Available online at www.sciencedirect.com
ScienceDirect
Nuclear Science and Techniques 19 (2008) 282-289
NUCLEAR SCIENCE AND TECHNIQUES

Availability of MCNP & MATLAB for reconstructing the water-vapor two-phase flow pattern in neutron radiography

FENG Qixi FENG Quanke* TAKESHI Kawai
School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

Abstract The China Advanced Research Reactor (CARR) is scheduled to be operated in the autumn of 2008. In this paper, we report preparations for installing the neutron radiography instrument (NRI) and for utilizing it efficiently. The 2-D relative neutron intensity profiles for the water-vapor two-phase flow inside the tube were obtained using the MCNP code without influence of γ-ray and electronic-noise. The MCNP simulation of the 2-D neutron intensity profile for the water-vapor two-phase flow was demonstrated. The simulated 2-D neutron intensity profiles could be used as the benchmark data base by calibrating part of the data measured by the CARR-NRI. The 3-D objective images allow us to understand the flow pattern more clearly and it is reconstructed using the MATLAB through the threshold transformation techniques. And thus it is concluded that the MCNP code and the MATLAB are very useful for constructing the benchmark data base for the investigation of the water-vapor two-phase flow using the CARR-NRI.

Key words China advanced research reactor (CARR), Neutron radiography, Water-vapor two-phase flow, MCNP, MATLAB, Reconstruction

CLC number TL816

1 Introduction

To study what happens inside an opaque container without any destruction to it is a wonderful idea. Neutron radiography (NR) is one of the nondestructive test techniques[1].

The principle of discriminating objective elements or materials from the surroundings is that the neutron absorption and scattering cross section differ significantly from element to element. Thermal neutrons and hard X-rays share common properties: They are not charged and have wavelengths comparable with the mean separation distance of atoms in solids. However, what is important here is that light elements are transparent to the X-rays and heavy elements are relatively opaque to hard X-rays, while light elements such as hydrogen, lithium and boron are highly neutron absorbent, and many heavy elements, e.g., lead and bismuth, let neutrons go freely.

Another difference is that neighboring elements in the periodic table, e.g. boron and carbon, or cadmium and tin, are virtually indistinguishable by X-rays, but neutrons see clearly the neighboring elements, and even different isotopes of an element, e.g., ^{1}H and ^{2}H, or ^{3}He and ^{4}He.

Thus, NR is advantageous over X-ray radiography to investigate the water-vapor two-phase flow inside the steam generator and the heat exchangers, the main components of a nuclear power plant.

A static neutron radiography is obtained using X-ray films with a neutron converter[2] that converts neutrons to visible light, or using 2-D pixel detector[3] for measuring neutrons transmitted through the sample tube, in which the two-phase flow occurs. The transmitted neutrons are measured as a function of the

Supported by National Natural Science Foundation of China (Grant No.50876080)
* Corresponding author. *E-mail address:* qkfeng@xjtu.edu.cn
Received date: 2008-07-04

position and orientation of the tube under examination, and variations are observed due to large scale heterogeneity, e.g. vapor, droplets and liquid, which affect absorption and large-angle scattering of neutrons. As the film provides 2-D image, not 3-D image, only the average value like the steam quality of the two-phase flow can be estimated.

Usually, depending on the input heat load, patterns of the two-phase flow change from bubbly flow to annular flow. An approximate image of the two-phase flows in the steam generator is shown in Fig.1.

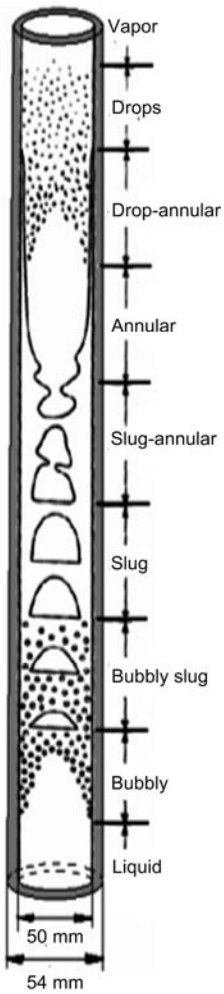

Fig.1 Various kinds of flow patterns of the water-vapor two-phase flow.

