Abstract

The study is one on the series of the study on two-phase flow under earthquake, in which the two-phase flow behavior under the seismic vibration is systematically investigated by using both an experimental method and a numerical situation. The present study focuses on a bubbly flow behavior in a horizontal pipe under flow rate fluctuations. The periodical flow rate fluctuation was added to the bubbly or plug flow in a horizontal pipe, and the flow behavior was mainly measured by using image processing and PIV (particle image velocimetry). In the result of the image processing, the characteristic bubble deformation near the pipe wall was observed and the bubble deformation was synchronized with the flow rate fluctuation. The velocity field obtained by PIV showed the characteristic shear flow under the deformed bubble. The motion of both the liquid and the bubble responded to the pressure gradient fluctuation under the flow rate fluctuation, but the response of the bubble motion to the pressure gradient was slightly faster than that of the liquid motion. It indicated that the relative velocity between the bubble and the liquid changed with time. Therefore, the shear flow under the bubble was caused by the relative velocity between the bubble and the liquid, and the bubble was deformed by the shear flow due to the flow rate fluctuation. The numerical simulation code for the gas-liquid two-phase flow with an advanced interface tracking method, TPFIT, also showed the same mechanism of the bubble deformation, i.e., the shear flow under the bubble caused by the flow rate fluctuation.

Key words: Earthquake, Bubbly flow, Flow rate fluctuation, PIV, TPFIT

1. Introduction

Safety design of nuclear plants against an earthquake is important, especially in Japan. Therefore, a lot of knowledge about earthquake-resistant of the nuclear plants has been obtained for their structures. The safety of the nuclear plant under an earthquake, however, doesn’t relate to only structural resistant but also the behavior of gas-liquid two-phase flow in the plant (Mikami, A. et al., 2004). Especially, its thermal characteristics and the void fraction behavior relating to core reactivity are important in a reactor core (Hirano and Tamakoshi et al., 1996, Chen, S.W. et al., 2010, Ohtake, H. et al., 2010).

In order to clear the two-phase flow behavior under the earthquake, it is studied systematically in the project of “Development of Prediction Technology of Two-Phase Flow Dynamics under Earthquake Acceleration” carried out under the strategic promotion program for basic nuclear research by the Ministry of Education, Culture, Sports, Science and Technology of Japan. The research project focuses on the two-phase flow behavior in the reactor system under the earthquake conditions. In the project, two main experiments were done; one is the experiment on bubbly or plug flow in a horizontal pipe on an oscillating table (hereafter, called as “structural vibration experiment”) and the other is on the flow in a fixed horizontal pipe under the flow rate fluctuation (called as “flow rate fluctuation experiment”).
Under the earthquake conditions, vibration by the earthquake acceleration is added to all fluids (including single phase water and two-phase steam-water mixture) in the nuclear reactor system. Therefore, all fluids move in accordance with the vibration. Considering a component of reactor systems, inlet (and of course outlet) flow rate changes by result of movement of the fluid in the inlet side and the outlet side components. For example, Satou pointed out that the inlet flow rate of BWR core changes dramatically under the earthquake conditions by results of numerical analysis (Satou, A. et al., 2011). Furthermore, in the structural vibration experiment, both vibration and flow rate fluctuation were included in experimental results. Therefore, the flow rate fluctuation experiment is important to evaluate the effects of vibration on the two-phase flow.

Considering above reasons, the flow rate fluctuation experiment was needed in addition to the structural vibration experiment. In the previous work, the flow rate fluctuation experiment and the structural vibration experiment were performed by Okachia and Mizuno, respectively. (Okachi, S. et al., 2012; Mizuno, K. et al., 2012). Moreover, the numerical simulation code which can express the flows obtained in the structural vibration and the flow rate fluctuation experiments was also developed in the project (Yoshida H. et al., 2011).

As the study on two-phase flow fluctuations, the void fraction fluctuation in a vertical bubbly flow was studied experimentally and theoretically (Boure, 1988, van Wijngaarden, L. and Biesheuvel, A., 1988), but the knowledge of detail flow structure of the two-phase flow was not obtained enough. On the other hand, recently, new measurement methods such as image processing have been developed and an instantaneous detailed flow structure can be obtained. (Choi, H. M. et al., 2002)

In the study, the behavior of bubbly or plug flow under the flow rate fluctuation was investigated by the image processing and PIV. The periodical bubble deformation synchronizing with the flow rate fluctuation was observed. The mechanism of the bubble deformation was discussed with the velocity field around the bubble obtained by PIV and the response of bubble motion to the flow rate fluctuation. Furthermore, the numerical simulation code for the gas-liquid two-phase flow with an advanced interface tracking method, TPFTT, also showed the same mechanism of the bubble deformation (Yoshida, H. et al., 2006).

