, C.-C., Chien, K.-H. and Wang, C.-C.: Two-phase flow pressure change subject to sudden contraction in small rectangular channels, *Int. J. Heat and Fluid Flow*, **32**(2009), 297-306.

[9] Ali, I.M., Sadatomi, M. and Kawaji, M.: Adiabatic Two-Phase Flow in Narrow Channels Between Two Flat Plates, *Can. J. Chem. Eng.*, **71**(1993), 657-666

[10] Moriyama, K., Inoue, I. and Ohira, H.: The Hydraulic Characteristics of Two-Phase Flow in Extermely Narrow Channels : The Frictional Pressure Drop and Void Fraction of Adiabatic Two-component Two-phase Flow (in Japanese), *Trans. JSME.*, **58**-546(1992), (B) 401-407.