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FLOW PATTERNS OF GAS-LIQUID TWO-PHASE FLOW IN ROUND TUBE WITH SUDDEN EXPANSION

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ABSTRACT

Experimental studies were made on the multi-dimensional behavior of upward gas-liquid two-phase flow through the vertical round tube with an axisymmetric sudden expansion, which is one of the typical multi-dimensional channel geometry. The aims of this study are to clarify the multi-dimensional behavior of bubbly or slug flow affected by sudden expansion channel geometry, and to accumulate the experimental data for two-phase flow analysis, which is applicable to predict with appropriate accuracy the multi-dimensional its behavior. The direct observation using high-speed video camera was performed and revealed the multi-dimensional dynamic flow behavior with bubbles and gas-slug affected by the sudden expansion part (20 mm-tube to 50 mm-tube). The characteristic phenomena were observed such as bubble break-up, deformation due to the strong shear of liquid flow, or liquid micro jet penetration through the gas-slug, and so on. From these results, the flow regime map and the flow patterns at the below and above of the sudden expansion part were classified in relation to the bubble diameter. Additionally, the measurement of the void fraction profiles in the tube cross sections of sudden expansion were conducted at the different axial positions. The void fraction was measured using a point-electrode resistivity probe. The void fraction measurements in this study showed in detail that how the two phase flow develops along the direction of the downstream of the sudden expansion. In just above the sudden expansion, the void fraction distribution appeared the wall peak or the core peak in void fraction in the upstream of the sudden expansion. In the downstream of the sudden expansion, the void fraction distribution changes from a saddle shape or power-low shape into finally the saddle shape as the bubbly flow develops along the downstream of the sudden expansion. These experimental data in the sudden expansion of a vertical upward bubbly flow would become benchmark with respect to the multi-dimensional behavior of the two-phase flow analysis.

INTRODUCTION

Investigating the physical mechanism of two-phase flow is very important to design or carry out the reliability analysis for boiling heat transfer facilities such as a boiler, nuclear reactor, etc. Though one-dimensional simulation is mainly made for the numerical simulation of two-phase flow in nowadays, we must consider various peculiar properties, which provoke significant modifications of the flow. Therefore, such peculiar properties i.e. the experimental data of the multi-dimensional behavior of gas-liquid two-phase flow are significant to describe the two-phase flow. Under these circumstances, the case of a sudden expansion part corresponds to a current situation in practice. Furthermore it is also interesting geometry in fluid dynamics. In single-phase flow, this type geometry is largely studied in the literature both theoretically and experimentally [1]-[3].

Several studies have been made on two-phase flow in sudden expansion. Aloui and Souhar (1996) carried out the experimental study of bubbly flow in a flat horizontal sudden expansion channel [4][5]. It showed the visualization of bubbly flow and the experimental data of pressure, void fraction, liquid and bubble velocities, and bubble size. Besides, the theoretical and experimental study carried out by Aloui et al. (1999) [6] showed the experimental data such as pressure drop, wall shear stress, void fraction bubble velocity and bubble size and proposed the prediction model for pressure drop and. Rinne and Loth (1996) presented the experimental data in round tube such as void fraction, bubble velocity, bubble size and interfacial area concentration [7].

In recent years, a study for the multi-dimensional behavior of two-phase flow becomes more and more important. The theoretical or experimental studies on the prediction of void fraction and liquid velocity distributions in bubble induced natural circulation were performed in the rectangular vessel by Murai and Matsumoto (1992) [8], in the cylindrical vessel performed by Gofuku et al (1993) [9], and in the rectangular vessel with obstacle by Tomiyama et al (1994) [10], respectively. Through these studies, certain knowledge has been obtained. However, experimental data with regard to the multi-dimensional behavior is not sufficient. Therefore the mechanisms of these phenomena have not been fully clarified. As a result, numerical simulation models for the multi-dimensional two-phase flow analysis are not completely established [11].

This paper presents experimental studies of multi-dimensional behavior of upward gas-liquid two-phase flow through the vertical round tube with an axisymmetric sudden expansion, which is one of the typical multi-dimensional channel geometry. The aims of this study are to clarify the multi-dimensional behavior of bubbly or slug flow affected by sudden expansion channel geometry, and to accumulate the experimental data for two-phase flow analysis, which is applicable to predict with appropriate accuracy the multi-dimensional its behavior.

As the first step, the direct observation using high-speed video camera was performed and revealed the bubble and gas-slug multi-dimensional behavior affected by the sudden expansion part. Secondly, the flow regime map and the flow patterns at the below and above of the sudden expansion part were classified in relation to the bubble diameter. Additionally, the measurements of the local void fraction profiles in the tube cross sections of sudden expansion were conducted at the different axial positions.