2. Experiment
2.1 Experimental Equipment

Fig. 1 (a) shows the experimental apparatus used in the study. It mainly consists of a water tank, a pump, an oscillator, a nitrogen gas cylinder, a gas-liquid mixer, a test section, a gas-liquid separator and pipes connecting them. The working fluids were water and the nitrogen gas.

At the gas-liquid mixer shown in Fig. 1 (b), the two-phase flow was generated with the water supplied from the tank and the nitrogen gas supplied from the gas cylinder. The nitrogen gas was injected into the water through the nozzle of I.D. 0.58 mm. The two-phase flow generated at the mixer flowed to the test section.

The distance between the gas-liquid mixer and the test section was 2.5 m. Fig. 1 (c) shows the schema of the test section. A high speed video camera and a blue LED were set for the flow observation and the image processing. The high speed video camera was used to observe the bubble behavior and the blue LED was used for a back light system. The test section was a part of transparent acrylic pipe surrounded by a water jacket to reduce distortion of the bubble image. The inner diameter of the pipe was 14 mm and the water jacket length was 400 mm. In addition, the pressure sensors were attached to the pipe wall at the gas-liquid mixer, the inlet and the outlet of the test section.

Fig. 1 (d) shows a gas-liquid separator attached at the exit of the test section, which was open to the atmosphere. The boundary condition at the test section was simple. At the separator, the gas was released to the air and the water returned to the tank.

2.2 Oscillator

The oscillator shown in Fig.1 (a) is attached to the flow loop in order to give the flow rate fluctuation to the main flow. It is a piston-crank mechanism shown in Fig. 2 (a). The driving disk is changeable and the proper crank arm length \( r \) can be chosen. The velocity of the piston, \( v_p \) was expressed as Eq. (1).
Here, $\omega$ and $l$ denote the angular velocity of the driving disk and the connecting rod length, respectively. Fig. 2 (b) shows the oscillator at the angle of the crank arm $\theta$. The velocity of the piston $v_p$, corresponding to the velocity fluctuation in the main flow, is not a sine wave strictly as shown in Eq. (1), but very similar to the sine wave as shown in Fig. 2 (b). The sine wave is a basic wave because complicated wave form is composed by the sine waves of various amplitude and frequencies.

The piston may affect the flow rate upstream and downstream. In order to grasp the flow rate fluctuation, the flow rate was directly measured downstream of the oscillator. Fig. 2 (c) shows an example of the flow rate measurement under the condition of $r = 7.8$ mm, the fluctuation frequency of $f = 3$ Hz and the cross sectional average velocity of the main flow of 1 m/s. In Fig. 2 (c), the superficial velocity is shown as the liquid velocity based on the flow rate and the cross section of the pipe.

$$v_p = \omega r (\sin \theta + \cos \theta \tan \varphi) \quad (1)$$

$$\varphi = \sin^{-1}\left(\frac{r}{l} \sin \theta \right) \quad (2)$$

Fig. 1 Experimental apparatus used in the study. The apparatus is a loop including the test section with a water jacket. A nitrogen gas was injected into the water through a nozzle at the mixer. The two-phase fluid flowed to the test section, and to the separator under the atmosphere.

Fig. 2 Oscillator. The oscillator is a piston-crank mechanism and the velocity of piston $v_p$ is almost a sine wave. The flow rate fluctuation was measured by the flow meter in Fig. 1 (a).
2.3 Measurement of Bubble Velocity

Fig. 3 (a) shows the two successive flow images, Nth and N+1th, with the time delay Δt in the experiment. The bubble velocity on the horizontal direction, \( u_b \), is calculated based on the shift \( Δx_N \) of the bubble image as shown in Fig. 3 (b) (Mizuno, K. et al., 2012). In order to determine the shift \( Δx_N \), the cross correlation coefficient \( c \) is calculated by Eq.(3).

\[
    c = \frac{A_{N,x} \cdot A_{N+1,x+Δx_N}}{A_{N,x} \cdot A_{N+1,x+Δx_N}}
\]

