Dynamic neutron computer tomography technique for velocity measurement in liquid metal flow
- Fundamental PTV experiment -

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Abstract. The aim of this development is to visualize and measure the velocity distribution in liquid metal flow using the neutron beam with the high-speed imaging technique, computer tomography (CT) technique and particle tracking velocimetry (PTV). Final research purpose is to obtain the velocity distribution and flow profile data of liquid metal flow in a heated rod bundle for development of the advanced fast breeder reactor (FBR) core. In this paper, visualization and measurement method using the high intensity and large size neutron beam port of the research reactor JRR-4, design and manufacturing of the experimental apparatus, spring model PTV method for this technique and results of the fundamental PTV experiment were reported. The test section for the fundamental experiment was a revolving aluminum column with cadmium tracers which simulated the liquid metal flow. As the result, cadmium tracers buried in the column with the speed of 1.5 revolving per second could be visualized as the 3D movie under 125Hz and 250Hz sampling conditions, the profile of the tracer could be traced, and fundamental velocity distribution measurement method could be conformed.

1. INTRODUCTION

Evaluation of the advanced thermal-hydraulic detail analysis codes for the design of the liquid metal cooled fast breeder reactors is one of the important research targets. Velocity distribution data for thermal-striping phenomenon at the top part of the core and for circular flow between fuel rods are requested in order to proof the codes. On the other hand, since it was very difficult to measure the velocity distribution of liquid metal in the heated test section by the conventional measurement techniques, flow behaviour was not made clear and no suitable data existed. If we can get the suitable fine velocity data, we can make clear the thermal-striping phenomenon and circular flow between fuel rods and also increase the reliability of the design codes. As mentioned above, development of the new velocimetry was expected. Therefore, we have developed the dynamic neutron tomography velocimetry. Final purpose of this development is to measure 3D velocity distribution and flow profile of liquid metal flow in heated rod bundle which simulated the fuel assembly of the fast breeder reactor and to understand the flow behaviour in detail.

The dynamic neutron radiography velocimetry is the most advanced neutron radiography dynamic imaging technique. This technique is developed based on the neutron radiography technique, high-speed imaging technique, computer tomography (CT) technique, particle tracking velocimetry...
PTV), neutron Monte Carlo analysis technique and parallel supercomputer technique. Kureta et al. (2001) developed the high-frame-rate neutron radiography (HFR-NR) void fraction measurement system. Saito et al. (2005) studied the void fraction and velocity of liquid-metal two-phase flow by the HFR-NR and the PTV. Dimension of above mentioned techniques are (2D+Time). The 3D neutron tomography void fraction measurement techniques were developed by Kureta (2007) and Takenaka (1999) from the different approach. Measured data were time-averaged 3D scalar data. Kureta and Iikura (2008) have developed the ultra-high-speed scanning (UHSS) neutron tomography system to improve the 3D data quality and to realize 4D (3D+Time) visualization. Scanning time was reduced to 1 s or less by the UHSS neutron tomography. However, since it was requested from the fluid measurement point of view that time resolution of 0.1s or more less and spatial resolution of 1mm or less, we needed to develop the new 4D velocimetry. The dynamic neutron tomography velocimetry was thereby developed to realize the 4D velocimetry for liquid-metal flow.

In this paper, dynamic neutron tomography technique, fundamental experimental studies and discussions are described.

2. DYNAMIC NEUTRON TOMOGRAPHY VELOCIMETRY

Since the dynamic neutron tomography velocimetry is a new method, the principal, design and manufacture of the imaging system are reported in this section in detail.

2.1 Dynamic Neutron Tomography

Figure 1 indicates the overall sketch of the principal of the dynamic neutron tomography velocimetry. This new technique is classified in a scan-less CT, that is, real 4D CT imaging method. Test section is fixed and liquid-metal with tracer flows inside of the test section. Multi neutron beams are generated and frigate to the test section from the different direction as shown in a left caricature of Fig. 1. Instantaneous neutron radiography images are recorded by multi high-speed video cameras. From the instantaneous 2D brightness images, instantaneous CT value distributions can be reconstructed by the 3D CT technique. After discrimination of the tracer position, instantaneous 3D velocity distribution is calculated using the PTV. 3D flow profile can be obtained by tracing the individual tracers.

We had to design the imaging system, data processing software from zero. We selected the research reactor JRR-4 of Japan Atomic Energy Agency as the neutron source. We needed large size and high neutron flux beam. The beam size of the JRR-4 neutron irradiation room is 771x771mm in the beam port, 400x400mm at the collimated point. Thermal neutron flux at the core side is simulated about 1x10^11 [n/(cm^2 s)] by the neutron Monte Carlo code, MCNP.