NOMENCLUTURE

C_0 : distribution parameter, dimensionless
d_b : bubble diameter, mm
d_x : minor axis of bubble, mm
d_y : major axis of bubble, mm
g : gravity, m/s^2
j : superficial velocity of two-phase mixture, m/s
j_k : superficial velocity of k phase, m/s
Q_k : volume flow rate, l/min
Re : Reynolds number, dimensionless

Greeks
α : local void fraction of gas phase, dimensionless
σ : surface tension, N/m
ρ_k : density, kg/m^3
$\Delta\rho$: absolute value of density difference, kg/m^3

Symbols
R : tube radius, mm
y : distance from wall, mm

subscript
k : phase k
L : liquid phase
G : gas phase
20 : 20 mm-tube
50 : 50 mm-tube

EXPERIMENTAL SETUP

A schematic of experimental apparatus is shown in **Fig.1**. In the experiment, the data was obtained from a vertical, upward air-water two-phase flow at near atmospheric conditions in an optically clear pipe with an axisymmetric sudden expansion, which consists of the pipes of from 20 mm to 50 mm in diameter.

The water, pumped out by the centrifugal pump, reaches to the air-water mixing chamber passing through the flow control valve, the flow rotameter. After passing through the test channel, the air or bubbles are removed at an air-water separator, and water flows back to a storage tank through the water cooler. The air is pressurized using air compressor, and accumulated in the pressurized air tank through the air dryer. The air of pressurized tank is introduced to the bubble generator passing through flow control regulator, flow rotameter, and the air is injected into the water through the bubble generator. The bubble generator in this case installed at the center of the tube consists of a sintered stainless steel tube, 10 mm in diameter and 38 mm in height, having a particle passing diameter of 1.0 μm.

The vertical test channel consists of 20 mm-tubes and 50 mm-tubes, the vertical section is about 6.0 m in length. The upstream of sudden expansion is a 2.4 m-long and 20 mm in diameter of entrance section, and the downstream of sudden expansion is a 3.3 m-long and 50 mm in diameter. The outer surface of the viewing section for observing the sudden expansion is square acryl part (70×70 mm, 200 mm length), so as to prevent distortion of the images when captured by a video camera. The characterisity of two-phase flow phenomena in the sudden expansion, including the bubble diameter, were obtained through back-light image. However, there are some distortion of the images due to the difference in refractive index

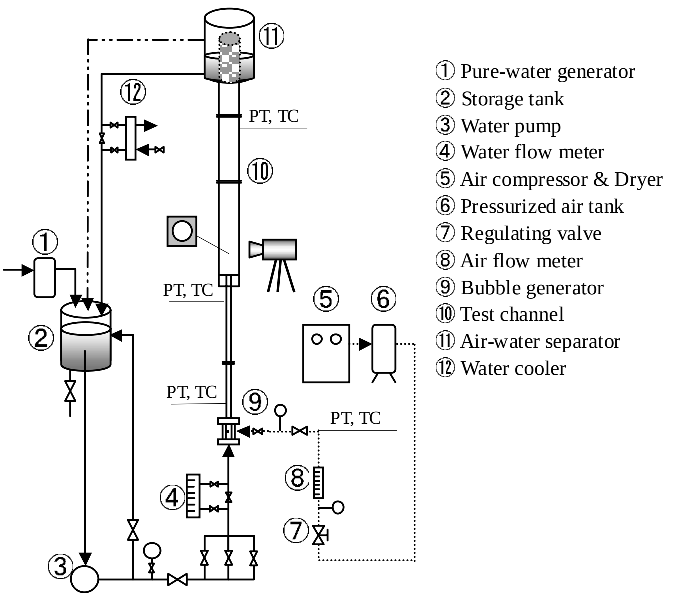

Fig.1 Experimental apparatus

between water and acryl part. A preliminary test was performed using a standard subject (see **Fig.2**) to confirm the distortion caused by reflection and curvature. The images are shown in **Fig.3**. **Figure 4-6** shows the void fraction measurement system. The resistivity probe design is schematically shown in **Fig.4**. A point-electrode probe material used was stainless wire with a diameter of 0.2 mm. The wire was also inserted into Teflon-insulated tube of 0.36 mm in diameter. The tip of wire was coated with insulating enamel, and it was dried up to ensure a well insulation at 200 degree centigrade. This wire was inserted into another stainless tube 2.0 mm diameter tube. The probe is a straight type, or so-called I-type; it is considered the influence of the re-circulation flow in sudden expansion. The electric signal from the probe is come in to the PC using data processing system (see **Fig.5**). The test channel of the local void fraction measurement is shown in **Fig.6**, and it can be traversed the radial and axial position. Therefore the measurement of the local void fraction distribution in the tube cross sections of sudden expansion were conducted by changing the axial positions. The void fraction data was detected by sampling frequency; 10 kHz and sampling time; 60 sec. The void fraction measurement between this I-type probe and the vertical probe or L-type probe was confirmed by another experiment. It was not a serious problem in void fraction measuring. Therefore we preferably employed the I-type probe for measuring the radial void fraction accurately.

