3D Velocity Vector Measurements in a Liquid-metal using Unsharpness in Neutron Transmission Images

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Abstract. To measure the two/three-dimensional velocity vectors in a liquid metal flow, a new neutron imaging method was applied. By using a conventional transmission neutron imaging (neutron radiography) only two-dimensional information of tracer particles can be obtained. In this study, three-dimensional position was measured by analyzing the image unsharpness (blurr) of tracer particles depending on the distance between the particle and the imaging screen in the neutron beam direction. Neutron imaging has been performed at the Kyoto University Research Reactor and the variation of image unsharpness of particles was investigated.

Introduction
Detailed modelling of liquid-metal two-phase flow is needed not only for safety analysis of liquid-metal fast breeder reactors (LMFBRs) [1] but also for development of accelerator-driven system (ADS) that makes use of lead bismuth as a spallation target and coolant. Liquid-metal two-phase flow has a larger liquid-to-gas density ratio and a higher surface tension in comparison with those of ordinary two-phase flows such as air-water flow. In order to predict the flow behavior of a gas-molten metal mixture in a pool precisely, it is essential to examine the applicability of the existing model to the gas-molten metal mixture pool, and if necessary, to propose suitable constitutive relations in the momentum exchange between phases. From this point of view, present authors [2,3] performed study on the flow characteristics of nitrogen gas-molten lead bismuth eutectic (LBE) mixture in a rectangular pool and measured the void fraction distribution and time averaged liquid velocity field using neutron imaging and particle image velocimetry techniques [4].

However, only two-dimensional positions of tracer particles can be obtained from the conventional neutron imaging method. Three-dimensional position of particles can be measured by using more than two neutron beams. The purpose of this study is to measure the distance between tracer particles and the imaging screen (scintillator) by analyzing the image unsharpness of the neutron transmission imaging.

Experimental setup and method
Figure 1 shows the schematic of experimental setup. The test section consists of a Newton alloy (Pb:50%, Bi: 25%, Sn:25%) rod and a rotating table. Four cadmium particles of 2mm in diameter were cast in the Newton alloy rod with 18 mm in diameter. The imaging system consists of a scintillator screen (LiF/ZnS:Ag), mirrors, and a CCD camera (Princeton Instruments, PIXIS 1024B). Experiments were performed at the B-4 port of Kyoto University Research Reactor. Figure 2 shows the neutron image of the test section and the cadmium particles, where the coordinate system x, y, z and rotating angle θ of the particle are also shown. Neutron imaging was performed with rotating step of 6 deg. And the exposure time was 10 s.
Evaluation of the image unsharpness

Two-dimensional position of tracer particle can be easily obtained from the neutron transmission images. Applying Particle Tracking Velocimetry (PTV) to the successive images of moving tracer particles, two-dimensional velocity vector can also be estimated. However, the remaining position, the distance between the particle and the scintillator screen, cannot be directly obtained from them. In this study, the image unsharpness information of tracer particles are analyzed to obtain the distance \( z \) in Fig.2.

The divergent incident neutron beam generates geometric unsharpness in the neutron transmission images as shown in Fig.3. The image unsharpness \( U_g \) due to the divergence of the incident beam is simply expressed by

\[
U_g = \frac{L'}{L/D}
\]

where \( L' \) is the distance between the object and the scintillator screen. \( L \) and \( D \) denote the length and the inlet aperture diameter of the collimator, respectively. Thus, the image unsharpness includes the information of the distance between the object and the screen. As it is known, the measured profile can be expressed by the following convolution [4]:

\[
G'(x,y) = G(x,y) * h(x,y)
\]
where $G'(x,y)$ is the measured profile of the blurred image, $G(x,y)$ the original profile, and $h(x,y)$ a point spread function. The point spread function can be modeled by Gaussian form:

$$h(x,y) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right)$$

(3)

where $\sigma$ is the standard deviation of the Gaussians as shown in Fig.4.

Thus, if the original image and the blurred image is known, the standard deviation in the point spread function can be calculated. However, the shape of the tracer particles employed in this study was not perfectly spherical. Therefore, the binarized image was calculated and the convolution in Eq.(2) was conducted with point spread function Eq.(3) to obtain the optimum value of standard deviation of the point spread function as shown in Fig.5. Then the standard deviation can be converted to the image unsharpness $U_g$ or the distance between the object and the screen, $L'$ or $z$. Once $x$, $y$, and $z$ of each tracer particle are known, three-dimensional velocity vector of tracer particles can be measured using PTV method.

Fig. 4 Mathematical expression of image blur due to beam divergence.

Fig. 5 Mathematical expression of image blur due to beam divergence.
Results and Discussions

Figure 6 shows the two-dimensional position of Cd particles obtained from the transmission images for each Cd particle (No.1-4). Position of Cd particle was calculated by using a cross correlation method of tracer image. Since the Newton alloy rod was rotated around the vertical axis, the y-position of each tracer particle was kept constant during the rotation. Then, the image unsharpness of the tracer images was calculated for each particle, as shown in Fig. 7. As shown in these figures, the image unsharpness, the standard deviation, corresponds to the rotation angle for each Cd particle.

![Figure 6: Variation of x-position with rotating angle.](image)

![Figure 7: Variation of image unsharpness with rotating angle.](image)

Figure 8 shows the variation of image unsharpness with x-position of particles. As can be seen, variation of the standard deviation shows two tendency. When the particle stays near the scintillator, the standard deviation, image unsharpness, shows smaller value. In contrast, when the particle stays at the opposite side, the standard deviation takes larger value even at the same x-position. From such tendency, we can roughly detect the position of particle, which side the particle stays, near the scintillator or opposite side.

If the image unsharpness is caused only by the beam divergence, the experimental results should show a circle shape, however, the shape of trajectory in Fig. 8 is clearly distorted. Such distortion may be caused by the additional image unsharpness due to the imaging system itself such as lens aberration, image distortion through the image intensifier and so on. Therefore, z distance can be estimated by modifying the image unsharpness information by taking the distortion due to the imaging system. The solid lines in Fig. 7 show the average tendency of the
image unsharpness along the x direction, which may denote the image unsharpness due to the image unsharpness. If the image unsharpness due to the imaging system can be assumed to be constant depending on the location in the image plane, z position of each Cd particle can be correlated to the imaging system.

Figure 8 shows the comparison of calculated z position from the image unsharpness and that measured from the x position of the particles. As shown in this figure, good agreement can be achieved between calculated and measured z position.

**Summary**

To develop three-dimensional velocity vector in a liquid-metal flows, neutron imaging was applied and the image unsharpness was estimated by changing the distance between tracer particles and the imaging screen. From the preliminary experiments, the variation of image unsharpness was clearly observed depending on the distance. However, to estimate the z position of particles accurately, the other origin of image unsharpness due the imaging system should be taken into account. In addition, image blur due to the moving object should be considered to establish the 3D measurements of tracer particles in the actual applications.
Fig. 9. Variation of image unsharpness with x-position.

References


