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A Preliminary Study on the X-ray Bubble Visualization in Liquid-gas Two-phase Flow Using 90° Compton Scattering

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1. Introduction

In pressurized nuclear reactor, local boiling at fuel surfaces is allowed for more cooling rate. This state is bubbly flow where small and discrete bubbles are observed. However, if the boiling is increasing by temperature rise of the fuel, the bubbles interact with each other and coalesce to form larger bubbles [1]. It can lead to slug flow or churn flow that can make serious impact on the fuel integrity. Therefore, it is important to understand bubble formation in order to avoid fuel damage due to sudden temperature rise. In order to observe bubble motion, some techniques have been introduced. X-ray imaging is one of the techniques [2]. In x-ray radiography, mono-energy and mono-direction x-ray beam generated by synchrotron accelerator is generally used. It is easy to process data and has high resolution. However, synchrotron is hard to use because of its high cost and large scale of the facility. X-ray Particle Tracking Velocimetry (XPTV), other x-ray imaging technique, has been developed. In XPTV, tracer particle is used as photon absorption material [3]. It has significant challenge with developing proper tracer particle. In this study, preliminary study of 3-D imaging technique to inspect bubble form in two-phase flow using cone beam bremsstrahlung x-ray without tracer particle is performed.

2. Methods and Results

2.1 Bubble Size Reconstruction by Transmitted Radiation

In our previous study [4], bubble size estimation technique was proposed. Geometrical overview of the previous study is given a shown in Fig. 1. A boiling pool is located in a straight line between the cone beam x-ray source and the multi-channel detector. The x-ray source is 450 kVp and average energy is about 70 keV. The 9 x 9 multi-channel detector is assumed that has 3 mm grid size. Collimator is attached to each multi-channel detector. In that case, bubble length *d* is estimated by intensity contrast according to density difference between gas and liquid phase. Radiation projection data on multi-channel detector provides two dimensional information of the bubble. Consequently, three-dimensional bubble size information is derived by radiation intensity contrast and spatial data of multi-channel detector.

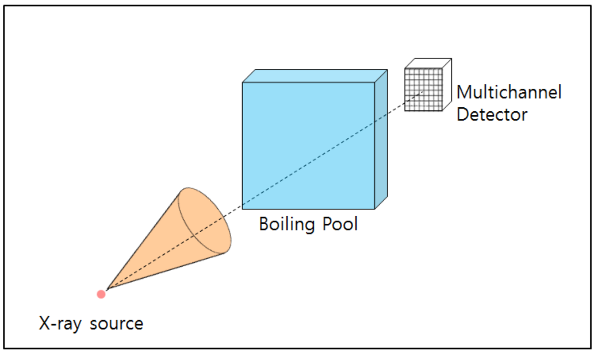

Fig. 1. Overview of X-ray Imaging System for Bubble Size Inspection

For inspection simulation, a case as indicated in Fig. 2 is assumed. Two bubbles which have 0.5 cm radius are located in boiling pool. The size of the boiling pool is 6 cm cubic. Temperature is 100 ℃ and pressure is 1 atm. At this condition, the density of liquid and gas phase is 1 and 0.000598 g/cm^3, respectively. MCNPX 2.7 code [5] was used for the x-ray imaging simulation of the case.

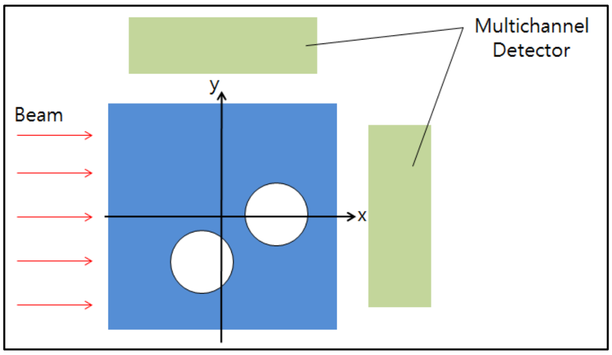

Fig. 2. Bubble Location for Inspection Simulation

By the transmitted intensity data, the bubble size and position is obtained and the result is shown in Fig. 3. A peak and two circles are appeared in yz-plane. It shows that two bubbles are located at y = 0 cm, z = 0 cm and y= -0.6 cm, z = 0 cm respectively. Also, their radiuses are estimated as about 0.5 cm and they are partially overlapped.