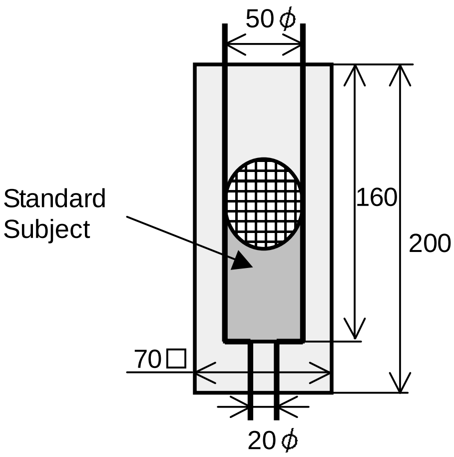

Fig.2 Viewing Section

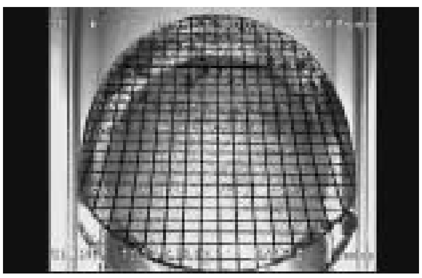

Fig.3 Image of standard subject

For the experiment, the water and the air superficial velocities in 20 mm-tube were set to be at j_{L20} = 0-5.31 [m/s], j_{G20} = 0.0533-0.696 [m/s], respectively.

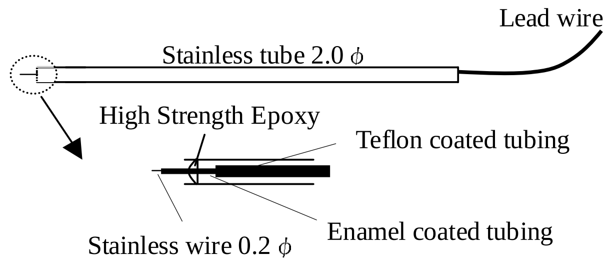

Fig.4 A point-electrode resistivity probe

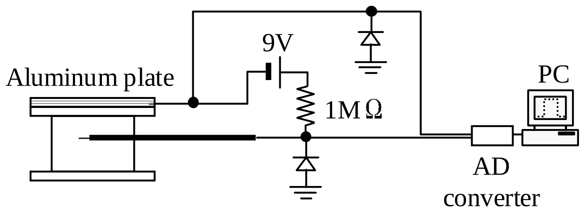

Fig.5 Data processing system

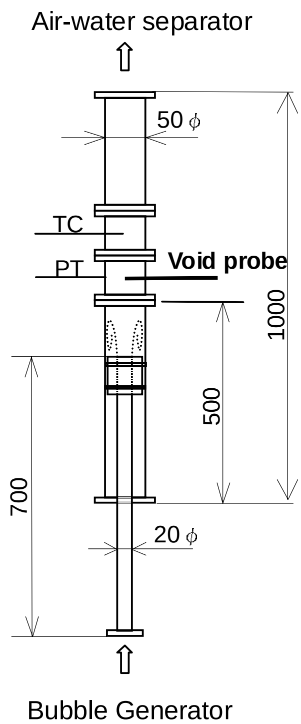

Fig.6 Test section for measurement of void fraction

RESULTS AND DISCUSSION

Flow patterns & Bubble diameter

As the first step, the direct observation in sudden expansion using high-speed video camera was performed to classify the flow patterns. **Figure 7-9** shows the relationship between bubble diameter and flow patterns of below and above of the sudden expansion part. From **Fig.8** and **Fig.9**, the flow patterns at the sudden expansion had the multi-dimensional structure that consists of (a) straight-up flow, (b) wall re-attachment region, and (c) re-circulation flow; the marks of circle, square and triangle represent the above flow patterns (see **Fig.10**). These multi-dimensional flow patterns and structure change depending on the superficial velocity of gas and liquid phase. Furthermore, as the characteristic phenomena, such as deformation and breakup of bubbles or gas-slug, will be described later, are induced in the sudden expansion part, the flow patterns would be more complicated. The characteristics phenomena affected by the sudden expansion can be described by comparing the results of below of the sudden expansion part or 20 mm-tube (**Fig.7**) with that of downstream of the sudden expansion (**Fig.9**). The bubble diameter of downstream of the sudden expansion is smaller than that of the below of the sudden expansion part. This tendency becomes much remarkable because the bubbles tear off due to the high shear layer.

