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Evaluation of Motion Blur in High-Speed Neutron Imaging at Kyoto University Research Reactor

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Abstract. The rapid multiphase flow phenomena such as the flow with vaporization and condensation must be clarified for the safety analysis and severe accident analysis for light water reactors. To understand the multiphase flows experimentally, measurement technique with high temporal resolution is required. In addition, the multiphase flow has spatial distributing characteristics, thus two- or three-dimensional visualization techniques are suitable for the understanding of the flow structure. In this study, temporal resolution of the neutron imaging technique was enhanced for the observation of rapid multiphase flow behavior. The existing imaging system was upgraded to improve the frame rate, and imaging with a frame rate of 10,000 fps could be achieved at B-4 port in Kyoto University Research Reactor (KUR) at 5 MW operation. Then, the imaging results were evaluated by using a rotational disc system. The relation between the rotational speed and motion blur was investigated in the high-speed neutron imaging.

Introduction

Multiphase flows appear in many industrial applications like power reactor and chemical reactor, and are phenomena which show large temporal fluctuation and characteristic spatial distribution. Therefore, the flow structure is very complicated and difficult to understand in detail. However, the multiphase flow should be clarified for the safety analysis and severe accident analysis for light water reactors. Especially, in the nuclear severe accident, several rapid multiphase flows might be seen, for example, steam explosion and re-flooding etc. Although it is difficult to investigate these phenomena experimentally and analytically, their understandings are essential for safety analysis of the nuclear reactors.

Usually, optical imaging technique using a high-speed camera has been applied to rapid flow observation. Very fast imaging (>1,000,000fps) can be performed using the high-speed camera [1] and the bubble shape and motion in bubbly flow can be detected easily. However, it is difficult to measure the flow behavior inside metal vessel which is generally used in the experiments at high temperature and high pressure conditions. The radiation imaging technique is very effective for such two-phase flow measurement in opaque vessel. In particular, neutron transmission imaging which has high sensitivity to the water and transparency to the metal has been applied various multiphase flow studies. The interaction of molten metal and water [2] and the bubble behavior in liquid metal pool [3] were visualized by thermal neutron imaging with the frame rate of 500 fps in JRR-3M. Kureta et al. also applied the neutron imaging to study the subcooled flow boiling in a narrow rectangular channel [4]. Two-phase flow behavior in porous media was observed at the frame rate of 200 fps in KUR B-4 port [5]. In addition, air-water two-phase flow was visualized at 800 fps using cold neutrons at ICON beam line in PSI [6] and boiling of pentane inside a steel tube was observed at 154 fps using NEUTROGRAPH in ILL [7]. High-speed neutron imaging with a 10μs exposure time was also performed at ANTARES facility in FRM II [8]. However, the

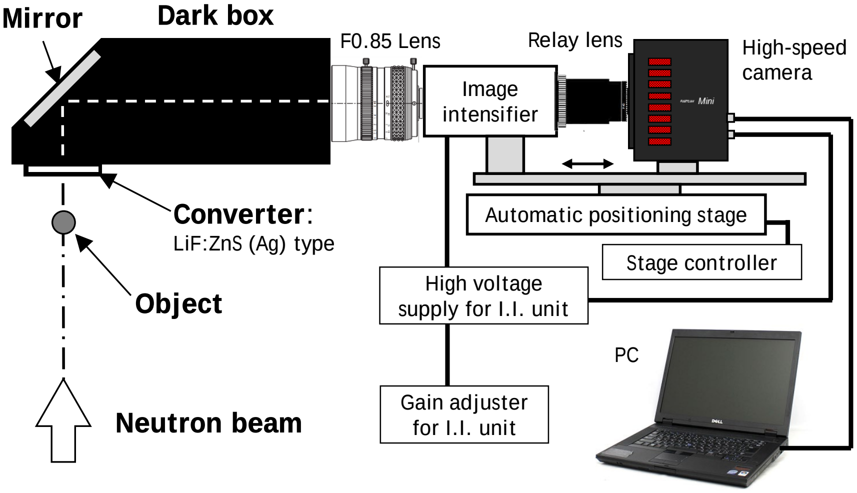


Fig. 1 High speed neutron imaging system

improvement of temporal resolution in neutron transmission imaging is still required for rapid multiphase flow observation. For high-speed flow observation using neutrons, high sensitivity imaging system and high neutron flux source are required. Since the construction of new high-power neutron source has large difficulty, the imaging system was upgraded in this study.