Cut view of the dynamic neutron tomography imaging system was shown in Fig. 2. Neutron source is located in the left side of the figure. Six neutron beams are generated using the neutron control units as indicated in Fig.2. A cross point of the beams is designed to the center of the test section. Three neutron radiography converters are fixed behind the test section. Visible light on the converter is transferred by the mirror to the high-speed video camera with the image intensifier (Photoron Fastcam MAX-II, NEO-II). These imaging devices are fixed in the camera obscure.
Multi Neutron Beam Test Section

Instantaneous Neutron Radiography Images

Instantaneous CT Value Distribution

Instantaneous Velocity Distribution

Recorded by Multi High-Speed Video Cameras

Value(Dimension): Brightness(2D, Instantaneous) CT(3D, Instantaneous) V(3D, Instantaneous)

Fig. 1 Sketch of the principal of the dynamic neutron tomography velocimetry

Fig. 2 Cur view of the dynamic neutron tomography imaging system
2.2 Design and Manufacture of the Imaging System

All imaging system was designed for the JRR-4 by using the MCNP. Figure 3 shows the outside view of the final design of the imaging system. Most important parts are neutron control units which are consisted of the collimators, scatter blocks and neutron absorbers as shown in Fig. 4. 3D arrangement of the imaging system was designed as shown in Fig. 5. Each position is fixed by the neutron beam design, optical design and radiation shielding point of view. Figure 6 indicates the 3D view of the neutron beam lines and visible light lines from the backside of the test section. Front and back side mirrors reflect the side converter image to the high-speed video camera. Design of the neutron control units and radiation shielding were carried out using the MNCP. Figure 7 shows the 3D distribution of thermal neutron around the test section. Six neutron beams are generated and penetrating the test section. Figure 8 shows the simulated distribution of thermal neutron on the neutron radiography converters. We confirmed that the distribution was relatively uniform. Horizontal cross-section view and size of the parts near the test section are indicated in Fig. 9. Two neutron radiography images are projected on one converter. Diameter of the test section and width of one beam are 58mm. Width of the converter is 140mm. Beam height and imaging height are 240mm and 214mm, respectively as shown in Fig. 10.

Here, the test section was designed to simulate the 7-rod bundle of the fast breeder reactor. Main material of the imaging system is listed as follows:

- Macro collimator and neutron scatter block: Polyethylene (PE)
- Parallel collimator: B⁴C
- Neutron absorber: B⁴C, ⁶Li
- Converter: ⁶Li+ZnS(Ag)
- Mirror: Aluminium on the quarts glass

![Fig. 3 Outside view of the dynamic neutron tomography imaging system](image-url)
Fig. 4  Neutron control units (collimator, scatter/absorber parts)

Fig. 5  3D arrangement of the imaging system
Fig. 6 3D view of the neutron beam lines and visible light lines

Fig. 7 3D distribution of thermal neutron around the test section
(Simulation result by the Monte Carlo code)
Fig. 8  Simulated distribution of thermal neutron on the neutron converters

Fig. 9  Horizontal cross-sectional view and size of the parts near the test section
2.3 Image Data Processing
The data processing is classified into (A) Pre-CT processing, (B) CT processing and (C) Post-CT processing. In the Pre-CT processing, final output is \((\Sigma \delta)\) value for calculation of the CT value at the CT processing. In the CT processing, the instantaneous 3D CT value distribution is calculated. Post-CT processing is to measure the 3D velocity distribution and the flow profile.

(A) Pre-CT processing
- Read the consecutive three camera images (1024x1024pixel or 512x512pixel, 10bit)
- Kureta filter (2007) for reduction of the white-spot-noise
- Butterworth filter for reduction of the high frequency noise
- Brightness correction
- Vertical correction
- Projection angle correction
- Scale correction
- Brightness correction between imaging units and time directional
- Mirror image correction
- Cut two images from one converter image
- Calculation of \((\Sigma \delta)\) value

(B) CT processing
- CT data processing by an improved MAP-EM algorism

(C) Post-CT processing
- Normalization and scaling to 8bit scale
- 3D binarization
- Shrinkage processing
- Swelling processing
- Labelling

Fig. 10 Vertical size of the test section and beams
- Calculation of the tracer center
- Calculation of velocity by the spring model PTV (Okamoto, 1995)
- Smoothing processing
- Flow profile processing

We developed original data processing software named "RAIDEEN" and the 4D data viewer named "TRITON". Since the data size and the processing time were extremely large, RAIDEEN was designed to work on the parallel supercomputer system. Nominal CPU number was 128.