The bubble diameter, d_b, was calculated from the equation (1) by assuming a distorted ellipsoidal bubble or a spherical bubble with the length along the minor–axis, d_x, and major-axis, d_y.

$$d_b = \sqrt[3]{{d_x}^2 \cdot d_y} \tag{1}$$

In this observation, it is difficult to estimate the bubble diameters using the images accurately due to the one-directional observation and the characteristic phenomena. This method includes the distortion errors of the images. The distortion errors, about ±20 %, of the images were confirmed by the preliminary test performed using a standard subject.

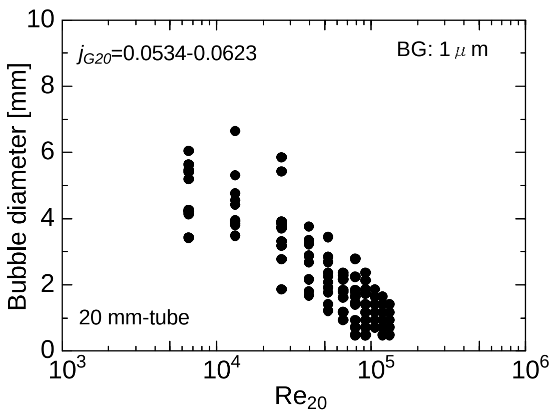

Fig.7 Bubble diameter in 20mm-tube

Characteristic phenomena

The detailed observation of the high-speed video camera captured 2 types of the interesting phenomena, that is, the deformation and the breakup of bubbles or gas-slug at the sudden expansion part.

In the slug breakup process (see **Fig.11**), at first, the gas-slug is divided into smaller gas-slug in the sudden expansion part, secondly, the liquid micro jet penetrates suddenly the divided slug, and the next, the micro liquid jet breaks up the gas-slug to some smaller bubbles. We could also observe the unique phenomena: formation of a liquid droplet in its

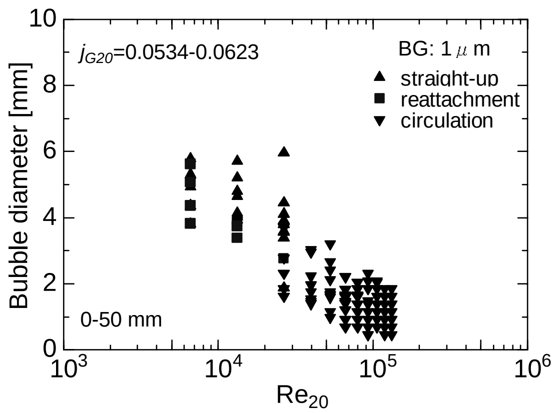

Fig.8 Flow pattern in sudden expansion part (0-50 mm)

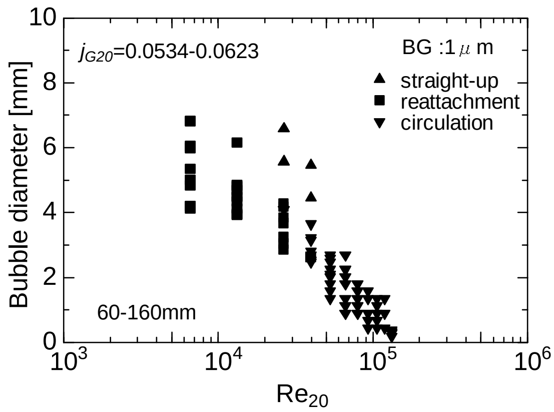

Fig.9 Flow pattern in sudden expansion part (60-160 mm)

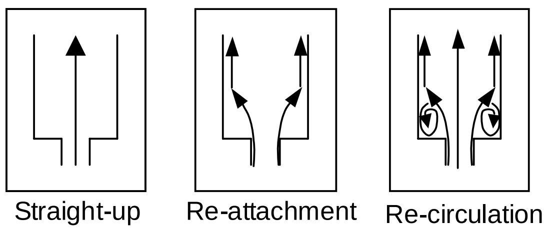

Fig.10 Typical flow pattern in sudden expansion part

projection and the nodal points due to collision at the tip of the projection of the droplet. This physical mechanism, however, has not been investigated in detail yet.

Bubble deformation and breakup phenomena are shown in **Fig.12.** In this case, the high-velocity liquid flow of 20 mm-tube rushes into the sudden expansion (50 mm-tube), like stick-in. As a result, the strong shear layer is produced at just above the sudden expansion. Therefore, the bubbles were deformed due to the strong shear layer of liquid flow formed just above the sudden expansion, and broken up to small ones. These phenomena became significant as the liquid flow rate becomes larger.

