DEVELOPMENT OF PHASED-ARRAY UVP TECHNIQUE FOR TURBULENT PIPE FLOW

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ABSTRACT

This study is about two-dimensional velocity profile measurement of the turbulent pipe flow. The purpose is to investigate the secondary swirling flow in a horizontal straight pipe and just downstream of the double bent pipe using Phased-Array UVP technique. From the straight pipe flow measurements, axisymmetric swirling flow structure downstream of the swirling generator can be measured successfully. In the case of double bent pipe, the measurements were taken at two positions (downstream from the bent) to examine secondary swirling flow and velocity distortion caused by the double bent pipe. The asymmetric swirling flow and the influence of swirl intensity on the flow structure were clarified by using Phased Array UVP.

INTRODUCTION

Fluid flow measurement is one of the most important things in the fluid engineering, in research fields and the industries. The various measurement techniques have been developed for different purposes. In the previous studies, Laufer. J. (1954) carried out the measurements principally with a hot-wire anemometer to study fully developed turbulent flow in a 10-inch pipe (1). In the applications of Laser Anemometry to fluid mechanics, Landreth. C. C et al., (1990) applied laser beam for measurement and refinement of velocity data using Particle Image Velocimetry (2). Moreover, three-dimensional Laser-Doppler Velocimetry measurement in swirling turbulent pipe flow was investigated (3) by Gerta Rocklage-Marliani et al., (2003). However, this kind of measurement methods have some challenges to apply in opaque fluids and treatment of these optical systems is difficult for the monitoring applications in actual plant process. Therefore, Takeda (1986) developed Ultrasonic Velocity Profiler (UVP) for optically non-transparent liquid flows such as mercury flow (4). UVP is non-intrusive measurement method, utilizes a pulsed echo-graphic technique of ultrasound, and can measure an instantaneous velocity profile on a measuring line.

In the case of two-dimensional velocity profile measurement (flow mapping), Takeda and Kikura (2002) investigated velocity field of the mercury flow using UVP (5). Flow mapping was accomplished by using multiple transducers, which are arranged in different positions and set to multiple angles. On the other hand, this measurement system becomes larger as the number of transducers is increased. To overcome such problems in conventional UVP (multiple sensors and mechanical movement), A. Hamdani et al., (2016) has developed a phased array sensor, which has multiple ultrasonic elements to conduct two-dimensional velocity profiles with multiple measurement lines (6). They used 8 elements phased array sensor. To increase the measurement area, we are developing a new sensor by increasing number of elements. In other words, as the next step, recently, we are developing 32 elements phased array sensor to increase the measurement area. In this paper, especially, we described the measurement results by using 8 elements phased array sensor. We measured some turbulent swirling flow in a horizontal straight pipe with the swirling generator. Also, we measured the secondary flow just downstream of the double bent pipe with and without swirling effect. The investigation of the secondary swirling flow is significant for the maintenance of the piping system in the industries and the power plants because it can cause the asymmetric pipe wall thinning and the pipe break accident.

MEASUREMENT PRINCIPLE

A phased array sensor emitted an ultrasonic pulse, and each element in the sensor receiving the echo reflected from the surface of a particle in the measurement line as shown in Figure 1 in the case of 8 elements sensor. The Doppler shift frequency observed at each element is described as;

\[ f_D = \frac{f_0}{c} (\hat{e}_x + e_1) \hat{V} \]  

(1)

where \( f_D \) is the Doppler frequency, which is observed at \( i^{th} \)-channel element, \( \hat{e}_i \) is the unit vector in the direction of the measurement line, \( \hat{e}_i \) is the unit vector in the direction from the particle to the \( i^{th} \)-channel element, \( c \) is the sound velocity in water, \( f_0 \) is basic frequency of phased array sensor and \( \hat{V} \) is the particle velocity. From equation (1), Doppler shift frequency observed at each element is different because of the difference of the element posions (7). In Figure 2, the 1st channel element and 8th channel element is considered, and the particle velocity is obtained as follow;

\[ \begin{bmatrix} f_{D1} \\ f_{D8} \end{bmatrix} = \frac{f_0}{c} \begin{bmatrix} e_1 + e_7 \\ e_1 + e_8 \end{bmatrix} \]  

(2)

\[ \hat{V} = \frac{c}{f_0} \begin{bmatrix} e_1 + e_7 \\ e_1 + e_8 \end{bmatrix}^{-1} \begin{bmatrix} f_{D1} \\ f_{D8} \end{bmatrix} \]  

(3)
Thus, a velocity vector in a measurement point can be calculated by analysing the echoes received by different elements in an array sensor. The flow visualization can be conducted with only one sensor by using phased array technique. The measurement system consists of a phased array sensor, pulse receiver, analogue to digital converter and personal computer as shown in Figure 3.

![Figure 1. Beam steering of Phased Array Sensor.](image1)

![Figure 2. Velocity vector reconstruction.](image2)

![Figure 3. Phased array UVP measurement system.](image3)

**EXPERIMENTAL SETUP**

The experiment was conducted in a water circulation system consisting of a swirl generator, cooling system and electromagnetic flow meter as shown in Figure 4. It is designed to emphasise the formation of fully developed turbulent pipe flow. The inner diameter of the pipe is 50 mm and made of acrylic. The double bent pipe has a bent angle of 90 degrees and curvature radius $R = 25$ mm.

