Flow rate measurement after 90 degrees bended pipe using multi-path ultrasound shift method

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High precision management and control has been important issue in energy plant or reaction device using such gaseous fluid as vapor and air. The objective of the study is to improve the accuracy of the ultrasound flow rate measurement after bended pipe. Firstly, the radial velocity profile after 90 degrees bended pipe was calculated by commercial CFD software. By using the result of calculation, the suitable estimation methods of flow rate in distorted velocity profile were examined and resulted that the three parallel measurement paths enable to determine the resultant flow rate even in distorted velocity profile. Inner diameter of pipe was 160 mm and the diameter of bend was 240 mm. The flow rate was varied from 2.0 m/s to 9.0 m/s. The frequency of ultrasound was 40 kHz. The test section was located after 90 degrees bended pipe. The estimated error was 5 % by numerical simulation and the value was 20 % in the actual measurement.

Keywords: Flow rate, Ultrasound flow meter, Ultrasound shift method, Signal processing

1. Introduction

High precision management and control has been important issue in energy plant or reaction device using such gaseous fluid as vapor and air. Accurate flow rate measurement generally requires a long straight section in order to stabilize the velocity profile. However, the space saving flow metering method that has low pressure drop and high reliability is desired. The ultrasound flow metering has the significant advantages that the pressure drop is negligible. Conventional transit-time method or sing-around method, however, have difficulties in measuring the flow rate of conduit flow with distorted velocity profile due to the secondary flow. The objective of the study to improve the flow rate measurement that can be applied to the distorted velocity profile with ultrasound shift method proposed by the authors[1,2]. In this method, the displacement of sound pressure distribution due to conduit flow is determined by the sensor array. The method could be extended to the multi-path measurement for the distorted flow velocity profile. In this paper, the amount of the flow rate modulation due to the velocity profile distortion after 90 degrees bended pipe was firstly obtained by CFD that is followed by the experimental validation of the measurement accuracy.

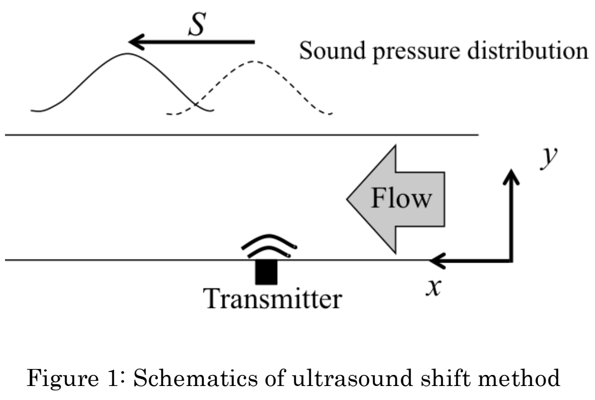

Figure 1: Schematics of ultrasound shift method

2. Theory of ultrasound shift method

In the ultrasound shift method flow rate is calculated from the displacement of sound pressure distribution due to conduit flow. Figure 1 shows the schematics of the ultrasound shift method. Ultrasound beam is shifted due to the flowing gas while transmitting perpendicularly to the main stream. Displacement of sound pressure distribution, S, can be calculated by the equation 1 as follow:

$$S = \int_0^D \frac{U(y)}{c} dy \tag{1}$$

Where c is sound speed, D is internal diameter of pipe, $U(y)$ is velocity distribution of gas flow. The average flow velocity, v, as

$$v = \frac{S \cdot c}{D} \tag{2}$$

and flow rate Q is given by equation 3.

$$\begin{aligned} Q &= v\frac{\pi D^2}{4} \\ &= \frac{S \cdot c}{D}\frac{\pi D^2}{4} \end{aligned} \tag{3}$$

Equation 3 describes the flow rate with certain flow condition such as fully developed conduit flow. When the flow is distorted, especially nearby a bend or an elbow.

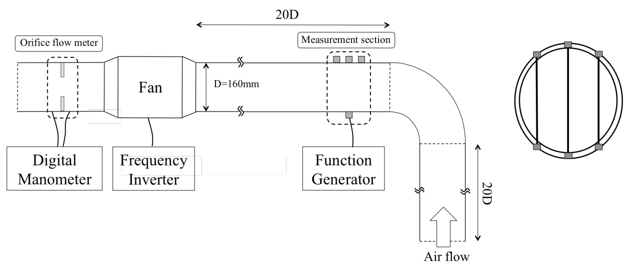

Figure 2: Experimental rig and location of test section

3. Experiments and results

Figure 2 shows the experimental setup. The internal diameter of pipe is 160 mm. A centrifugal fan is installed downstream the measurement section and it is powered with frequency-controlled inverter to generate the airflow in the way of suction. There are 20*D* length of flow pipe installed upstream and downstream of the centrifugal fan respectively. 90 degrees bended pipe is installed upstream of measurement section to generate distorted velocity profile. Measurement section is located at 220 mm from the exit of the bended pipe. 40 kHz transmit/receive dual-purpose ultrasound transducers are selected for the experiment. The ultrasound transducer for transmitting ultrasound is located wall of pipe. And the transducer for receiving ultrasound is located opposite wall of transmitting transducer. There are 3 parallel measurement paths. One measurement path is through the center of the pipe. Others are located at intervals of 45 mm.