Distribution of void fraction

In upstream of the sudden expansion at L/D=50 position from the bubble generator, the radial profiles of local void fraction have been measured. The studies on the characteristics of vertical, upward, dispersed bubbly flow indicate that the distributions of the void fraction appear a saddle shape ("wall peak" in void fraction) in the sliding bubbly flow or a power-law shape ("core peak") in core bubbly flow by changing the gas and liquid volumetric velocity and bubble diameter [12]-[15]. **Fig.13** and **Fig.14** show the results of local void fraction under j_{L20}=1.59 [m/s] and 5.31 [m/s] in 20 mm-tube (both j_{G20}=0.05 [m/s]) conditions. These results are consistent with the previous studies [12]-[15].

The distribution of the void fraction is measured in the tube cross sections and at the different axial positions of sudden expansion. Typical examples of the void measurements are shown in **Fig.15** and **Fig.16**. Each experimental condition is the same as **Fig.13** and **Fig.14**. In the case of **Fig.15**, that is, the distribution of wall peak in void fraction at the below of the sudden expansion, two void peaks are measured at the just above of the sudden expansion. As the two-phase flow develops along the direction of the main flow (upward flow), these peaks are gradually disappeared. At the same time, the void fraction near the wall increases due to the re-circulation flow affected by the wall re-attachment region. The distribution

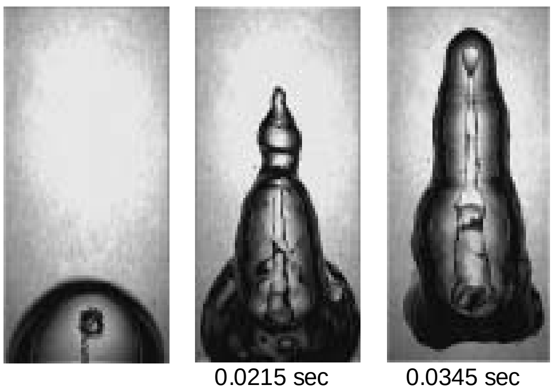

Fig.11 Break-up gas-slug in sudden expansion (j_{L20}=0.0m/s j_{G20}=0.0534m/s)

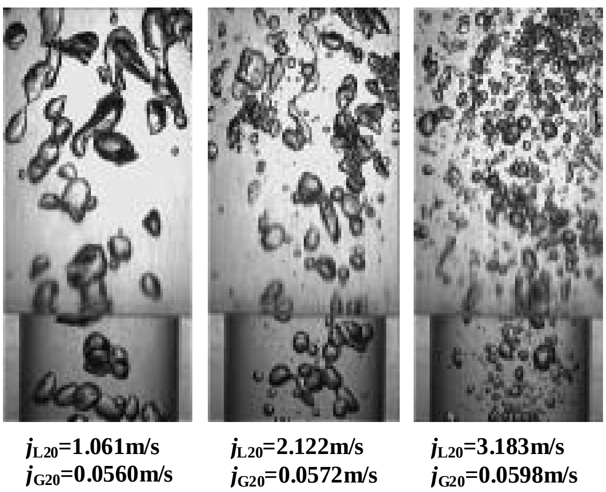

Fig.12 Deformation of bubbles in sudden expansion

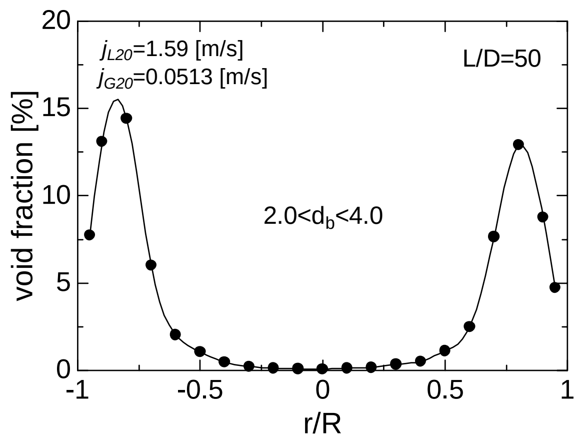

Fig.13 Wall peak void fraction in 20 mm-tube (j_{L20}=1.59 m/s j_{G20}= 0.0513 m/s)