From the 2-D radiogram, the irregular flow pattern during transition, e.g. the onset of dry-out relating the safety of the nuclear reactor, cannot be distinguished. Therefore, if a 3-D image can be obtained, the phenomena occurring inside the tube could be understood much more clearly. However, it is difficult to obtain the primary 3-D objective image by neutrons, because usually the direction of neutron beam incident on the sample cannot be changed. So, the 3-D objective images need to be reconstructed from the 2-D latent images.

Milczarek *et al*[4] investigated the capability of the Monte Carlo Code (MSX) they developed to estimate the effect of scattered neutrons on the neutron radiograms, which would be obtained from the sample with inhomogeneous distribution of water. Kardjilov *et al*[5] investigated how to correct the scattered neutrons arriving at the detector as function of distance between the sample and the detector using MCNP-4C code. Glickstein *et al*[6] used Monte Carlo code to evaluate the effect of scattered neutrons on the neutron intensity profile obtained from the water flow with various void fractions.

The thermal neutron flux in the heavy water tank of the CARR (China Advanced Research Reactor, which is scheduled to be operated in the autumn of 2008) is about 8×10^{14} $cm^{-2}\cdot s^{-1}$ and the cold neutron flux at the exit of the cold neutron source (CNS) is estimated at 10^{12} $cm^{-2}\cdot s^{-1}\cdot sr^{-1}\cdot meV^{-1}$[7]. So, it is desirable to prepare in advance to utilize the neutron radiography instrument (NRI) with high quality. This work aims at constructing a benchmark data base for the CARR-NRI. The data of the two-phase flow even in a complex piping system can be compared and its flow pattern can be identified. For this purpose, we investigated the availability and feasibility of the MCNP-code and the commercial software MATLAB for reconstructing the water-vapor two-phase flow pattern.

2 Principle and method

The MCNP code, developed by the Los Alamos National Laboratory for simulating the transportation of neutron and photon in various media, has the cross-sections and the kernels of various materials. A 2-D latent image was obtained by recording the neutrons transmitting through the tube, in which various types of two-phase flow occurred, and arriving at the line-point detector divided into segments. By scanning in the vertical direction, the 2-D intensity profile could be obtained (Fig.2). The 2-D area was divided into $(N-1)\times(M-1)$ segments, where N was the row number and M the column number.

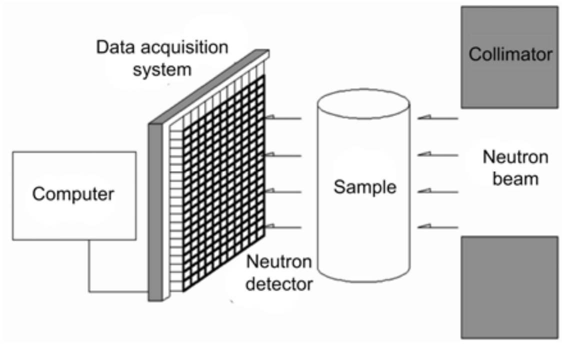

Fig.2 Schematic diagram of the neutron radiography.

The 2-D intensity profile was obtained by counting the number of neutrons arriving at the given segment of the 2-D position-sensitive detector without absorption and large-angle scattering. The neutron intensity of each segment was normalized by the total neutrons incident on the sample.

Next, the following was done to construct the 3-D objective image from the 2-D neutron intensity profile. At least two or three 2-D intensity profiles obtained by changing the neutron incidence, actually by rotating the sample tube, were needed. The intensity of neutron passing through the definite object position (x_i,y_j,z_k) inside the tube was given by superposing the neutron intensity of (y_j,z_k) and (x_i,z_k) as shown in Fig.3. The neutron intensity at this definite position gave the objective material, and thus the 3-D objective image, i.e. the flow pattern could be reconstructed. This process was done using the commercial software MATLAB.