In addition, the image distortion and degradation are influenced by a number of system components in neutron imaging experiments [9]. To perform accurate imaging, these factors should be clarified. Generally, converter unsharpness, object scattering and geometric unsharpness cause the image degradation in the neutron imaging and, they depend on the system and facility. In high-speed neutron imaging, motion unsharpness and statistical system noise are important and their effect on acquired image must be understood. Thus, the purpose of the present study is to improve the high-speed neutron imaging system and to evaluate the image quality degradation in high-speed neutron imaging.

High speed neutron imaging system

To enhance the temporal resolution in the neutron imaging, the imaging system was upgraded. The high speed neutron imaging system used in this study consists of a high-speed camera, an optical image intensifier, optical lens and a converter. The present major improvements are the uses of a high sensitivity high-speed camera (Photron AX-50, ISO 40,000), an ultra-high sensitivity lens (50mm F0.85, VS Technology VS-50085/C) and a thick scintillator (RC Tritec 6LiF/ZnS:Ag 200μm). The improved imaging system is shown in Fig.1. The neutrons transmitted through the imaging object converted to the optical light by the scintillator. The light enters an optical image intensifier via the lens and intensified. Finally, the high-speed camera records the image. The focus of the camera was adjusted by a positioning stage. In the previous imaging system, the frame rate was 200 fps [10], however, the present imaging system could achieve the frame rate of 10,000 fps at B-4 Port in KUR at operation power of 5MW.

Experimental setup

To evaluate the image quality in the high-speed imaging, the experiments using a rotating indicator were performed. The rotating disc system is shown in Fig.2. The gadolinium (Gd) plate which has high neutron attenuation characteristics was used as the indicator. The shape of the used indicator is shown in Fig.3. This simulates small bubble in water, because water has large attenuation

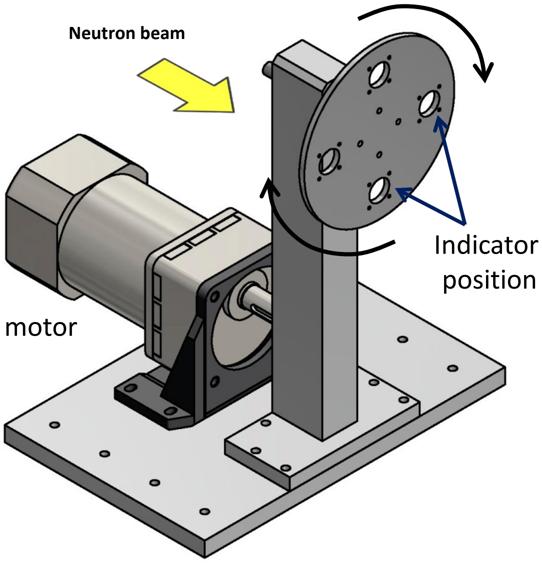


Fig. 2 Rotating disc system

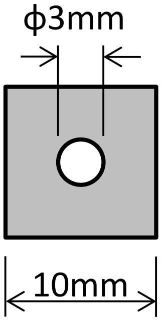


Fig. 3 Gd indicator plate

coefficient for thermal neutrons. The thickness of Gd plates is 0.2 mm. Four indicators can be fixed on the rotating disc equiangularly (circular holes in Fig. 2). The radial location of the indicators on the disc is 50 mm. The rotational speed of the disc was varied up to 960 rpm which is corresponding to the velocity of 5 m/s in the indicator position. The neutron imaging experiments were conducted at B-4 experimental room in Kyoto University Research Reactor (KUR). The thermal neutron flux at the beam exit is 8.5×10^7 n/cm^2 s. The beam size is 75 mm height and 10 mm width at beam exit. The distance between the indicator and the converter was 150 mm and the L/D in the present imaging was 150. The pixel resolution of the acquired image in the present experiments is 0.4 mm/pixel. The frame rate of the high-speed camera is 10,000 fps, and so the exposure time is 0.1 ms. The gate time of the image intensifier is also 0.1 ms.

Results and discussion

The neutron transmission image of a static indicator is shown in Fig. 4. 2,000 instantaneous images acquired with a 0.1ms exposure time were averaged. The neutrons are attenuated by the Gd plate, and the small hole could be observed. However, there is the blurring at the edge of the indicator and this may be caused by the converter thickness, object scattering and beam divergence. The neutron transmission profile along the vertical line in the center of the indicator is shown in Fig.5. The solid line denotes the transmission profile and the dashed line denotes the designed value of the indicator shown in Fig.3. The edge of the indicator is blurred even in the static observation.