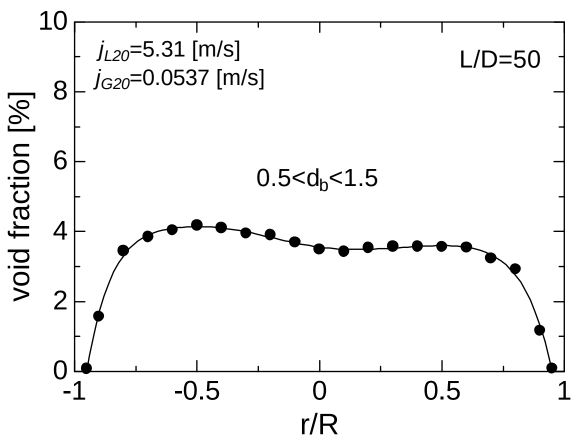

Fig.14 Core peak void fraction in 20 mm-tube (j_L=5.31 m/s j_G= 0.0537 m/s)

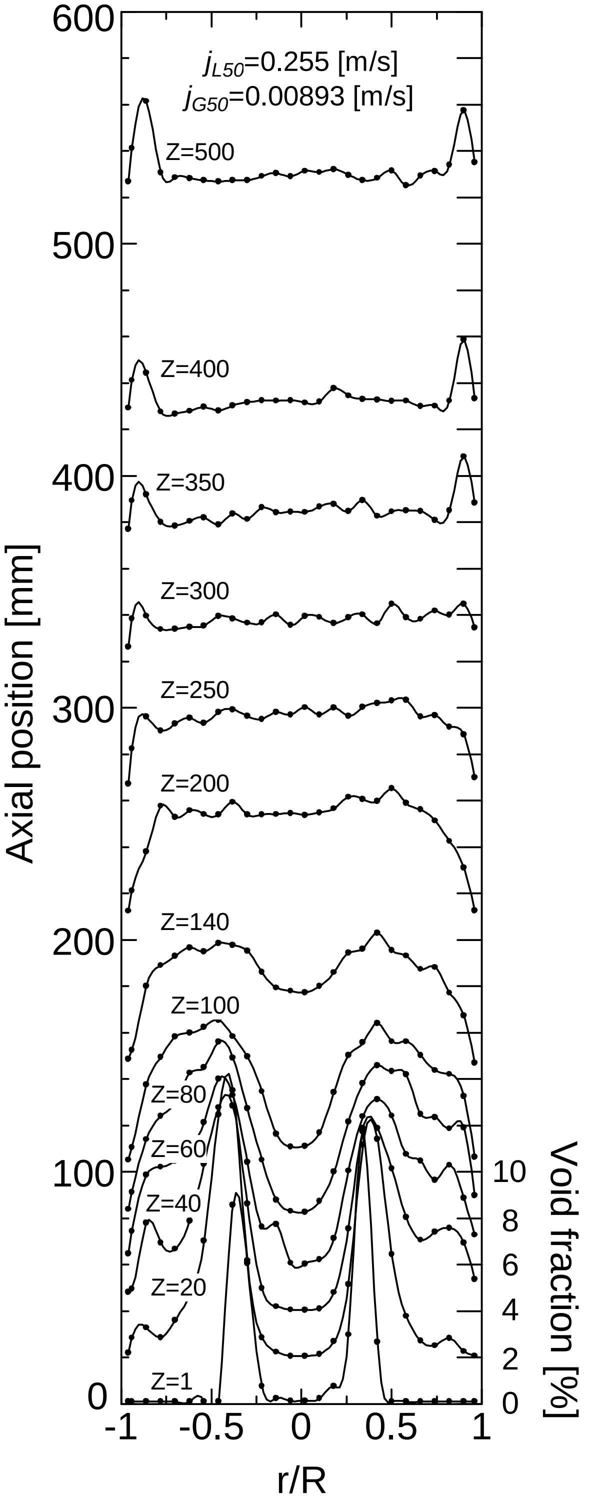

Fig.15 Distribution of wall peak in void fraction (j_{L20}=1.59 m/s j_{G20}= 0.0513 m/s)