(3)

where \( A_{N,x} \) denotes the array of the pixel number occupied by a bubble along the horizontal direction in Nth image. \( A_{N+1,x+Δx_N} \) also denotes the array of the pixel number occupied by the bubble along the horizontal direction in \( N+1 \)th image but the bubble image is shifted at \( Δx_N \) in the horizontal direction. Determining the shift \( Δx_N \) giving the maximum coefficient \( c \), the bubble velocity \( u_b \) is calculated with the following equation;

\[
    u_b = \frac{Δx_N}{Δt}.
\]

(4)

2.4 Measurement of Liquid Velocity Field

Fig. 4 (a) shows a general PIV system to measure a velocity field of a liquid single phase flow in a pipe. In order to obtain the tracer images clearly for PIV, the fluorescence particles of Rhodamine B were used as the tracers in the study. The average diameter of the tracer was 10 μm and its density was 1190 kg/m³. The pulse YAG laser sheet was irradiated to the test section.

Fig. 4 (b) shows the modified optical system used to obtain clearly both the fluorescence tracer image and a bubble image simultaneously in a gas-liquid two-phase flow. The system consists of two cameras, a notch filter and a dichroic mirror. The notch filter cuts off the light of the wave length range of 532±26.6 nm and lets others pass. Because the wave length of the YAG laser is 532 nm, the reflection of the laser light from the pipe wall and the bubble’s surface is cut off by the notch filter. The bubble image is taken by the blue LED light (wave length: 470 μm) as the back light. The blue light passes the notch filter and is reflected by the dichroic mirror, reaches to the high speed video camera recording the bubble image. The dichroic mirror reflects only the blue light and lets others pass. Because the fluorescence tracer image is about 600 μm, the light from the tracer passes the notch filter and the dichroic mirror, and reaches to the high speed video camera for PIV. Fig. 5 shows the images taken by the high speed video cameras. Fig. 5 (a) and (b) is tracer images and a bubble image, respectively. In order to eliminate the bubble image in Fig. 5 (a), the bubble image in Fig. 5 (b) is used as a mask. Fig. 5 (c) is the tracer images without the bubble image.

PIV processing is done for the tracer image without the bubbles as shown in Fig.5 (c). Fig. 6 (a) shows the liquid velocity field around the bubble obtained by PIV. In order to make the infarction between the bubble and the liquid phase clear, the relative velocity field for the bubble is obtained as shown in Fig. 6 (b). The relative liquid velocity was evaluated by subtracting the bubble velocity from the liquid velocity. The bubble velocity was obtained by the method explained in the previous section.

2.5 Experimental Condition

The superficial velocity of the water and the gas were 1.0 m/s and 0.022 m/s for a steady state. In the experiment, the water flow rate fluctuation was added by the oscillator. The frequency of the oscillator was 3 Hz and the wave form was almost a sine wave as shown in Fig. 2 (b). The main frequency of an earthquake was about from 0.5Hz to 10Hz and the fluctuation condition of 3 Hz is covered by the range of the earthquake. The amplitude of the liquid velocity fluctuation corresponding to the superficial velocity of the flow rate fluctuation was 0.171 m/s. The measured fluctuation of the water superficial velocity before the mixer is shown in Fig. 2 (c). Here, the
The experimental condition shows that $j_L = 1 \pm 0.171 \text{m/s}$, $j_G = 0.021 \text{m/s}$ and the frequency of 3Hz.

Fig. 3 Measurement of bubble velocity $u_B$. The bubble velocity on the horizontal direction, $u_B$, is calculated based on the shift of a bubble image in two successive flow images with the time delay.

Fig. 4 The schema of PIV and image processing system.

Fig. 5 Image processing for PIV. In order to eliminate the effect of a bubble, the masked tracer image was obtained based on the original tracer image and the bubble image.

Fig. 6 Liquid velocity fields and the relative velocity field around bubble. Arrows show the direction and the magnitude of the flow velocity. The relative velocity was evaluated by subtracting bubble velocity from the liquid velocity.

### 3 Numerical Simulation
3.1 Numerical Simulation Code TPFIT

The bubbly flow in horizontal pipe under the flow rate fluctuation is simulated by using the TPFIT (Two-phase Flow Code with Interface Tracking) (Yoshida, H. et al., 2006). TPFIT was modified for earthquake conditions (Yoshida, H. et al., 2011). TPFIT is one of the VOF (Volume Of Fluid) method. In the TPFIT, the time-dependent Navier-Stokes equation for compressible flow is considered with the conservative equations of mass and energy of phases.

A numerical domain is divided to the numerical grid which can capture the shape of gas-liquid interface and it tracks the position of gas-liquid interface by solving an equation to calculate the change volume ratio of liquid phase as shown in Fig. 7. A time series of velocity profiles around the bubbles and the shapes of the bubbles are compared with the experimental results under the flow rate fluctuation.