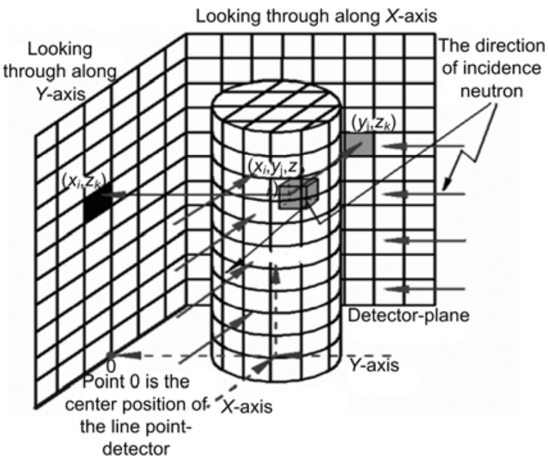

Fig.3 Schematic diagram for identifying the object at (x_i,y_j,z_k) inside the tube from the neutron intensities at the segments, (x_i, z_k) and (y_j,z_k) of the line point-detector. The center position 0 indicates the line corresponding to the center line of the tube.

3 Simulation

3.1 Simulation method for obtaining 2-D relative neutron intensity profile

The MCNP code simulated neutrons transmitting through the water-vapor two-phase flow inside the tube and arriving at the 1-D line point-detector of 19 segments, which captured neutrons from a plane neutron source that emitted parallel monochromatic beams. The 2-D relative intensity profile was constructed by arraying 7 to 11 line point-detectors longitudinally. Usually 10 million neutrons were tracked. The tube, made of aluminum, in *Φ*50 mm inner diameter and 2 mm wall thickness, was set perpendicularly without tilt. To prevent neutrons scattered in large angles from hitting the detector, the tube center was 100 mm away from the detector's central axis.

3.2 Result of simulation

3.2.1 Void fraction

The void fraction in the flow was important for heat transfer and safety. Fig.4 shows the relative counts of neutrons passing through the tube and arriving at the line point-detector. The 0 in the abscissa is the detector center. This figure shows an increase tendency of the void fraction in the water flow, because the average density of water was converted to the actual void fraction when it was calibrated by measured data. Therefore, when at least three points of void fraction were calibrated by data measured by the CARR-NRI, Fig.4 could be used as a benchmark data base for investigating void fraction in the water flow by this installation. The achievable resolution of void fraction was about 1% by the MCNP for the water-vapor flow.

3.2.2 Two large bubbles in bubbly slug flow

Fig.5 shows two *Φ*10 mm bubbles located respectively at (–12mm,0,0) and (12mm,0,0) of the tube, and impinged by a neutron beam into the tube along (a) the *X*-axis and (b) the *Y*-axis.

3.2.3 Spouted water in annular flow

Fig.6 shows the water spouted or splashed out from the surface with an irregular form, which was in half ellipsoid and tilted by 30° against *X*-*Y* plane. The center position of its base was at (0,0,0) and the long axis was 100 mm and the short axis 30 mm. However, from the 2-D relative intensity profiles, the objective image could not be understood clearly, and thus the availability of the MATLAB for restoration of the 3-D objective image from the 2-D relative intensity profiles should be investigated.