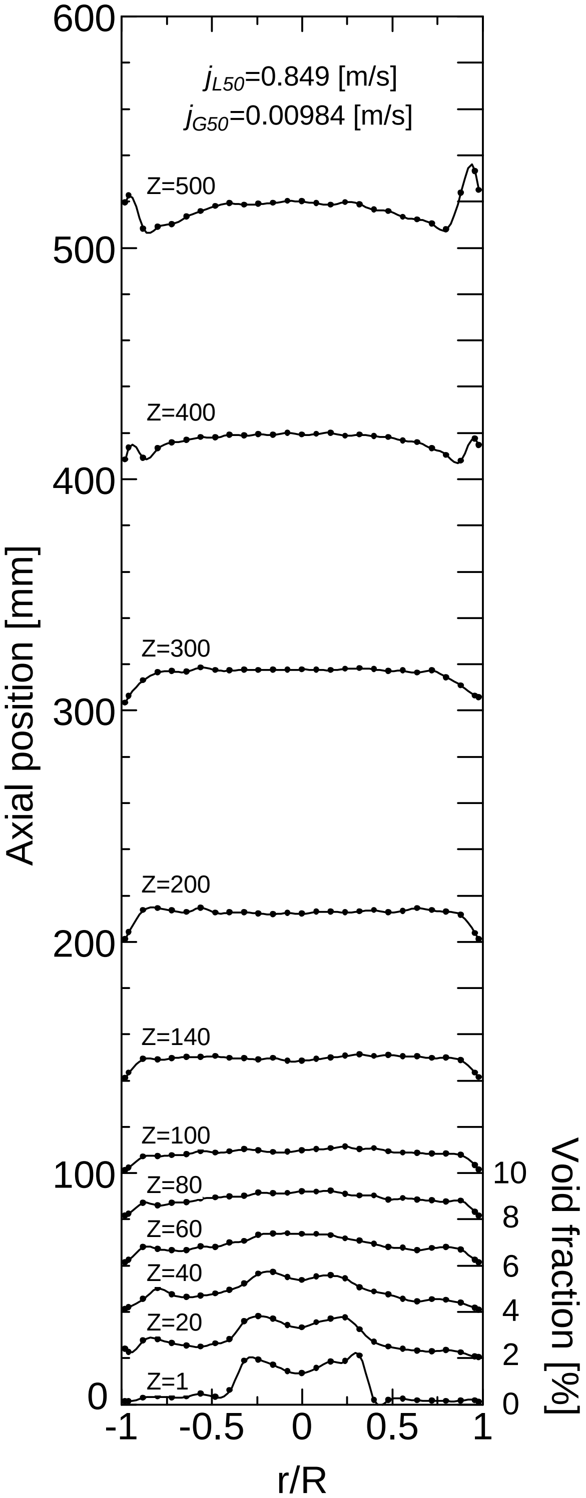

Fig.16 Distribution of core peak in void fraction (j_{L20}=5.31 m/s j_{G20}= 0.0537 m/s)

of void fraction changes from a saddle shape to a power-law shape. In the distribution of downstream of sudden expansion, moreover, the wall peak appears again, and a saddle shape in the sliding bubbly flow can be observed in 50 mm-tube. While, in **Fig.16,** the distribution of core peak in void fraction changes similarly to the case of wall void peak. This means the bubbles immediately travel near the inside wall at the just above of the sudden expansion. In this case, the void fraction has the intermediate peak distribution at the downstream of the sudden expansion in comparison with **Fig.15**. The bubble diameter in **Fig.15** is estimated 3.0 mm based on the bubble diameter and Reynolds number relation as shown in **Fig.7**, the diameter in **Fig.16** is also 1.0 mm.

Therefore, the results of void fraction measurements in this study showed that how the two phase flow develops along the direction of the main flow, and both typical distributions of the void fraction, a saddle shape in the sliding bubbly flow or a power-law shape in core bubbly flow, change to a saddle shape that has a local void peak near the wall passing through the sudden expansion part. The definitive conclusions should be done based on the detailed experiment of void fraction under the some bubble diameter conditions. However, such experimental data in the sudden expansion of a vertical bubbly flow would be benchmark with respect to the multi-dimensional behavior of the two-phase analysis.

Flow regime map

The flow regime maps are shown in **Fig.17** and **Fig.18**. **Figure 17** indicates the results of the flow regime map of 20 mm-tube and 50 mm-tube, **Fig.18** is in the case of sudden pipe expansion, respectively. The flow regime was distinguished at the position of 100D in 20 mm-tube and 50D in 50 mm-tube. In these figure, the solid line indicates bubbly flow to slug flow transition in case of the void fraction α =0.1, 0.2, 0.3. We use the following relationship between j_G and j_L, which is based on Mishima-Ishii's equation [16] derived from the drift velocity for bubbly flow.

$$\frac{j_G}{\alpha} = C_0 j + \sqrt{2}\left(\frac{\sigma g \Delta\rho}{\rho_L{}^2}\right)^{1/4} \tag{2}$$

where,

$$C_0 = 1.2 - 0.2\sqrt{\left(\frac{\rho_G}{\rho_L}\right)} \tag{3}$$

Comparison **Fig.18** with **Fig.17**, the flow regime maps with sudden expansion is different from the ordinary flow regime in the straight pipe without sudden expansion. Consequently, the flow regime far downstream from the sudden expansion is significantly affected by the characteristic phenomenon occurred in sudden expansion as mentioned above. In this experiment, it reveals that the flow regime of downstream of the sudden expansion part has to be considered the influence of the sudden expansion upstream. This indicates that the ordinary flow regime map, which was constructed to fit the two-phase flow in one-dimensional channel such as straight circular pipe, may be inapplicable to the multi-dimensional two-phase flow, and some modification should be considered.