3. EXPERIMENTAL

3.1 Fundamental Tests for the Principle Confirmation

In order to proof the principle of this technique, the fundamental experiments were carried out using a rotating test section as illustrated in Fig. 11. Photo in Fig. 11 shows the inside view of the test section. Controlled revolving column which is made of aluminium is rotating in the fixed aluminium case. Cadmium bars and grains are buried in the column. Here, aluminium column and cadmium bars/grains simulate the liquid-metal and tracer, respectively. Diameter of the cadmium bars/grains are 1.0mm and 2.0mm.

Fig. 11  Photo and sketches of the fundamental rotating test section

3.2 Test Conditions

Figure 12 shows the sketch of the control pattern of the rotating column. The rotating speed was 1.5, 1.0 and 0.5 rps. Surface speed of 1.5 rps was about 0.24 m/s. All imaging system was installed in the JRR-4, and fundamental tests were carried out with recording speed of 125 fps and 250 fps.
4. RESULTS AND DISCUSSIONS

Figure 13 shows the snapshots of the original neutron radiography images. Upper and lower images were recorded with recording speed of 250fps and 125 fps, respectively. When we obtained the consecutive image with synchronizing each other, rotating behaviour of the cadmium bars could be recognized on all images. Quality of the 125fps images was a little higher than that of the 250fps images. It was conformed from this result that we can recognize the motion of the tracer under the condition of 250fps. Quality of the images was low because of the low collimator ratio (L/D) of about 10 - 24 and low scattered neutron beam flux at this moment. If we can make the high collimator ratio beam and high neutron flux beam, then we could record much higher quality images.

After many types of calibrations were applied to the original images as shown in Fig. 13, we can get the instantaneous 3D CT value distributions. Furthermore, from the consecutive instantaneous 3D CT value data, velocity distributions of the tracers and its profiles were calculated using the PTV. Fig. 14 shows the consecutive instantaneous 3D CT value distributions and velocity profile of the tracers in the rotating test section. Revolving speed was 1.5rps and recording speed was 250fps. 3D CT value distributions were visualized using the volume rendering technique. As shown in Fig. 14, vertical cadmium bars were successfully visualized. After we made the movie of the 3D CT values, we could observe the motion of the cadmium bars as the tracer. Quality of the instantaneous 3D CT images was low. However, center points of the tracers could be recognized and velocity could calculate from its center points. Instantaneous velocity of the tracer and its profile data could visualized from the perpendicular eye point to the neutron beam as shown in Fig. 14. In this figure, line and marker for velocity view were eliminated when the large miss vector of velocity and impractical profile were recognized by the data processing software. When we observed the velocity and profile of tracer, we could understand the center position of the tracer here and there. Then, next, smoothing processing on time direction was conducted. Figure 15 indicates the results of profile after smoothing processing. As shown in Fig. 15, we can understand the tracer profile from the data more clearly.

As above mentioned, the principal of the dynamic neutron tomography velocimetry was confirmed by the fundamental rotating experiments. From the fundamental tents, followings were found,

1) Limitation of the recording speed was 250fps at this moment,
2) Diameter of the tracer should be larger than 2.0 mm. 1.0 mm was difficult to be recognized at the pre-PTV processing.
3) Improving of the original image quality is the most important subjects.

Fig. 13 Original neutron radiography images recorded on the imaging system (Upper: 250fps, Lower: 125fps)
(Revolving speed = 1.5rps, Recording speed = 250fps, XY-Plane)

Fig. 14  Consecutive instantaneous 3D CT value distributions and velocity and profile of the tracers in the rotating test section
5. CONCLUSIONS

Dynamic neutron tomography velocimetry technique was developed as the new visualization and measurement method using the research reactor JRR-4. Fundamental rotating experiments were carried out in order to proof its principal. As the result, cadmium tracers buried in the column with the speed of 1.5 revolving per second could be visualized as the 3D movie under 125Hz and 250Hz sampling conditions, the profile of the tracer could be recognized well by the movie, and fundamental velocity distribution measurement method could be confirmed.

ACKNOWLEDGEMENTS

This paper contains some results obtained within the task "Development of High-speed three-dimensional measurement technique for Liquid Metal Thermo-fluid Dynamics" entrusted from the Ministry of Education, Culture, Sports, Science and Technology of Japan. This research was conducted using a supercomputer and the research reactor JRR-4 of the Japan Atomic Energy Agency (JAEA). The authors would like to acknowledge Messrs. M. Katagiri, K. Soyama for their help on making the neutron radiography converters and collimators, H. Tamai, T. Sato, K. Sakamoto, N. Kurata, H. Yokota and M. Nemoto for their assist on experiment and software.
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