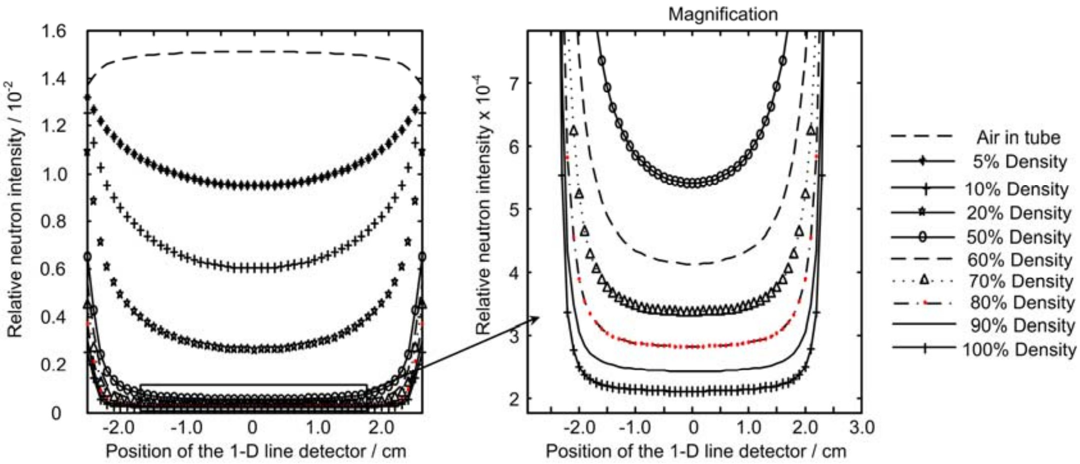

Fig.4 Relative counts of neutrons passing through the tube and arriving at the detector. The 0 in the abscissa is the detector center.

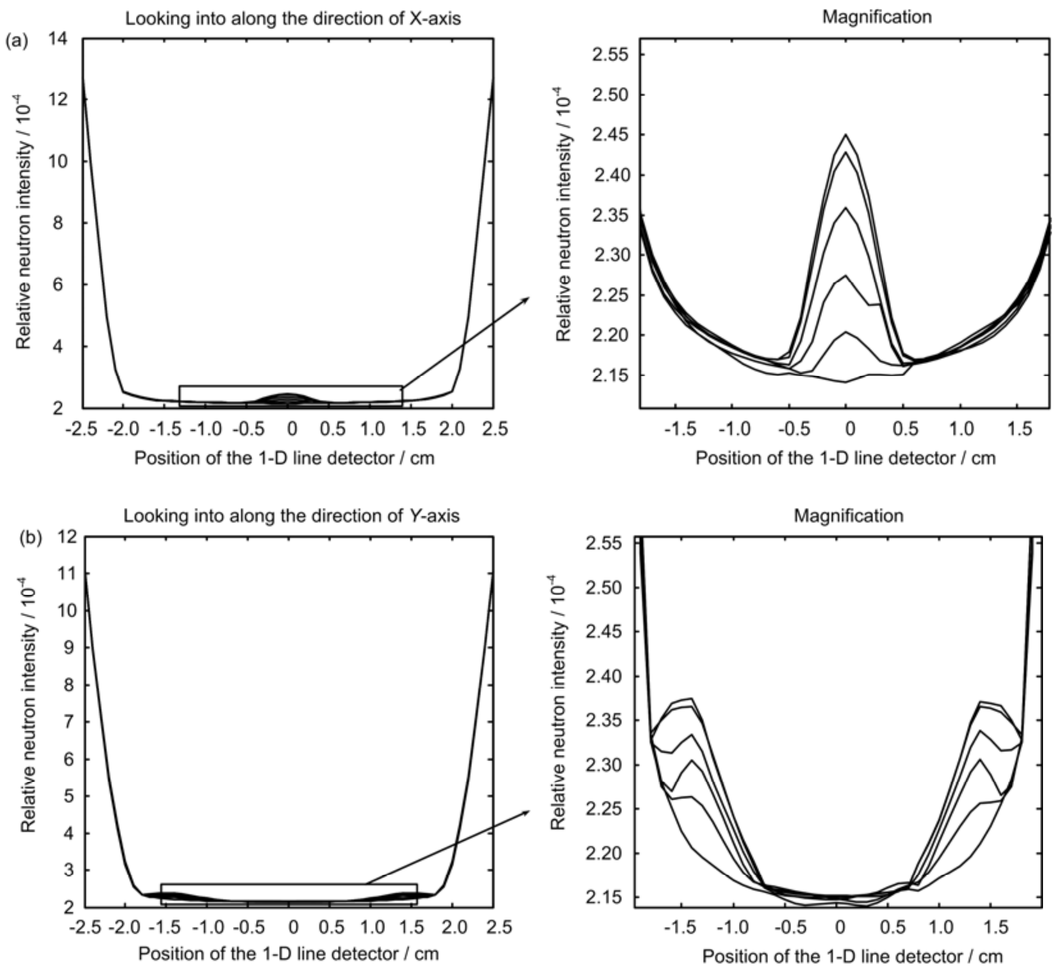

Fig.5 Two Φ10-mm bubbles located respectively at (–12 mm,0,0) and (12 mm,0,0) in the tube, and impinged by a neutron beam into the tube alongthe *X*-axis (a) and the *Y*-axis (b).

