Quantitative CT-reconstruction of void fraction distributions in two-phase flow by neutron radiography

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Quantitative CT-reconstruction of void fraction distributions in two-phase flow by neutron radiography

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Abstract

A quantitative void fraction measurement method based on the umbra method using a neutron absorber grid was applied to the void fraction measurement of two-phase flow in a rod bundle. The grid 3 mm in width and 3mm in interval was made from B4C. The two-phase flow direction was vertical and the grid was placed vertically between the rod bundle and the neutron source. A cooled-CCD camera in the JRR-3M thermal neutron radiography system was used. CT reconstruction was carried out for sixty horizontal slices with a vertical interval of 3 mm. Sub-channel void fraction distributions were also calculated. The quantitative measurement with spatial resolution 0.1 mm, size of the image element, horizontally and 3 mm vertically was carried out.

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Keywors; CT-reconstruction, Quantitative measurement, Void fraction, Two-phase flow, Neutron radiography

1. Introduction

Two-phase flow studies are important for safety considerations of water-cooled nuclear reactors. X-rays and γ-rays have been used to measure the void fraction of the two-phase flow in a rod-bundle under the same conditions as those in a BWR and a PWR. CT methods have also been employed to obtain void fraction distributions in the horizontal cross sections of the rod bundles. Attenuation coefficients of X- and γ-rays for water are lower than those for metals of the wall materials in two-phase flow equipments. On the other hand, those of thermal neutron rays are low for most of metals and high for hydrogenous material like water and some special elements. Therefore, neutron radiography is suitable for visualization and void fraction measurement of water two-phase flow in a metallic wall. A cooled Charged Couple Device (CCD) camera was employed for high resolution and high dynamic range imaging for both visualizations.

2. Experimental apparatus and procedures

The experimental apparatus and details of the rod bundle were shown in Figs.1 and 2. Aluminum rods of 10 mm in diameter and 450 mm in length, half circular cylinder rods of 10 mm in diameter and 450 mm in length were used as simulated fuel rods. All rods were fixed by the baffle board and inserted in an aluminum rectangular duct of 56x56 mm^2. Water was supplied under the baffle board and air was supplied over the baffle board. The water and the air were mixed in the bundle to form a two-phase flow. After the test section, the two-phase flow was separated in the upper chamber. The air released to atmosphere and the water returned to the magnet pump. The test section was placed on the turntable for the CT testing. The rotating angle was 1.8 degree. Experimental conditions were the volumetric fluxes of the liquid j_l from 0.026 to 0.26 m/s and those of the gas j_g from 0.018 to 8.80 m/s.

3. Image processing methods and results

The brightness distributions of the images with and without the two-phase flow are expressed as below,

$$S(x,y) = G(x,y)\exp[-\rho_w \mu_w t_w(x,y) - \{1-\alpha(x,y)\}\rho_l \mu_l t_l(x,y)] + O(x,y) \quad (1)$$

$$S_1(x,y) = G(x,y)\exp\{-\rho_w \mu_w t_w(x,y)\} + O_1(x,y) \quad (2)$$

where S, G, O are the brightness of the image, the gain and the offset, ρ, μ_m, t, α are the density, the mass attenuation coefficient, the thickness, the void fraction and suffixes w and ℓ mean wall and liquid, respectively. From Eq.(1) and Eq.(2),

$$\{1-\alpha(x,y)\}\rho_l \mu_l t_l(x,y) = -\ln\left\{\frac{S(x,y)-O(x,y)}{S_1(x,y)-O_1(x,y)}\right\} \quad (3)$$

The cross-sectional-averaged void fraction is obtained by integrating Eq. (3) by x. The values of the right hand side can be obtained by the image processing procedure of two images with the umbra method. The umbra method was modified for two-dimensional measurement by using a neutron absorber grid. A image processing methods to compensate for the effects of neutrons scattered in the object and optical rays scattered in camera were developed. [1]

Fig.3 shows examples of one-dimensional cross sectional averaged void fraction distribution by the methods mentioned above. It can be seen that the void fraction increases along the flow direction. It can be considered that the gas phase was diffused in the bundle and the velocity of rising decreased along the flow direction.

