# PIV Analysis of RBC Flows Using Synchrotron X-ray Imaging Technique

Guk Bae Kim* · Sang Joon Lee*

## 1. Introduction

Several experimental techniques which are useful in general fluid mechanics research area have been employed to investigate blood flows, however most of them were unsatisfactory due to difficulty encountered in visualizing the opaque blood. Therefore most hemodynamic researches have mainly been carried out in vitro using transparent substitutes of the blood. On other hand, the conventional medical instruments such as MRI (Magnetic Resonance Imaging) and ultra-sonography have also several limitations in direct velocity measurements, despite of their permeability to blood flows and blood vessels. These are mainly attributed to the following facts; At first, the properties of blood cells and plasma are too similar to distinguish each other with medical instruments. Secondary, since red blood cell (RBC) is smaller than 10 m, it is difficult to be detected by medical instruments having relatively poor spatial resolution. Therefore, it is difficult to acquire quantitative velocity information of real blood flow with conventional instruments.

In this research, the third generation synchrotron radiation source was used to visualize real RBC flows inside an opaque microchannel. In order to investigate blood flow quantitatively, we applied this radiation source to PIV velocity field measurement technique. Recently, we developed the x-ray PIV technique combining synchrotron radiation source and PIV technique, and applied to a flow of glycerin in an opaque Teflon tube[1] The resulting amassed velocity field data were in reasonable agreement with theoretical predictions. In the x-ray PIV technique, the refraction or Fresnel edge diffraction mechanism of an x-ray was used to improve the image quality. The relative weights of refraction and Fresnel edge diffraction in the x-ray imaging depend on the given experimental conditions, type of specimen and information to be extracted.[2] To get clear RBC flow images applicable to PIV algorithm, we need to optimize the diffraction inducement and interference inducement of RBC flows by synchrotron radiation source

## 2. Experimental procedure and Results

The experiments were performed at the "white beam" line (1B2) of the Pohang Accelerator Laboratory (PAL). A schematic diagram of the experimental setup for the x-ray PIV measurements is shown in Fig. 1. The x-ray beam of sub-nanometer scale is converted into visible wavelength by arriving on a thin $CdWO_4$ scintillator crystal. X-ray flow images of RBC flow were recorded on a cooled inter- line transfer CCD camera of $1280 \times 1024$ pixels resolution. The lateral resolution ($\Delta x$) was better than 5 m when the CCD camera was coupled with a $10\times$magnification lens. Because the x-ray beam used is continuous beam, we installed a mechanical shutter to make pulse type x-ray beam for PIV measurements. A delay generator was used to synchronize the mechanical shutter and the CCD camera. The time interval between consecutive images was fixed at 10 msec. The x-ray PIV technique was applied to a RBC flow in a microchannel of 490 m wide and 1390$\mu$m deep. A syringe pump was used to supply the volumetric flow rate of 0.5 ml/hr through the microchannel installed vertically. The field of view was about $514 \times 686 \mu m^2$ in physical size. A two-frame cross-correlation PIV algorithm was applied to each pair of consecutive x-ray flow images to obtain the corresponding instantaneous velocity field.

The PIV measurements were performed with varying the sample-detector distance and the thickness of sample fluid to optimize the diffraction inducement and interference inducement. Fig. 2 shows raw images of RBC flow in a Teflon tube of 550 m in diameter with

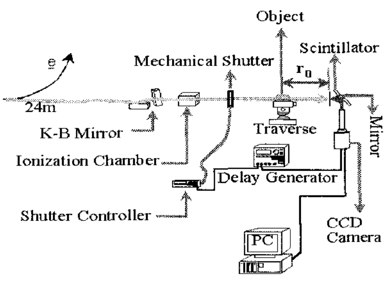

Fig. 1 Schematic diagram of experimental setup for the x-ray PIV measurements

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* 포항공과대학교 기계공학과

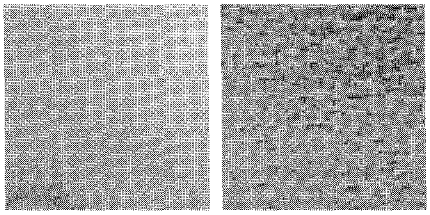
(a) $d$ = 3.4 cm (b) $d$ = 40 cm

Fig. 2 Raw images of RBC flow with respect to the sample-detector distance ($d$)