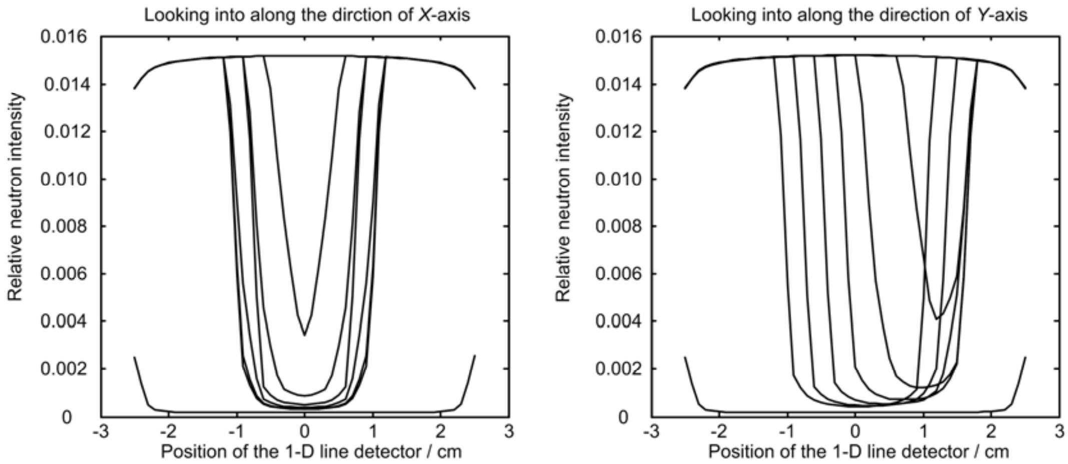

Fig.6 Spouted water from the surface of a half ellipsoid tilted by 30° against X-Y plane. The center position of its base was at (0,0,0) and the length was 100 mm and the width 30 mm.

3.3 Restoration of 3-D objective image

One understands a simple flow pattern of a void fraction in the water flow from the 2-D neutron intensity profile. However, the complex flow pattern of two big bubbles in the slug flow and spouted water from the surface in the annular flow cannot be understood easily from the 2-D neutron intensity profiles. Therefore, using the MATLAB, the 3-D objective image was reconstructed from several 2-D neutron intensity profiles taken by changing the neutron beam incidence. In practice, the 2-D relative intensity profiles to reconstruct the 3-D image were taken by rotating the sample, because the neutrons were extracted from a fixed direction.

A spatial filtering method was used when the 3-D objective image was reconstructed from the 2-D neutron intensity profiles using the MATLAB, because the 2-D neutron intensity profile was totally gray level image. And the 2-D binary image consisting of logical arrays of 0s and 1s or black and white, was obtained using the threshold transformation method from the gray-level image of the neutron intensity profile. When the gray level image or neutron counts of the intensity profile expressed by $f(x,z)$ was bigger than the definite value m, it was segmented as a “1”, that was, as a vapor component, and when it was less than m, it was segmented as a “0”, i.e. water, and thus the binary image $F(x,z)$ with arrays of 0s and 1s was obtained.

Combining the $F(x,z)$ with the $F(y,z)$, the 3-D binary image expressed by $F(x,y,z)$ was obtained through the logic operation, e.g. $F(x,y,z)$ becomes 0 when $F(x,z)$ and $F(y,z)$ were 0 simultaneously, and vice versa.

Fig.7 shows the 3-D objective image of two large bubbles and Fig. 8 the spouted water with an irregular form.