Three-dimensional images of the water fraction distributions, $1-\alpha(x,y)$, by the CT method were shown in Fig.4 where z is distance in the vertical direction. The test section was rotated by 100 steps for 180 degree. The filtered back projection method is employed for the CT-reconstruction. It can be seen that water gathered at the four corners in Fig.4 (a) and the water distribution spread out and almost uniform in the bundle in Fig.4 (b).

Fig.5 shows the subchannel void fraction distributions. It can be seen that the values of the void fraction at the center of the bundle were higher than those of the corners in Fig.5 (a) and the void fraction was almost uniform in the bundle in Fig.5 (b).

It was shown that the gas injected into the center of the bundle was diffused to the corners flowing vertically.

Skewness was introduced in order to analyze phase distribution shape in the two-phase flow. If the distribution has a longer tail less than the maximum, the skewness has a negative. Otherwise, it has positive value. The Fisher skewness, the most common type of skewness, is defined by

$$\gamma = \frac{B_3}{B_2^{1.5}} \quad (4)$$

where B_i is the i-th central moment. For the flow in the channel, the fist raw moment or the expectation value, namely a simple area average over the cross-sectional area A, can be given by

$$\langle \alpha \rangle = \frac{1}{A}\int_A \alpha dA \qquad (5)$$

The second and the third central moment can be given respectively by

$$B_2 = \left\langle (\alpha - \langle \alpha \rangle)^2 \right\rangle = \frac{1}{A}\int_A (\alpha - \langle \alpha \rangle)^2 dA \qquad (6)$$

$$B_3 = \left\langle (\alpha - \langle \alpha \rangle)^3 \right\rangle = \frac{1}{A}\int_A (\alpha - \langle \alpha \rangle)^3 dA \qquad (7)$$

When the skewness, γ, has a negative value, it indicates a core peak phase distribution pattern in the two-phase flow. Otherwise, it has a wall peak phase distribution pattern. The larger $|\gamma|$ is, broader or shaper core or wall peak is. $|\gamma| = 0$ shows the change between the wall peak and core peak phase distribution.

Calculated results of the skewness were shown in Fig.6. The areas from A to D separated the bundle. The skewness was averaged in each area. The values of skewness were negative. The skewness at the z=0 were relatively small. It was shown that the skewness is small since the gas phase is concentrated at the center of the bundle. $|\gamma|$ increases with increasing the distance z. Values of $|\gamma|$ in the area A were smaller than the other areas regardless of increasing the distance z. It was shown that the void fraction distribution in the area A was sharp since the gas injected into the center of the bundle. The skewness in the areas B and C showed similar tendency. It meant that these phase distributions were similar in shape, that is, the gas phase diffused quickly from the areas A to B and C. The values of $|\gamma|$ in area the D were larger with increasing the distance z than those in the other areas. It was shown that the void fraction distributions in the area D were small effected by the corners. The void fraction distributions in the area D were sharper with increasing the distance z.

4. Summaries

Void fraction distributions of gas-liquid two-phase flow in the rod bundle was visualized and measured by neutron radiography. One-dimensional cross sectional void fraction and three-dimensional void fraction distributions were obtained by image processing methods. Subchannnel void fraction distributions were calculated by CT reconstruction. The diffusion in the rod bundle of void fraction distribution can be clearly shown. Skewness was introduced in order to analyze phase distribution shape in the two-phase flow. Sharpness of the phase distributions in each area of the bundle was discussed.