3.2 Analytical Model and Boundary Condition

Fig. 8 show a numerical model of a horizontal circular pipe, where the diameter of the pipe is 14 mm and the length is 1000 mm. The size of the numerical grids is $\Delta x = 0.5$ mm, $\Delta y = \Delta z = 0.25$ mm, the total number of numerical grids is 6272000 ($56 \times 56 \times 2000$). The gravity force acted on the negative y-direction was considered. The bubbles were injected by replacing the liquid to the gas. The diameter of initial bubbles, $d_p$, was 4mm. The time step was less than $10^{-6}$ s and adjusted to the flow situation. The flow was simulated for 2 s. After the flow became a quasi-steady state, the data were acquired from the simulation results. In order to give the same inlet condition as the experiment, the flow rate fluctuation was set as the same as the experimental data measured by the flow meter.

![Numerical domain](image)

Fig. 7 Numerical domain is divided to the numerical grid which can capture the shape of the gas-liquid interface and it tracks the position of gas-liquid interface by solving an equation to calculate the change volume ratio of liquid phase.

![Numerical domain](image)

Fig. 8 Numerical donate used in the study. The horizontal circular pipe was modeled as the numerical domain. Gravity force acted on the negative y-direction was considered.

4. Experimental Results and Discussion

4.1 Bubble Deformation

Fig. 9 (a) shows the time series of the superficial velocity of the liquid and the bubble velocity at the test section. The experimental condition was $j_L = 1 \pm 0.171$ m/s, $j_G = 0.021$ m/s, $f = 3$ Hz as mentioned in the section 2.5. The red point in Fig. 9 (a) is the bubble velocity and the blue line is the superficial velocity of the liquid. Fig. 9 (b) shows the time series of the flow imaged and the characteristic bubble deformation near the pipe wall. The bubble shape was stretched to the vertical or radial direction as a bubble marked by a red circle. The time mentioned by the number (i)
to (vi) in Fig. 9 (b) corresponds to the time mentioned by the same number in Fig. 9 (a). Considering Fig. 9 (a) and (b), the bubble deformation synchronized with the flow rate fluctuation. When the bubble velocity was almost same as or smaller than the superficial velocity of liquid, the stretching of bubble is observed. Such bubble deformation was a characteristic phenomenon under the flow rate fluctuation, comparing with the steady state (Okachi, S. et al., 2012). In the section 4.3, the condition and the mechanism of the bubble deformation is discussed in detail based on the velocity field.

\[ \text{(a) The superficial velocity of liquid} \ j_L \text{ and bubble velocity} \ u_B \ \text{(b) Bubble images} \]

Fig. 9 The superficial velocity of liquid and bubble velocity. The experimental condition was \( j_L = 1 \pm 0.171 \text{ m/s}, \ j_G = 0.021 \text{ m/s}, \ f = 3 \text{Hz} \) mentioned in the section 2.5. The characteristic bubble deformation near the pipe wall was observed and bubbles deformations synchronized with the flow rate fluctuation.

4.2 Response of Liquid and Bubble Motion to Flow Rate Fluctuation

In order to investigate the response of the liquid phase under the flow rate fluctuation, the liquid phase acceleration and the pressure gradient in the test section were obtained in the flow rate fluctuation condition mentioned in the section 2.5 (\( j_L = 1 \pm 0.171 \text{ m/s}, \ j_G = 0.021 \text{ m/s} \) and the frequency of 3Hz) as shown in Fig. 10 (a). The liquid phase acceleration is calculated with the time derivative of the cross sectional average flow velocity based on the velocity field measured by PIV. The pressure gradient was calculated as following equation.

\[ \frac{dP}{dx} = \frac{P_1 - P_2}{L} \tag{5} \]

Where \( P_1 \) and \( P_2 \) were measured the liquid pressure at the inlet and the outlet of test section, respectively, and \( L \) is the distance of between the measurement locations of \( P_1 \) and \( P_2 \).