When only two different intensity profiles were used, the actual boundary of the spherical bubbles and ellipsoidal spouted water were not identified because their circumferences in simulation were expressed by the rectangular form different from their original forms. With many 2-D intensity profiles obtained by changing the neutron incidence, the reconstructed 3-D image describes the objective boundary with high spatial resolution. Fig.9 shows the spherical bubble by using 360 2-D neutron intensity profiles.

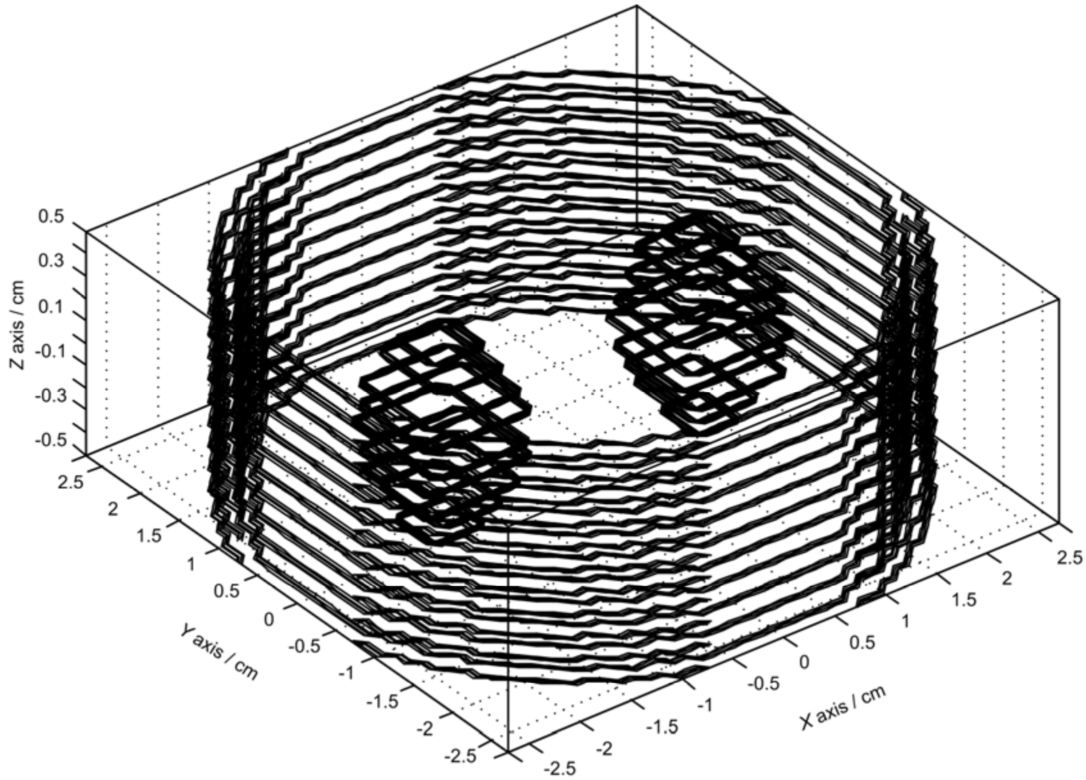

Fig.7 3-D objective image of two large bubbles.