References

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[2] N.Takenaka, H.Asano, T.Fujii, N.Maeda, S.Hayama, M.Matsubayashi, "Application of Quantitative Measurement Method of Void Fraction Distroibution of Two-phase Flow in a Rod Bundle by Neutron Radiography", Non-destructive Test. Eval. Vol.16, 2001, pp.355-362.

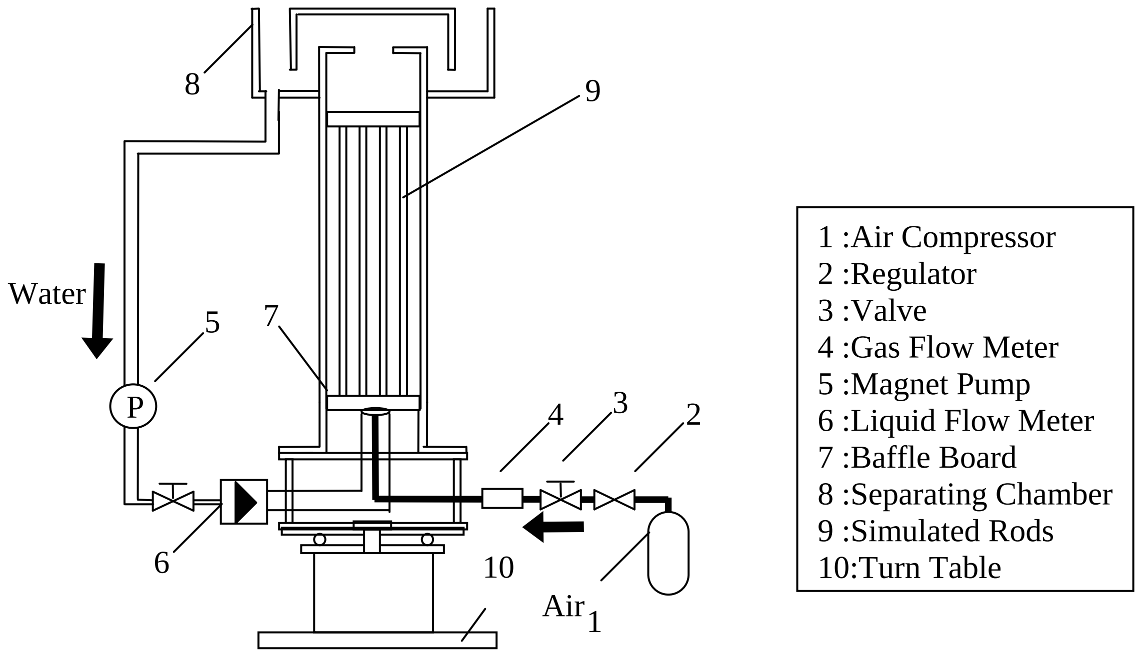


Fig.1 The experimental apparatus

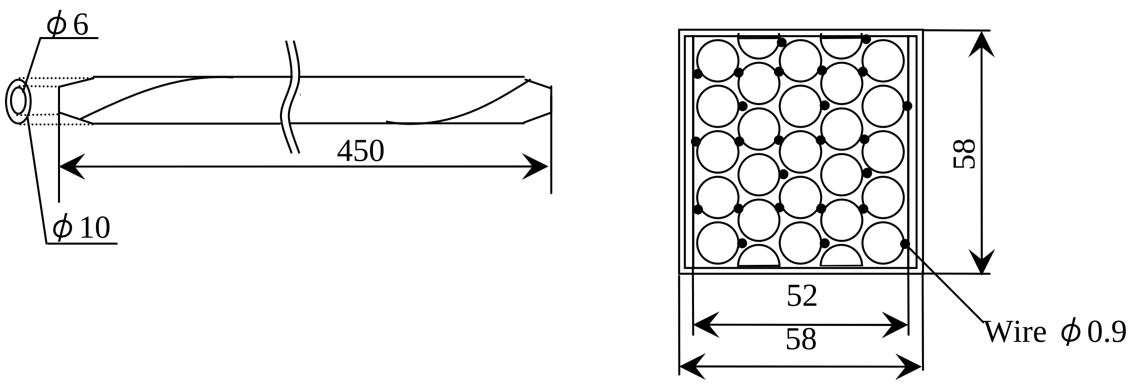


Fig.2 Details of the rod bundle

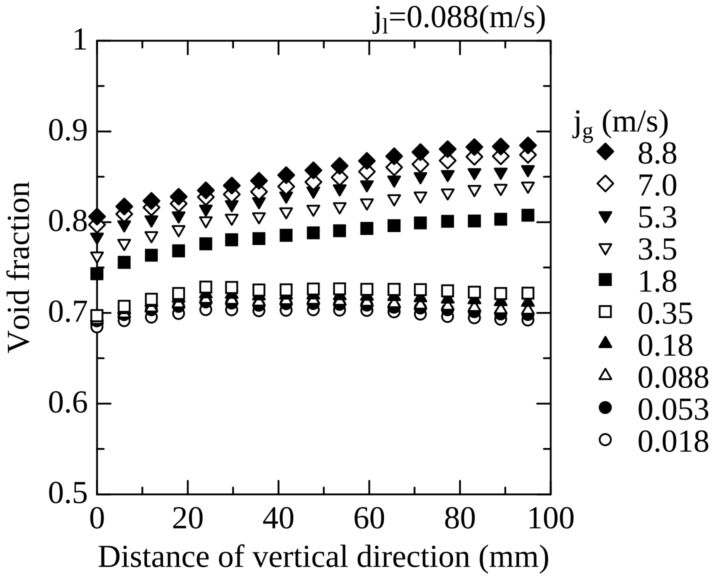
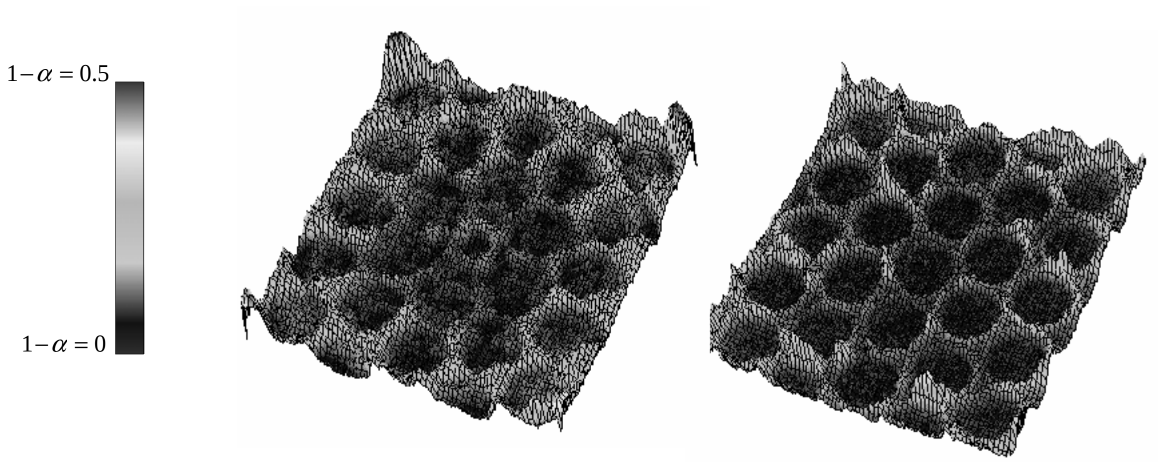
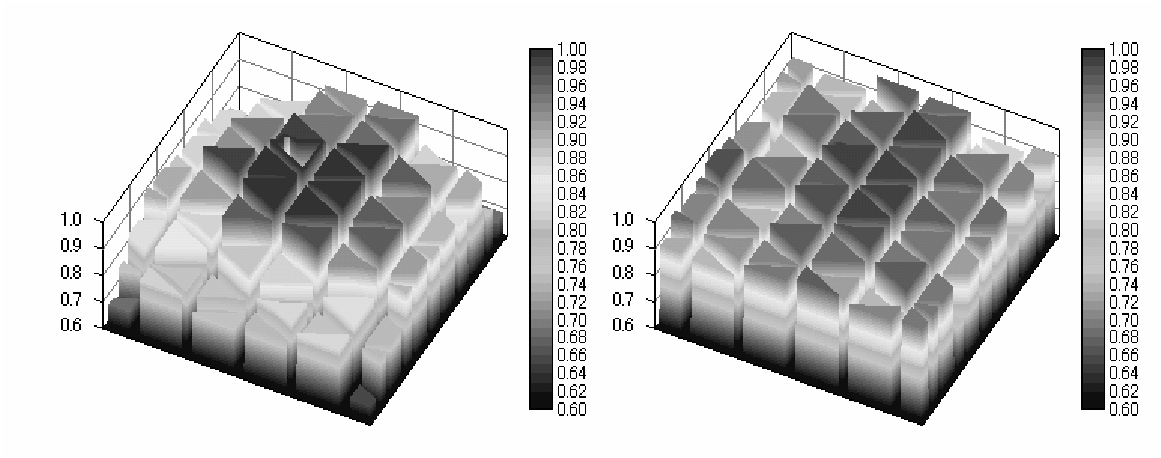