The averaged images of the rotating indicator are represented in Fig. 6. The center of mass of the indicator in each image was estimated and those images were rotated around the center of rotation disc so as to be the same indicator location with the image in Fig.4. Then, 70~180 images at the same position are averaged. The rotational speed was changed from 0.6 m/s to 5 m/s. In these images, the indicator was moved from top to bottom. The difference between static and rotating indicators is obvious and the image degradation due to the indicator motion becomes strongly as the rotation speed increases. Especially, the rear side edge is more blurred. In addition, it is hard to recognize the circular hole in the indicator in 5 m/s motion. As a result, the effect of motion blur in high-speed neutron imaging corresponds to the rotating speed.

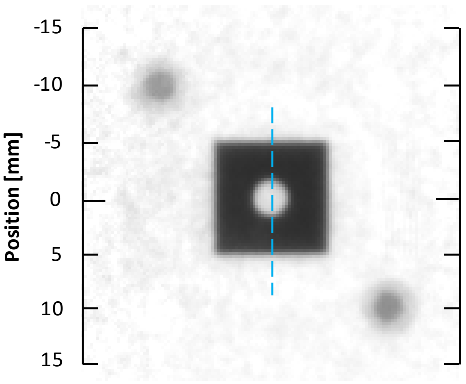


Fig. 4 Neutron transmission image of static indicator

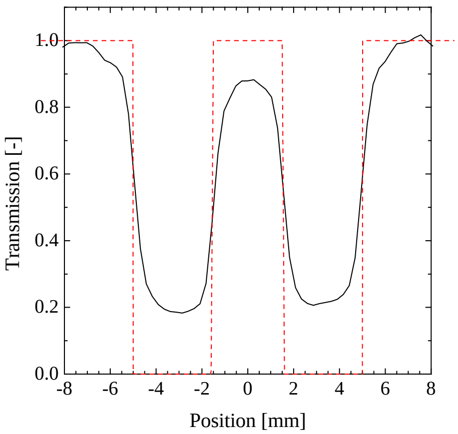
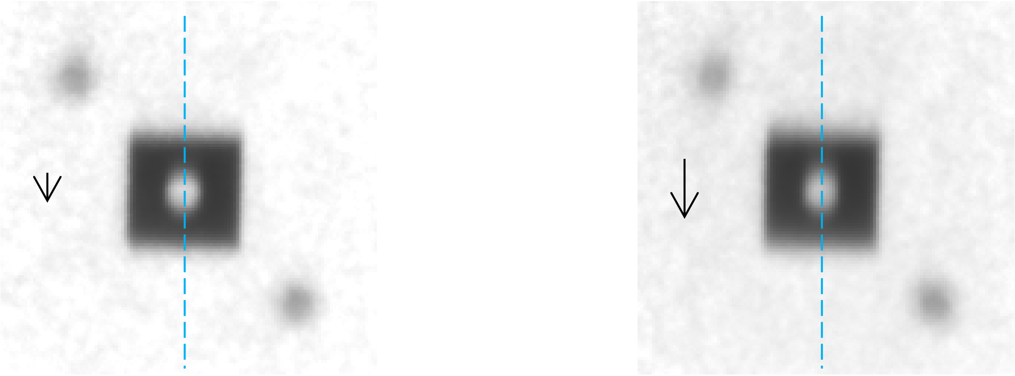


Fig. 5 Neutron transmission profile along the vertical line shown in Fig.4


(a) 0.6 m/s (b) 1.2 m/s

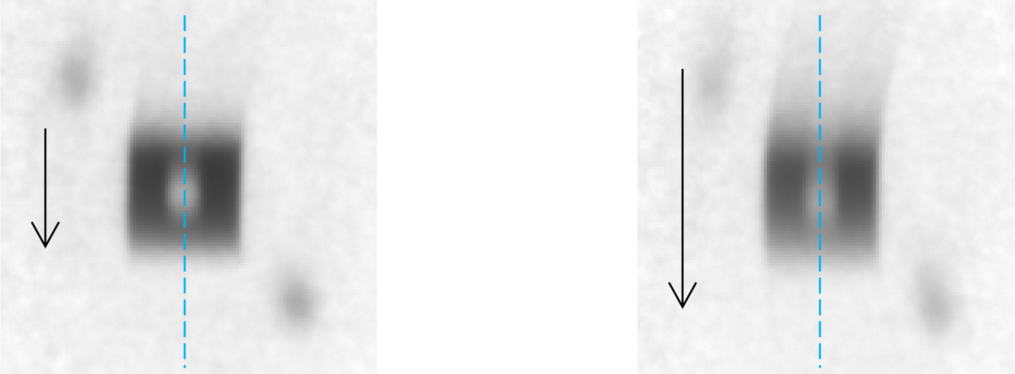

(c) 2.5 m/s (d) 5 m/s

Fig. 6 Neutron transmission images of indicator rotated at different rotation speed

The neutron transmission profiles along the center line were made from the images in Fig. 6, as shown in Fig. 7. As the rotation speed increases, the edges become smoothly. In addition, the decay time characteristics of the scintillator might be one of the causes of the image degradation. Therefore, the smoothed edge characteristics due to the motion should be clarified and the image restoration method must be established by considering the motion blur and the afterglow. In this study, the image restoration using a point spread function (PSF) was applied to investigate the effect of the motion blur.