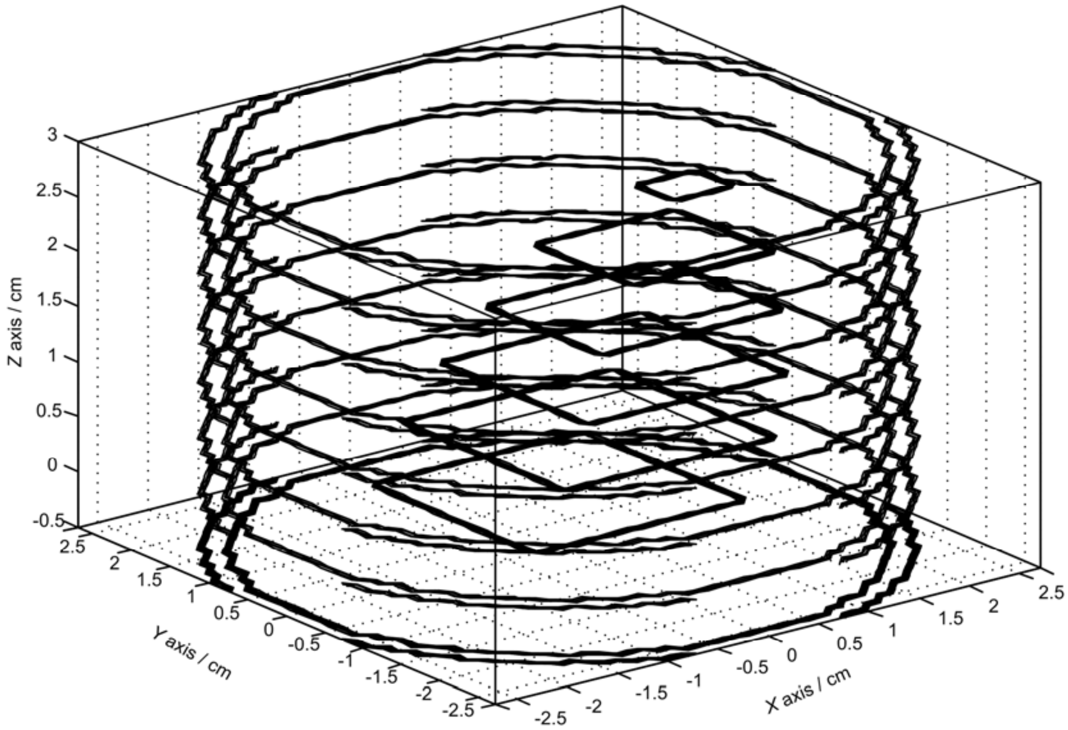

Fig.8 Spouted water with an irregular form.

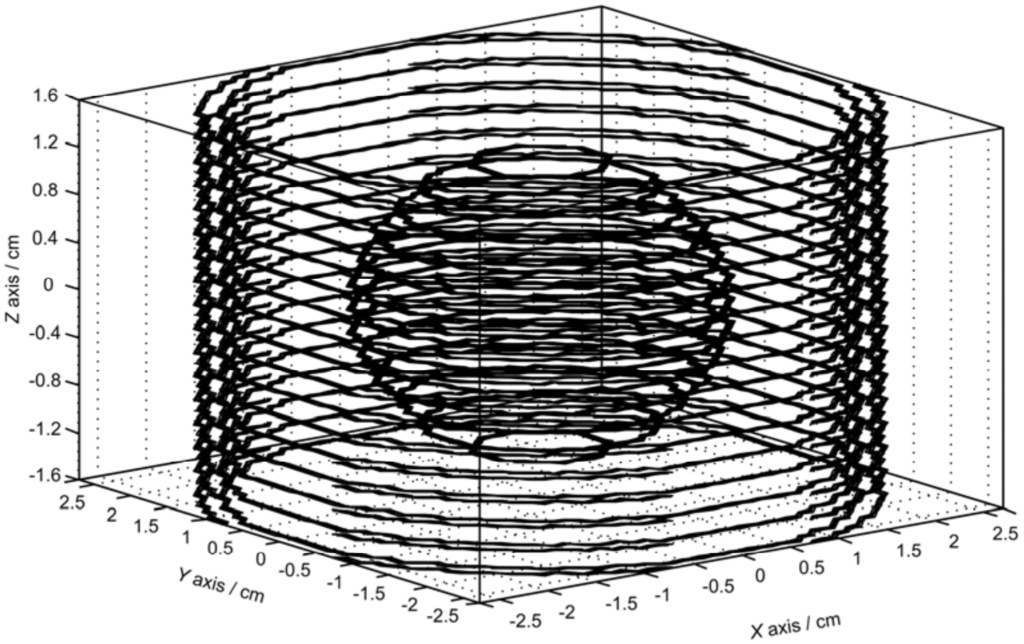

Fig.9 Spherical bubble using 360 2-D neutron intensity profiles.

