Opaque flow measurement in the pipe system using echo-PIV and UDV method

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ABSTRACT

In this paper, echo-PIV and UDV technique were applied to measure the velocity fields of a pipe flow system. The working fluid is mixture of water and kaolin particle. The flow rate of mixture is 0.15 lpm. The error of peak velocity between echo-PIV and UDV were obtained and compared with the theoretical values. This study indicates the feasibility of echo-PIV and UDV methods for measuring the opaque flow which flow medium is water-kaolin mixture.

1. INTRODUCTION

Opaque flow in the pipe system is easily seen in various engineering fields such as the chemical process, oil plant and so on. Although the flow information will be very useful to design the fluid machinery, the computational studies of opaque flow have been mostly applied and the flow measurement of opaque flow \cite{1-3} is limited. Therefore, the direct flow measurement is essential to validate and improve the knowledge of the opaque fluid flow.

To measure the opaque flow, several non-intrusive measurement techniques were proposed. Magnetic Resonance Imaging (MRI) can provide non-invasive measurement of velocity fields for in vivo study and wall shear stress. However, the poor temporal resolution and the difficult identification of the wall boundary are the limitation of MRI method. Special precautions are required to study the dynamic processes involving temporal evolution and movement of boundary \cite{3}. In addition, it cannot penetrate inside the metal.

Several researchers tried to measure the wall shear stress by using ultrasound Doppler method. The ultrasound Doppler method is attractive due to its ease of use \cite{4}. This method applied the Doppler effect in which a sound wave, scattered from a moving scattering object, is subjected to a frequency shift, which is proportional to the velocity of the particle. If the reflected ultrasound signal are received continuously within the definite time windows. The velocity profile with an oblique angle to the flow direction can be plotted instantaneously.

Since the ultrasound wave was introduced as a novel useful diagnose technique for penetrating opaque medium, many researchers applied this technique for illumination of ultrasound contrast agent (UCA) in opaque flow condition. The B-mode images of the UCA were captured sequentially and processed by conventional cross-correlation based method to obtain the instantaneous velocity vector field. This technique was referred as Echo-PIV or ultrasound particle image velocimetry. After this concept was originally proposed by Kim et al in 2004 and validated in steady/pulsating pipe flow, rotating flow \cite{5, 6}. This technique originally takes advantage of strong backscattering characteristics of scattering particles and ultrasound B-mode to trace the motion of seeding particle. The application in clinical diagnose and development of measurement method was widely conducted.

In the present study, the echo-PIV (particle image velocimetry) and UDV (ultrasound Doppler velocimetry) method were used to investigate the velocity profiles in a conventional pipe system.

2. EXPERIMENTAL APPARATUS AND METHOD

2.1 Experimental apparatus
Fig. 1 shows experimental setup. A pump was employed to drive the fluid to flow. The working fluid was water-kaolin mixture. The flow rate could be adjusted from 0 to 0.7 lpm. The straight pipe was 725mm long with a 16mm inner diameter and a 2mm wall thickness.

A common formula for inlet length $L$ is calculated as the following.

$$L = 0.04dRe$$  

$$Re = \frac{v_d\rho}{\mu}$$  

where $d$ is the inner diameter, $v$ is the mean velocity, $\rho$ is the fluid density and $\mu$ is the dynamic viscosity. In this research, the maximum flow rate was 0.15 lpm, so the inlet length was 126.5mm according to Eqs. (1) and (2). The inlet length of 415mm was guaranteed that the flow was fully developed.

![Figure 1](image1.png)