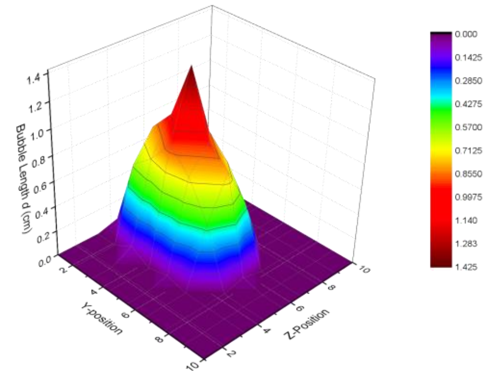

Fig. 3. Bubble Size Reconstruction Result by Transmission Data

2.2 Bubble Separation Using 90° Compton Scattering

However, it is difficult to clearly separate the several bubbles in flow with high void fraction because its data are obtained from only projection data. As shown in Fig. 4, supplementary multi-channel detector is added in order to detect several bubbles separately. The additional detector is located perpendicularly to the beam direction. In gas phase, scattering is rarely occurred due to its low density. Thus, in case of that the gas bubble is existed, it is expected that scattered intensity is relatively lower.

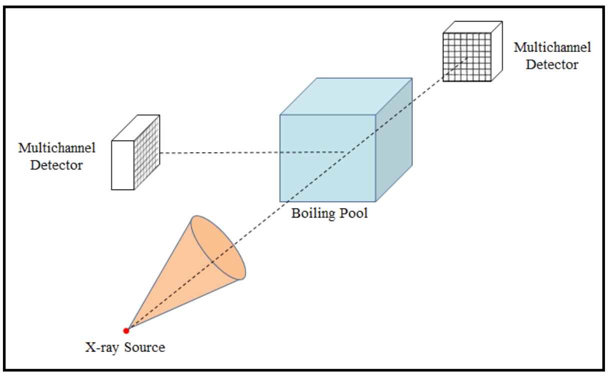

Fig. 4. Overview of X-ray Imaging System for Bubble Size Inspection Using 90° Compton Scattering

To analyze the difference according to bubble existence, bubble/non-bubble ratio of additional detector response is calculated. The result is shown in Fig. 5. Response of the multi-channel detector which is placed on the side was relatively low in case that the bubbles are located. This ratio shows two holes which are estimated the position that the bubble is placed. The location of the hole in the ratio graph approximately indicates that two bubbles are centered on near the point of x = -0.4 cm, z = 0 cm and x = 0.8 cm, z = 0 cm respectively.

By combination of data of two multi-channel detectors, transmitted and 90° scattered, three dimensional position and size information of bubbles can be obtained. In the simulation case above, it was estimated that one bubble is centered nearby x = -0.4 cm, y = -0.6 cm, z = 0 cm and has 0.5 cm radius, the other is centered nearby x = -0.8 cm, y = 0 cm, z = 0 cm and has 0.5 cm radius.

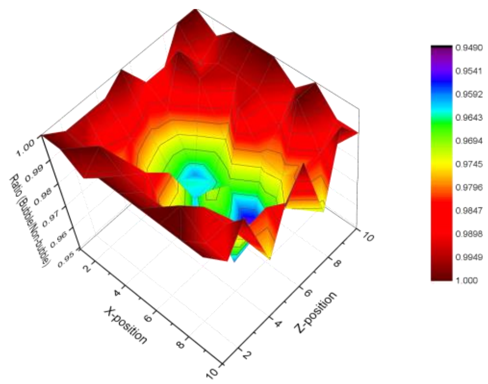

Fig. 5. Bubble/Non-bubble Response Ratio of the Additional Multi-channel Detector

3. Conclusions

In this study, a reconstruction technique for acquiring bubble size and position information in gas-liquid two-phase flow was performed. The analysis shows that bubble length and y, z-position can be obtained by transmitted data and bubble x-position can be obtained by 90° scattered data from additional multi-channel detector placed on the side. It shows that several bubbles in two-phase flow can be detected separately. As using bremsstrahlung cone beam x-ray, which is relatively affordable than synchrotron facility, and making images without tracer particles, it is expected that this inspection technique can contribute to analyzing change of boiling regime in two-phase flow.

4. Acknowledgement

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