Flow pattern and fluctuation of void fraction of two-phase flow through a vertical channel with contraction were examined experimentally. The two-phase fluid consisted of water and nitrogen gas. The pipe diameters were 0.1[m] and 0.05[m], which were before and after the contraction, respectively. Superficial gas and liquid velocity were changed form 0.42 to 2.55[m/s] and from 2.26 to 4.53[m/s]. Time series data of void fraction were measured using a single-needle void probe and flow pattern at downstream from the contraction was visualized using a high-speed video camera. Intermittent flow was observed at downstream of the contraction. The pulsation can be seen to be caused by wave of bubbles thick and thin. Frequency of fluctuation of the void fraction was almost constant when flow pattern before the contraction was bubble flow. In the case where flow pattern before the contraction was churn flow, the frequency increased with superficial liquid velocity. The frequency was also confirmed with the result of image processing using the movies captured by the high speed video camera.

**KEYWORDS:** two-phase flow, void fraction, contraction, intermittent flow, pipe flow, pulsation

I. Introduction

Research on Internal CRD (Control Rod Drive) system has been proposed and developed as a technology for future BWR (Boiling-Water Reactor). CRD is installed inside the pressure vessel in Internal CRD design. The position of Internal CRD is above the core, which is downstream concerning coolant water.

Advantages of Internal CRD system are economical efficiency and safety of nuclear power plants. Economical efficiency can be implemented by reducing volume of CRD and reactor containment, which are the result of installing CRD in the pressure vessel of nuclear reactor. Safety is attained by no pressure boundary of CRD and setting the core on the RPV (Reactor Pressure Vessel) lower part.

It is essential to solve some problems for realization of the Internal CRD technology. One of the problems is establishment of the method which evaluate fluid stability and structural safety of reactors. In the Internal CRD design, boiling water (two-phase flow) heated by the core pass through vertical ducts to prevent striking control rods and CRD directory. The vertical ducts are called "Guide Chimney." Guide Chimney is installed in the plenum and among CRD. The plenum is necessary to withdraw the control rods completely. Guide Chimney has contraction because cross-section area of the gaps among CRD is narrower than that of the plenum. In order to assess safety of Internal CRD system, it is indispensable to evaluate fluid stability of two-phase flow through Guide Chimney and structural safety of Guide Chimney excited by two-phase flow.

In the case of investigation of two-phase flow, flow pattern is one of the most important characteristics. Flow pattern is determined by flow velocity, void fraction, and shapes of the flow channel, etc. Guide Chimney can be seen as a channel with contraction. Many studies for flow pattern with multiple types of channels have been reported, for example, bend and coil\(^1\), T-junction\(^2\), with groove\(^3\), and rod bundles\(^4\). However, it is not clear how the shapes of channels affect flow pattern of two-phase flow, moreover, little is known about two-phase flow pattern with contraction.

The goal of this study is evaluate safety of Internal CRD system. As the first step for this goal, this paper is focused on flow pattern and fluctuation of two-phase flow through a channel with contraction. Flow pattern of water-nitrogen gas in a pipe with contraction are examined experimentally. Fluctuation of void fraction are measured by a single-needle void probe and high speed video camera. And then, the characteristics of flow pattern and fluctuation of void fraction are clarified.

II. Experimental Apparatus and Conditions

Flow pattern and fluctuation of void fraction of two-phase flow through a vertical channel with contraction are examined experimentally. The two-phase fluid consists of water and nitrogen gas. A pipe with concentric contraction is used as the channel to investigate typical characteristics of two-phase flow with contraction.

The experimental apparatus is shown in Fig.1. Nitrogen gas in containers is supplied to the gas-liquid mixing section. Rate of gas flow through a regulator is measured by the rotameter. Gas is injected into the vertical upward water flow through sintered alloy pipes. Water in the tank is pumped into the gas-liquid mixing section through the orifice flowmeter. Two-phase flow made in the mixing section goes up vertically into the stabilization section and subsequent test


section. The measurement section is installed after the test section. Water and nitrogen gas are separated at the separation section, and then nitrogen gas is emitted to the atmosphere and water goes back to the tank.

The diameter of the pipe at stabilization section and test section before contraction is 0.1 [m]. The test section has sudden contraction which is located at 2.5 [m] downstream from the mixture section. The diameter of the pipe is contracted concentrically to half size, 0.05 [m]. The void probe is installed at 2 [m] downstream from the contraction.

The test section is made of transparent acrylic plastic and the other sections of the pipe are made of stainless steel.

Time series data of void fraction are measured using a single-needle void probe. The void probe is inserted into the pipe horizontally at the measurement section. The tip of the void probe is located at the center of the pipe. The void probe detects whether the tip contacts water or nitrogen gas by difference of conductivity. The probe is energized with frequency of 10,000 [Hz]. We can obtain the 10,000 [Hz] signals which indicate the tip of void probe contacts water or gas. Void fraction is calculated as the sum of the signals per 100 [ms] and recorded by a personal computer.

Flow pattern at 1.5 [m] downstream from the contraction is visualized using a high-speed video camera. A halogen lamp illuminates the transparent test section from about 120 degree behind. The images are recorded by a computer for image processing.

Table 1 shows the experimental condition of superficial gas velocity and superficial liquid velocity. The data of void fraction are measured in each condition. Images are recorded in one condition when \( J_L \) is 2.55 [m/s] and \( J_G \) is 0.424 [m/s]. Flow pattern on these conditions can be expected from bubble flow to slug or churn flow according to the Sekoguchi regime map.

---

### III. Result and Discussion

#### 1. Observed Phenomenon

Bubble flow was observed in the pipe before the contraction under the condition that \( j_g \) was low. Flow pattern before the contraction changed from bubble flow to churn flow as the superficial gas velocity increased.