Fig.3 Examples of one-dimensional cross sectional averaged void fraction distributions



(a) Z=0mm (b) Z=72mm

Fig.4 Examples of 3-D water fraction distributions (j_g=8.8[m/s], j_l=0.026[m/s])



(a) Z=0mm (b) Z=72mm

Fig.5 Examples of subchannel void fraction distributions (j_g=8.8[m/s], j_l=0.026[m/s]

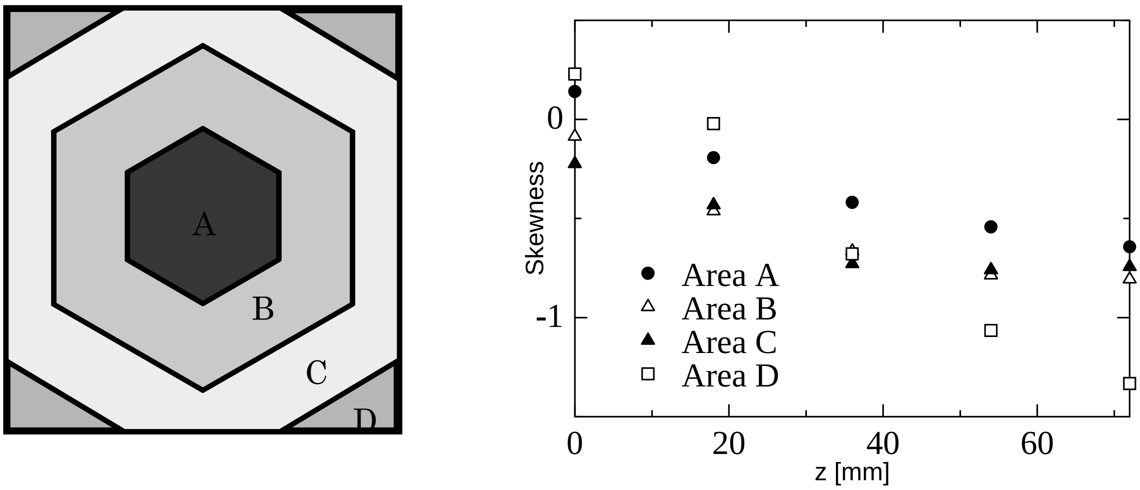


Fig.6 Examples of the calculated results of skewness (j_g=8.8[m/s], j_l=0.026[m/s])