![Figure 4. Schematic view of the experimental setup.](image4)

For the generation of swirl, some different methods exist (pipe rotation, tangential injection and vanes), which have a different effect on the base flow (8). In this present study, we used the pipe rotation method (9) as shown in Figure 5. The swirl generator is installed at 12D (D=50 mm) upstream of the double bent pipe. The honeycomb is inserted into the rotary pipe to generate homogeneous swirl. The rotary pipe is used as the swirl generator because it is easy to control the swirl intensity. The swirl intensity is defined as the ratio of the circumferential momentum to the axial momentum (9); it can be evaluated as follows:

$$
S = \frac{R}{2} \frac{\int_{0}^{R} U_{z} U_{\theta} r^{2} dr}{\int_{0}^{R} U_{z}^{2} r dr} = \frac{1}{2} \frac{R \omega}{U}
$$

(4)

where $r$ is the radial distance from a pipe axis, $U_{z}$ is the stream wise mean velocity and $U_{\theta}$ is the circumferential mean velocity. The equation (4) indicates that the swirl intensity can be evaluated directly from the angular velocity $\omega$ of the rotary pipe, the radius $R$ of the pipe and the bulk velocity $U$ of the flow through the pipe.

![Figure 5. Detail view of the Double bent pipe and swirling generator.](image5)

For the turbulent swirling flow measurements, the measurement is done at 7D downstream of the swirling generator to measure the developed swirling flow in the straight pipe. Then, we measured downstream of the double bent pipe at ($z = 30$ mm, and $z = 50$ mm, see Figure 5) using 8 elements phased array sensor. In order to include the whole 360 degrees of the pipe in our measurements, one will be
taken every 20 degrees, which adds up to 18 measurement lines.

Phased array sensor, which has basic frequency 2 MHz, is installed through the pipe wall. Thus, there is a direct contact between sensor and fluid to overcome the refraction in pipe wall and fluid medium.

RESULTS AND DISCUSSION

We visualized two-dimensional cross-sectional velocity profiles for upstream and downstream of the double bent pipe. Table 1 shows experimental flow condition for these measurements. Figure 6 shows two-dimensional turbulent swirling flow upstream of the double bent pipe, which generates by swirl generator with rotation speed (ω = 480 min⁻¹) at 7D from the swirling generator. It means that the generated turbulent swirling flow from the swirling generator is symmetric and the velocity distribution is homogenous. In the core region of the pipe, the velocity magnitude is lower than near wall region. The highest velocity magnitude is between the core and near wall region.

Table 1. Experimental conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds numbers for main flow [-]</td>
<td>10000</td>
</tr>
<tr>
<td>Fluid (water) temperature [°C]</td>
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</tr>
<tr>
<td>Angular velocity of rotation pipe ω [min⁻¹]</td>
<td>480</td>
</tr>
</tbody>
</table>

Figure 6. Two-dimensional measurement results (ω = 480 min⁻¹) upstream of the double bent pipe at 7D from swirling generator.

Figure 7 shows the measurement results from (z = 30 mm) downstream of the double bent pipe in case of pipe rotation and non-rotation. Two-dimensional velocity profile across a pipe cross-section is visualized from each measurement line of phased array sensor. The upper part of the cross-section is the outer pipe wall of the elbow, and the bottom is inner pipe wall. When the fluid passed through the double bent pipe, the high-velocity fluid pushed towards the outer wall of the pipe, and the secondary flow occurred along the pipe wall in clockwise and counterclockwise directions, due to the centrifugal forces. In the pipe rotation case, the core of the secondary flow shift to pipe wall region and the flow pattern is asymmetric because the fluid itself is swirling before entering the double bent pipe.

Figure 8 shows two-dimensional velocity profile across a pipe cross-section downstream of the double bent pipe (z = 50 mm) in the case of pipe rotation and non-rotation. In the upper part of the cross-section, the main flow is starting to develop along the streamwise direction. Therefore, the secondary flow is weak, and the flow pattern is more complex in the upper part of the pipe. Also, the high-velocity fluctuations occur in this region. Therefore, two-dimensional vector quantity is week to compare the upstream measurement result.
In the case of rotation pipe flow, the secondary flow is still strong to compare with the non-rotation case because of swirling fluid. The axial main flow can be observed in the upper part of the cross-section above the swirling core region. In this region, the velocity distortion occurs caused by the streamwise main flow.

CONCLUSIONS

Two-dimensional swirling flow structure is visualised upstream and downstream of the double bend pipe using Phased Array UVP system. We confirmed the symmetric turbulent swirling flow upstream of the double bent pipe in a rotation speed ($\omega =480$ min$^{-1}$). The swirling flow structure, which generated by the rotary pipe, is homogenous. The developed phased array measurement system can measure the turbulent swirling flow successfully. In addition, turbulent swirling flow structure downstream of the double bent pipe is observed in the two positions with pipe rotation case and without pipe rotation. The double bent pipe itself can generate the secondary swirling flow. Therefore, the velocity fluctuation is very high at the downstream area and the flow structure is complicated. In case of pipe rotation, the secondary swirling flow is strong and the main flow is weak just downstream of the double bent pipe.

The present study contributes the development of measurement system in the turbulent swirling flow using Phased Array UVP technique with 8 elements sensor. In the future, we are planning to conduct using 32 elements phased array sensor.

NOMENCLATURE

- $\bar{e}_i$: unit vector in the direction of measurement line
- $\bar{e}_i$: unit vector in the direction from the particle to $i^{th}$ channel elements
- $\vec{v}$: velocity from the moving particle [mm/s]

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REFERENCES