The orderly bubbles went up through the pipe in bubble flow, however, turbulent churn was caused in churn flow.

Intermittent flow was observed in downstream channel of the contraction. Pulsation phenomenon occurred under all conditions in Table 1. The pulsation consisted of thick and thin bubbles, not slug. This phenomenon, which can be said as density wave of bubbles, was confirmed by the photos and movies captured by the high speed video camera. Pulsation was caused regardless of flow pattern before the contraction.

The above phenomenon would be examined in detail using the void probe and high speed video camera in the following.

#### 2. Void Probe Measurement

The void probe was installed at the center of the pipe 2 [m] downstream from the contraction. The probe measured time-average void fraction per 100 [ms].

Fig.2 shows the time series data of void fraction under the condition that \( J_L \) was 2.83 [m/s] and \( J_G \) was 0.424 [m/s]. The horizontal axis and vertical one indicate time [s] and void fraction [%], respectively. Pulsation can be seen in this figure. Void fraction rises periodically. This phenomenon seems to be caused by periodical passage of cluster of bubbles. Amplitude of the pulsation increased with superficial gas velocity. The pulsation under the condition that \( J_L \) was 2.83 [m/s] and \( J_G \) was 2.55 [m/s] is shown in Fig.3. It can be confirmed that amplitude of fluctuation in Fig.3 is three times or more as large as that in Fig.2, however, the values of frequency in these figures seem not to be different.

We need to analyze the data measured by the void probe using FFT for investigating the detail property of the pulsation. The time series data obtained by the probe were 300 [s] long and 500 [Hz]. First 262.144 [s] of the data were analyzed by FFT. Fig.4 shows the results of FFT with variety of superficial liquid velocity remaining superficial gas velocity constant at 0.424 [m/s]. The horizontal and vertical axes indicate frequency [Hz] and power spectrum, respectively. Fig.5 - Fig.9 show the results of FFT when \( J_G \) was 0.849, 1.70, 2.12, 2.55, like Fig.4. When \( J_G \) was 0.424 or 0.849 [m/s](Fig.4 and 5), the peaks of void fraction frequency were constant regardless of the values of \( J_L \). On the other hand, when \( J_G \) was 1.70, 2.12, or especially 2.55 [m/s] (Fig.7, 8, and 9), the values of peak frequency increased gradually with increasing \( J_G \). In the case where \( J_G \) was 1.27 [m/s] (Fig.6), the values of peak frequency were constant when \( J_G \) was 3.11 - 3.96 [m/s], however, the values increased with \( J_G \) when \( J_G \) was 2.26 - 2.83 [m/s]. The above difference was caused by the difference of the flow pattern in upstream of the contraction.
The flow pattern was bubble flow under the conditions of Fig. 4 and 5, churn flow under those of Fig. 7, 8, and 9, transition region under those of Fig. 6. This can be thought to be aftereffects of turbulence of churn flow on generation of bubble cluster.

3. High-Speed Video Camera Image Processing
For detail observation and image processing analysis of flow pattern after the contraction, two-phase flow around 1.5 [m] downstream from the contraction was visualized using a high-speed video camera.
Regarding the images, the image area was about 0.077 x 0.036 [m], resolution was 256 × 120, flame rate was 125 [Hz], and shutter speed was 1 x 10^{-4}. The condition of the flow was that \(J_L=2.83\) and \(J_G=0.424\) [m/s].

The series images are shown in Fig.10. The white areas in the figure indicate gas phase. This is because light was scattered by difference between flexibility of gas phase and that of liquid phase. The black areas indicate liquid phase. It can be observed that density wave of bubbles rose through the pipe.

Flow pattern at 0.5 [m] upstream from the contraction was also visualized under the same condition. The images are shown in Fig.11. It was confirmed that upstream flow was bubble flow without pulsation.

The images in Fig.10 were analyzed by image processing for calculating the frequency of passage of bubble cluster. The fluctuation of intensity in time indicated passage of bubbles cluster because bubbles were shown as the white areas in images. The average intensity in a rectangle of each image was calculated. The rectangle which is located at 100 [pixel] from bottom on the image has the area of 256 × 20 [pixel]. Fig.12 shows the time series data of the average intensity considering background noise. The data in Fig.12 analyzed using FFT is shown in Fig.13. Pulsation can be confirmed in this figure. The peak frequency of the pulsation in the figure was about 3-4 [Hz]. It is reasonable to think that the average intensity in the rectangle was in proportion to average void fraction. Let us compare the peak frequency in Fig.4 with that in Fig.13 under the same flow rate condition. It is a fact that Fig.4 and Fig.13 show about the same peak frequency, 3-4 [Hz]. Thus it is likely that image processing analysis was appropriate.

Image processing analysis is inferior to void probe measurement concerning accuracy and measurement time length, however, has advantage of isolated measurement and easy setup.

IV. Conclusion

The property of two-phase flow through a pipe with contraction was examined experimentally. Pulsation phenomenon was observed in downstream of the contraction, which was caused by density wave of bubbles.

Frequency of the pulsation was obtained by analyzing time series data of void fraction measured by single-needle void probe using FFT. The peak frequency was constant with various \(J_L\) when the flow pattern before the contraction is bubble flow. On the other hand, the peak frequency increased with \(J_G\) when the flow pattern before the contraction is churn flow. It was confirmed that passage of bubble cluster caused the pulsation by visualization of two-phase flow after the contraction using a high sped video camera. The frequency calculated by the images was almost same that by the void probe measurement.

Acknowledgment

This study is supported by IAE (The Institute of Applied Energy).

References