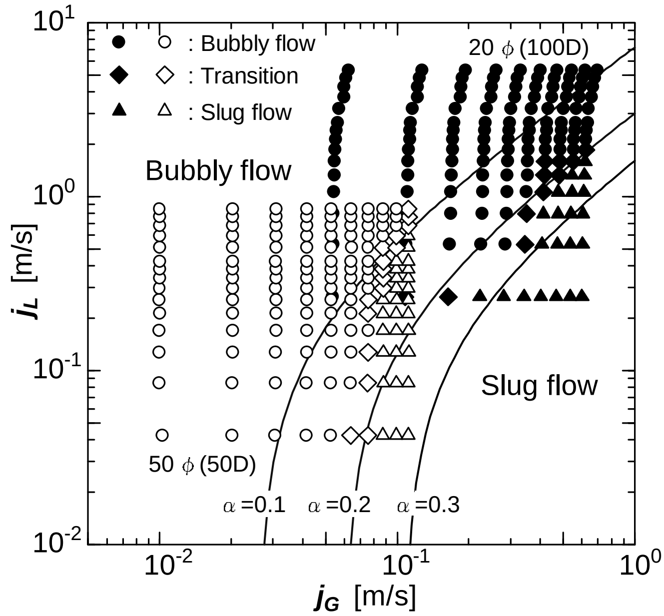

Fig.17 Flow-regime map without sudden expansion part

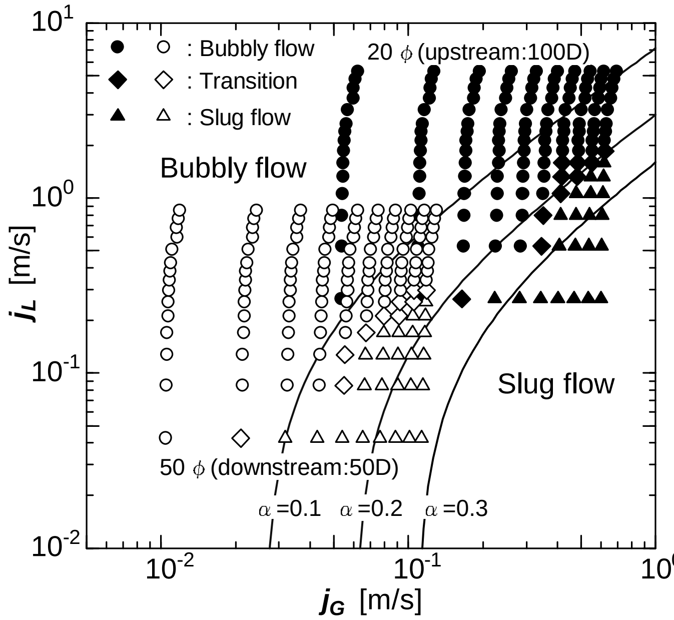

Fig.18 Flow-regime map with sudden expansion part

CONCLUSIONS

Experimental studies were made on the multi-dimensional behavior of upward gas-liquid two-phase flow through the vertical round tube with an axisymmetric sudden expansion, which is one of the typical multi-dimensional channel geometry. The aims of this study are to clarify the multi-dimensional behavior of bubbly or slug flow affected by sudden expansion channel geometry, and to accumulate the experimental data for two-phase flow analysis, which is applicable to predict with appropriate accuracy the multi-dimensional its behavior. In this paper, we performed the direct observation using the high-speed video camera and the measurement of distribution of local void fraction at the below and above of the sudden expansion part. Following are noted from the experimental results.

(1) The direct observations showed that the flow patterns at the sudden expansion had the multi-dimensional structure that consists of (a) straight-up flow, (b) wall re-attachment region, and (c) re-circulation flow. These multi-dimensional flow patterns and structure changed depending on the superficial velocity of gas and liquid phase.

(2) Characteristic phenomena, such as deformation and breakup of bubbles or gas-slug were observed at the sudden expansion part. These phenomena became significant as the liquid flow rate becomes larger.

(3) The local void fraction showed that how the two phase flow develops along the direction of the main flow, and both typical distributions of the void fraction, a saddle shape in the sliding bubbly flow or a power-law shape in core bubbly flow, changed to a saddle shape passing through the sudden expansion part.

(4) The flow regime far downstream from the sudden expansion is significantly affected by the characteristic phenomenon occurred in sudden expansion, and different from the ordinary flow regime in the straight pipe without sudden expansion. This indicates that the ordinary flow regime map, which was constructed to fit the two-phase flow in one-dimensional channel such as straight circular pipe, may be inapplicable to the multi-dimensional two-phase flow, and some modification should be considered.

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