4 Discussion

In the NRI, neutrons bombard the sample tube from a given solid angle, and are detected by the 2-D position sensitive detector to have the 2-D intensity profile. Spatial resolution of the objective image depends on the neutron intensity and energy. An optimal neutron intensity and energy is more practical. At the cost of CPU time, the more number of neutrons was traced, the higher the spatial resolution was, and the lower the energy of incident neutron, the higher the spatial resolution. As shown in Fig.10, the smaller droplet could be detected with decreased neutron energy.

In regard to time resolution, the MCNP was also applied to measuring the mass flow rate using micro-glass-balls because the variation of the density of the glass-balls in the flow was distinguished by neutrons.

Anyway, a part of the 2-D neutron intensity profiles obtained by the MCNP simulation must be calibrated by the measured data in order to use them as a benchmark data base, as we are preparing to do. However, for obtaining the calibration data, the simple structured equipment like a straight tube could be used. The benchmark data base would be used to evaluate the flow pattern, e.g. void fraction or heterogeneity flow pattern, even from the complicated piping system.

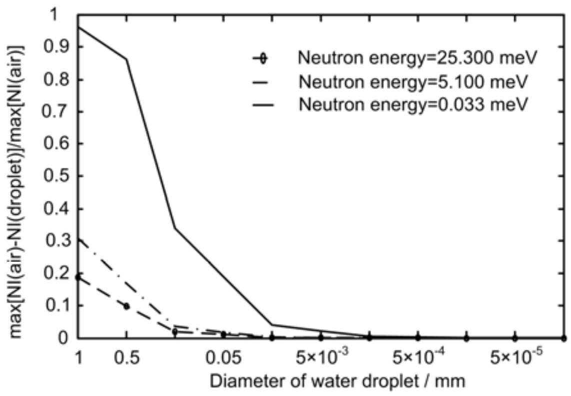

Fig.10 Variation of the neutron intensity arriving at the line point-detector after passing through the water droplet as a function of the droplet diameter. The ordinate is {[Neutron intensity (NI) transmitted through air component-NI transmitted through water-droplet]/[NI transmitted through air component]} and abscissa describes the droplet diameter floating in the air inside a tube. The neutron energies were 25.3, 5.1 and 0.033 meV, respectively.

5 Conclusion

The 2-D relative neutron intensity profiles for the water-vapor two-phase flow inside the tube were obtained using the MCNP code without influence of γ-ray and electronic-noise. And the availability of the MCNP code for simulating the 2-D neutron intensity profile for the water-vapor two-phase flow could be demonstrated. The 2-D neutron intensity profiles obtained by simulation could be used as the benchmark data base by calibrating a part of those with data measured by the CARR-NRI. The 3-D objective image allows us to understand the flow pattern more clearly and it is reconstructed using the MATLAB through the threshold transformation techniques. And thus it is concluded that the MCNP code and the MATLAB are very useful for constructing the benchmark data base for the investigation of the water-vapor two-phase flow using the CARR-NRI.

Acknowledgment

Authors would like to acknowledge Dr. Shen Feng of the CIAE for his collaboration in supplying the data of the CARR-CNS.

This work was performed as a part of the research program of the Neutron Radiography Instrument Department, CARR, CIAE.

References

1 Vontobel P, Lehmann E H, Hassanein R, *et al*. Phys B, 2006, **385:** 475-480.

2 Lehmann E H, Vontobel P, Frei G, *et al*. Nucl Instrum Methods Phys Res A, 2004, **531:** 228-237.

3 Jakubek J. Nucl Instrum Methods Phys Res A, 2007, **576:** 223-234.

4 Milczarek J J, Trzcinski A, Abd El-Ghany El Abd, *et al*. Nucl Instrum Methods Phys Res A, 2005, **542:** 237-240.

5 Kardjilov N, de Beer F, Hassanein R, *et al*. Nucl Instrum Methods Phys Res A, 2005, **542:** 336-341.

6 Glickstein S S, Murphy J H, Joo H. Nucl Instrum Methods Phys Res A, 1999, **424:** 209-214.

7 Shen F. Self-regulating characteristic of the CARR-CNS. Doctoral Thesis, China Institute of Atomic Energy, 2006 (in Chinese).