The liquid acceleration and the pressure gradient were almost the same behavior. Consequently, it is confirmed that the liquid phase under the flow rate fluctuation responded with the pressure gradient. Furthermore, in order to know the response of a bubble, the bubble acceleration and the pressure gradient in the test section were obtained as shown in Fig. 10 (b). The bubble acceleration was calculated based on the bubble velocity by the image processing (see Fig.9). Because the bubble velocity was discrete as shown in Fig.9 (a), a digital low-pass filter and interpolation were used to obtain a continuous bubble velocity. The cut off frequency of the filter was 4Hz. The bubble acceleration also responded with the pressure gradient. In the flow rate fluctuation condition, it was considered that the pressure gradient was the driving force of the bubble motion. Comparing with Fig. 10 (a) and (b), it was indicated that the bubble acceleration changed slightly faster than the liquid acceleration. The difference of the response between the bubble and the liquid may be caused by the inertia effect.
4.3 Interaction between Bubble and Liquid

In order to investigate the bubble deformation shown in Fig. 9 in detail, the relative velocity field to the horizontal motion of a bubble was obtained in the flow rate fluctuation condition mentioned in the section 2.5 ($j_L=1\pm0.171\text{m/s}$, $j_G=0.021\text{m/s}$ and the frequency of 3Hz). Fig. 11 (a) shows the relative velocity field around the bubble when the superficial velocity of the liquid at the test section was decreasing in the flow rate fluctuation, corresponding to the phase pointed by (i) in Fig.9 (a). The relative liquid velocity was evaluated by subtracting the bubble velocity from the liquid velocity, as mentioned in the section 2.4. In the phase of the decreasing liquid superficial velocity, the bubble shapes stretched in vertical direction. As shown in Fig.11 (a), the relative velocity in the center part of pipe was larger than that near the wall and the descent flow under the bubble was observed.

Fig. 11 (b) shows the relative velocity field around a bubble when the superficial velocity of the liquid was increasing, corresponding to the phase pointed by (iii) in Fig.9 (a). In the phase, the bubble shape wasn’t stretched in the vertical direction. The relative velocity in the center part of pipe was small comparing with the velocity field shown in Fig.11 (a) and the descent flow was not observed.

Considering Fig. 11, the flow field around a bubble influenced the bubble shape strongly. The descent flow near a bubble, which appeared in the phase when the superficial velocity of the liquid was decreasing, might cause the stretching bubble shape.
4.4 Compared with the Experimental Results and TPFIT

Fig. 12 and 13 show the relative velocity field and a bubble shape obtained by the experiment and the numerical simulation using TPFIT (section 3.2 and Yoshida et al., 2011). The relative velocity is the liquid velocity to the bubble motion, which is the same as discussed in the previous section. The experimental and numerical calculation conditions were the same and that as mentioned in the section 2.5 ($j_L = 1 \pm 0.171 \text{m/s}$, $j_G = 0.021 \text{m/s}$ and the frequency of 3Hz). In the numerical calculation result by TPFIT, the relation between the bubble velocity and superficial velocity of liquid as shown in Fig. 9 (a) had the same characteristics as the experimental results.

Fig. 12 shows the flow in the phase when the superficial velocity of the liquid at the test section was decreasing in the flow rate fluctuation. The numerical simulation result shown in Fig. 12 (b) shows the bubble’s characteristic deformation or a stretching shape which is similar to the bubble shape shown in experimental result of Fig. 12 (a). The relative velocity also is similar between the experiment and the numerical calculation result. The descent flow mentioned in the previous section is also observed in the numerical simulation result.

![Fig. 12 Bubble shape and relative velocity field in phase of decreasing liquid velocity. Decreasing of liquid velocity corresponds to the time mentioned by number (i) in Fig. 9 (a). The numerical simulation by TPFIT was done in the same condition of the experiment.](image)

![Fig. 13 Bubble shape and relative velocity field in phase of increasing liquid velocity. Increasing of liquid velocity to the time mentioned by number (iii) in Fig. 9 (a). The numerical simulation by TPFIT was done in the same condition of the experiment.](image)

5. Conclusion

To clear the bubbly or plug flow behavior in a horizontal pipe under the flow rate fluctuation, the experiment was done and the flow was investigated by image processing and PIV. The flow was also simulated numerically by TPFIT...
to confirm the flow mechanism. The main knowledge obtained in the study is as follow:

1. The characteristic bubble deformation or stretching shape was observed and the bubble deformation synchronized with the flow rate fluctuation.
2. Both the liquid phase motion and the bubble motion under the flow rate fluctuation were responded with the pressure gradient. The bubble responded slightly faster than the liquid, which is caused by the inertia effect.
3. The bubble deformation or a stretching shape was observed in the phase when the superficial velocity of the liquid at the test section was decreasing in the flow rate fluctuation. In the time, the descent flow under the bubble was observed in the relative velocity field. The descent flow near a bubble causes the stretching bubble shape.

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References