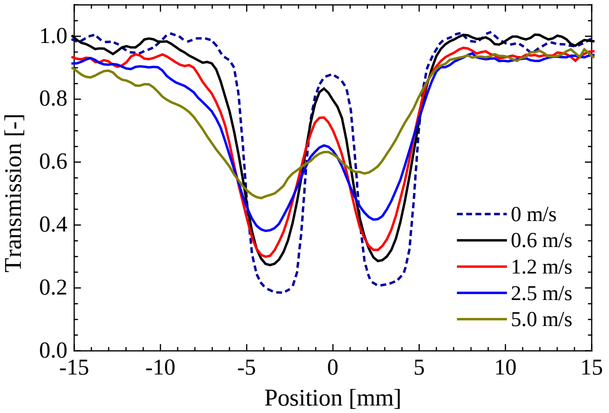
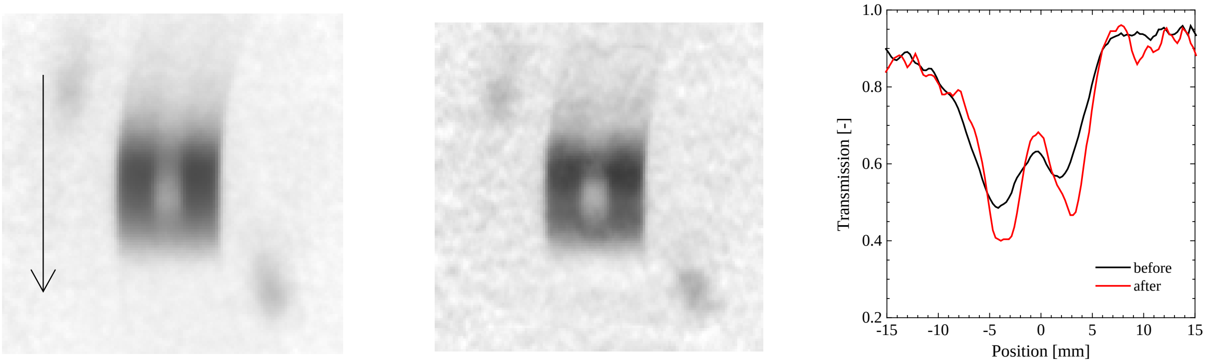


Fig. 7 Neutron transmission profile of rotating indicator



(a) distorted image
(5.0m/s motion)

(b) restored image
(blur width 15 pixels)

(c) comparison of the profile along
the center vertical line

Fig. 8 Blurred image restoration.

The distorted image *g*(x,y) can be represented by the convolution of the original image *f* (x,y) and the *PSF*(x,y), as follows.

$$g(x,y) = PSF(x,y) * f(x,y) \tag{1}$$

If the width and direction of the motion blur are known, the PSF can be estimated. However, it is not easy to evaluate such parameter from only the distorted images. In this study, the parameters are assumed and the image was restored using Winner filter with the blur width of 15 pixels. The restored result is shown in Fig. 8(b). The motion blur can be reduced by this process. In addition, the comparison of the profile before and after the filter is show in Fig. 8(c). Although the filtering parameters were assumed manually, the edge of the indicator could be enhanced. However, the blur could not be removed completely, because it might be affected by the decay characteristics of the scintillator. Therefore, the thickness of the scintillator and gate time of the image intensifier should be considered to establish the image restoration processing.

Summary

In this study, the high-speed neutron imaging system was upgraded to improve the temporal resolution for rapid multiphase flow observation. As a result of the use of high sensitivity high speed camera and high sensitivity lens, the frame rate of 10,000 fps could be achieved at B-4 port, KUR. The applicability to rapid multiphase flow observation would be extended by the present improvement. In addition, the image quality in the high-speed neutron imaging was evaluated by the rotating disc system and the image degradation due to the rapid motion was confirmed. The image distortion might be affected by not only the motion blur but also the decay characteristics of the scintillator and image intensifier. The image restoration processing method will be developed by considering the image distortion and the effect of the thickness of the scintillator and gate time of the image intensifier will be evaluated in the future.

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