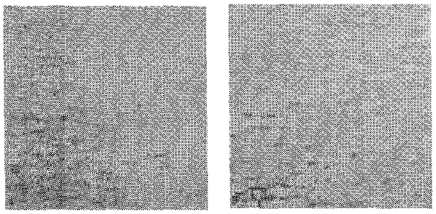
(a) $t$ = 350 $\mu$m (b) $t$ = 1390 $\mu$m

Fig. 3 Raw images of RBC flow in various microchannels of different thickness ($t$)

varying the sample-detector distance ($d$). When the distance $d$ is 3.4 cm we can not see any RBC pattern. As $d$ increases, the flow pattern of RBC becomes to be recognizable. From these preliminary parameter tests, we found that the RBC flow image at the condition of $d$= 40 cm is most suitable for PIV measurements. When $d$ is larger than 40 cm the RBC flow image is also acceptable for PIV algorithm application, however the blurry image by excessive diffraction enhancement brings out more error vectors.

Fig. 3 shows RBC flow images in various microchannels having different depth ($t$) along the direction of x-ray propagation. All images were captured at $d$ = 40 cm. When $t$ is 350 $\mu$m the x-ray image of RBC flow is very dim and not suitable to apply to PIV algorithm. As $t$ increases, RBC flow patterns become to be recognizable. When $t$ is 1390 $\mu$m, the RBC flow image is good enough to apply to PIV algorithm. When $t$ is over 1390$\mu$m the RBC pattern acquired is also acceptable for the application of PIV technique. From this, we can see that the interference inducement of RBC flows by synchrotron x-ray source requires the minimum thickness of RBC flows to acquire clear flow patterns. In order to explain a full mechanism about the diffraction inducement and interference inducement of RBC flows by synchrotron radiation source, the x-ray imaging technique should have better spatial resolution.

Fig. 4 shows the streamwise mean velocity field of RBC flow using the x-ray PIV technique, for which 200 instantaneous velocity fields were ensemble averaged. In order to get this quantitative velocity field data of real RBC flow, the two optimized conditions of the sample-detector distance(40cm) and the thickness of sample fluid(1390$\mu$m) were adopted. The dark area near the wall indicates low velocity and the bright part at the center of channel means high velocity. This velocity distribution corresponds to typical velocity profile in a macrochannel.

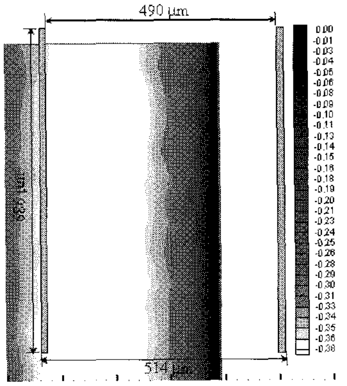

Fig. 4 Ensemble-averaged streamwise mean velocity field of RBC flow

## 3. Conclusion

The x-ray PIV velocity field measurement technique was applied to obtain quantitative information of real RBC flows in a microchannel. In this study, the optimum conditions for acquiring reasonable x-ray images of RBC from which velocity vectors can be extracted were derived through parameter study. As the sample-detector distance increases, the RBC flow pattern becomes to be detectable with the induced diffraction-based enhancement. The optimum distance is about 40 cm under the tested experimental conditions. When the thickness of sample fluid is lager than 1390 m, the RBC flow image becomes suitable for application of PIV algorithm. From the x-ray images of RBC flow captured, we measured the quantitative velocity field information of real RBC flows inside an opaque microchannel. The velocity field data show typical velocity profile in a rectangular channel. The x-ray PIV technique developed in this study has potential applications in the research areas of bio-fluid and hemodynamics.

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## References

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(2) Hwu, Y., et. al., 1999, Coherence-enhanced Synchrotron Radiology: Refraction versus diffraction mechanisms, J. Appl. Phys., vol. 86, pp.4613~4618.