**Figure 1** Experimental setup.

2.2 Experimental methods

2.2.1 Echo-PIV method

In this study, the B-mode images were generated by a commercial ultrasound apparatus (Capistrano Lab, Incorporated, USA). An ultrasound beam was emitted into the test section which is shown in Fig. 1. Scattering particles in the media generate echoes. In B-mode, the strength of echo signal determines the bright intensity of image. Time of flight is used to determine the location of the scatters. Sweeping (scanning) the beam builds up a two-dimensional echo image [7]. A sequence of beams at discrete angles was generated, resulting in a wedge-shaped measurement area. The measurement plane was located in the center of the pipe. The raw particle images were recorded in a cine animation file. The echo signal reflected from scattering particle was received by an ultrasound transducer with a depth of field of 18 mm. The measurement section was located within this range. It was not affected by ultrasound beam divergence along the propagation line. The ultrasound transducer was aligned such that the scanning plane coincided with the centerline of tube. The center frequency of transducer was 12.5 MHz. The ultrasound beam contains 64 vectors. The display angle of the transducer is $20^\circ$. The B-mode images of particles were recorded by a PCI card embedded in a computer and displayed in the monitor. In the present study, we applied conventional cross-correlation based PIV method with an interrogation window of $8 \times 24$ pixels.

2.2.2 UDV method

The velocities were measured by means of an Ultrasonic Doppler Velocity Profiler (Metflow SA, UVP-DUO), which allows an instantaneous measurement of the 1D velocity profile over the whole flow depth. The UVP instrument was connected to a master PC for data acquisition and was controlled by software, version 3.0, from Met-Flow SA. The measurement probes were mounted on the pipe and the ultrasonic transducer angle to the main flow $\theta$ is $45^\circ$ (Fig. 1). The emitting frequency of transducer (Met-Flow SA, Lausanne, Switzerland) is 4 MHz.

![Figure 2](image2.png)

(a) Water (b) Water-kaolin mixture

**Figure 2** Flow comparison with water and water-kaolin mixture.
Fig. 2 shows flow comparison with water and water-kaolin mixture. It can be seen that this flow belongs to opaque flow. After measuring, sound velocity of ultrasonic in this water-kaolin mixture is 2036 m/s. At flow rate of 0.15 lpm, four measurements were performed and profiles of velocity component were recorded at each time. In addition, number of channels is 128 and number of profiles is 1024.

3. EXPERIMENTAL RESULTS AND DISCUSSION

B-mode image of water-kaolin mixture was constructed from the acquired echo signal for this opaque flow, as shown in Fig. 3. The image clearly showed the scattering signal from the water-kaolin mixture. But there was an error region (shown in the oval area of Fig. 3) due to the reverberation near the wall boundary. Fig. 4 shows ensemble averaged velocity field within the test section. The arrows represent the velocity vector.

Due to the error region (Fig. 3), velocity curve from \( r/R = -0.3 \) to 1 was only analyzed. Fig. 5 shows comparison of velocity values at the different \( Y/R \). From this figure, the differences of velocity values are smaller. So the flow can be considered as uniform flow.
Fig. 6 shows velocity comparisons with echo-PIV and UDV. From \( r/R = -0.3 \) to 1, velocity values measured with echo-PIV and UDV are higher than theoretical values. Moreover, the peak velocity measured with echo-PIV and UDV are deviated from the center of the pipe. The peak velocity measured with echo-PIV at \( r/R = 0.17 \) is -0.0275m/s and error of peak velocity between echo-PIV and average analytic solution is 10.58%. While the peak velocity measured with UDV at \( r/R = 0.1 \) is -0.0264m/s and error of peak velocity between UDV and average analytic solution is 6.16%.

![Figure 6 Velocity comparisons with echo-PIV and UDV.](image)

4. CONCLUSION

In this paper, we presented a preliminary result of Echo-PIV and UDV measurements for opaque flow of the pipe system. Flow medium is water-kaolin mixture. The velocity distribution in the test region was obtained. Based on the velocity profile, the velocity curve from \( r/R = -0.3 \) to 1 was gotten and error of peak velocity between echo-PIV, UDV and average analytic solution are compared. Error of peak velocity between echo-PIV, UDV and average analytic solution are 10.58%, 6.16%, respectively.

This study demonstrated that opaque flow can be measured by using Echo-PIV and UDV methods. And the next step is to improve the measurement accuracy of opaque flow.

ACKNOWLEDGMENTS

One of the authors (Dr. Wang) was supported from the Priority Research Centers Program (2012-048078) through the National Research Foundation of the Republic of Korea. And the work was supported by the National Natural Science Foundation of China (Grant No. 51209105) and Senior Professional Scientific Research Project of Jiangsu University of China (Grant No. 12JDG045).

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