For the acquisition of sound pressure distribution, the peak positions of sound pressure distribution were measured at every flow rate. Therefore, the resultant accuracy to the flow measurement with ultrasound shift method rely on the accurate determination of sound pressure distribution and the degree of shift. In order to determine the peak position of sound pressure distribution, the reconstruction method of sound pressure distribution was used[3]. In this method, 3 transducer located pipe wall were used for measuring the sound pressure. These measurements were used to reconstruct the sound pressure distribution fitting function *f(x)*, which were assumed to be as same shape as Gaussian distribution:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(x-\mu)^2}{2\sigma^2}} \qquad (4)$$

Where x is measuring point position in longitudinal direction of pipe, σ and μ is standard deviation and median of *f(x)* respectively, which means μ is the peak position of sound pressure distribution. Assumed that x_1, x_2, x_3 are positions of 3 transducer and acoustic intensity measurements are y_1, y_2, y_3, sound pressure peak position μ can be calculated as follow:

$$\mu = \frac{(x_2{}^2 - x_3{}^2)\ln\frac{y_1}{y_2} - (x_2{}^2 - x_1{}^2)\ln\frac{y_3}{y_2}}{2\left[(x_2 - x_3)\ln\frac{y_1}{y_2} - (x_2 - x_1)\ln\frac{y_3}{y_2}\right]} \qquad (5)$$

By using this method, the sound pressure distribution can be determined and the peak position can be determined. Figure 3 shows the measured result of sound pressure distribution and fitting curve.

Equation 3 describes the flow rate with the certain flow condition such as fully developed flow. However, the flow is distorted, especially nearby a bend or an elbow. It becomes difficult to assume the axisymmetric velocity profile, and therefore the accuracy will decrease compared with the single path. In contrast, the multi-path measurement is effective in the accurate flow rate determination in distorted velocity profile. In this study, 3 parallel paths are used for flow rate determination. The distribution of shift (displacement of sound pressure distribution) is approximated by using results of 3 parallel paths measurements. Since the amount of shift is equal to the line integral of velocity on measurement path, flow rate is calculated as integral of distribution of shift. Figure 4 shows the velocity profile after 90 degrees bended pipe. The dimension of pipe used simulation and simulation condition are shown in Figure 5 and Table 1. The distributions of shift are shown in Figure 6. There are 2 types of the directions of three-parallel paths shown in figure 6 (horizontal and vertical). Using the shift of three

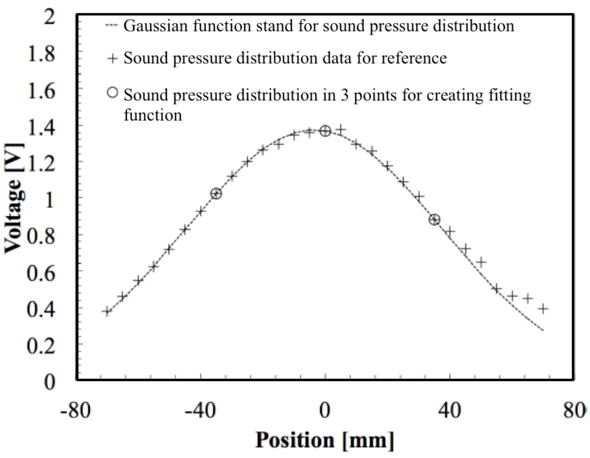

Figure 3: Sound pressure distribution

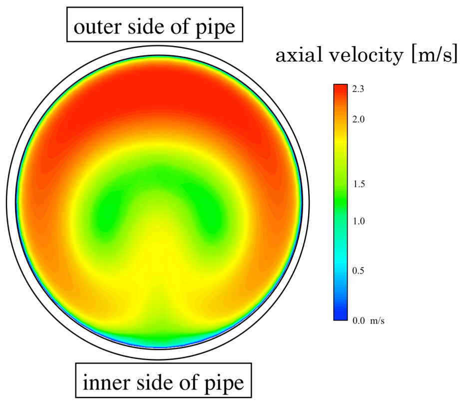

Figure 4: Result of simulation

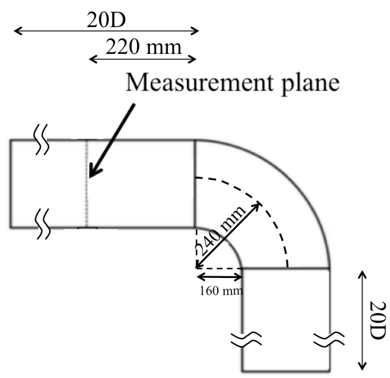

Figure 5: Dimension of bended pipe

Table 1: Simulation conditions

Software	ANSYS Fluent ver.16.2
Turbulent model	k- ε model
Boundary condition (inlet)	Uniform velocity
Boundary condition (outlet)	Uniform gauge pressure (0Pa)
Working fluid	air

measurement paths, the curve shown in figure 3 was estimated by the 4th polynomial approximation. The plots in figure 6 represent the measured quantity of shift, S, and the solid curve represents the estimated distribution of S. The flow rate could be obtained by integrating the curve.

The error, E, of flow rate was defined by equation 6.

$$E = \frac{Q_{ref} - Q}{Q_{ref}} \qquad (6)$$

where Q_{ref} is reference flow rate by Orifis, Q is measured flow rate by the preset method. The error by horizontal paths was -2.2 %, and by vertical paths was -0.5 %. From this result, the error of horizontal paths was less than vertical paths. So horizontal paths are more suitable for flow rate measurement after 90 degrees bended pipe than vertical paths.

Figure 7 compares the degree of shift of the direction of three-parallel path. The trend of the distribution of shift was agreed with the result of numerical simulation. Figure 8 compare the measured flow rate by Orifice and present method. The error by vertical paths was 21.6 % and horizontal paths was 17.6 %. This error is due to the measurement uncertainty of shift values. The error by single path[4] which through the center of pipe was varied from 7.3 % to 30.5 % depending on directions of

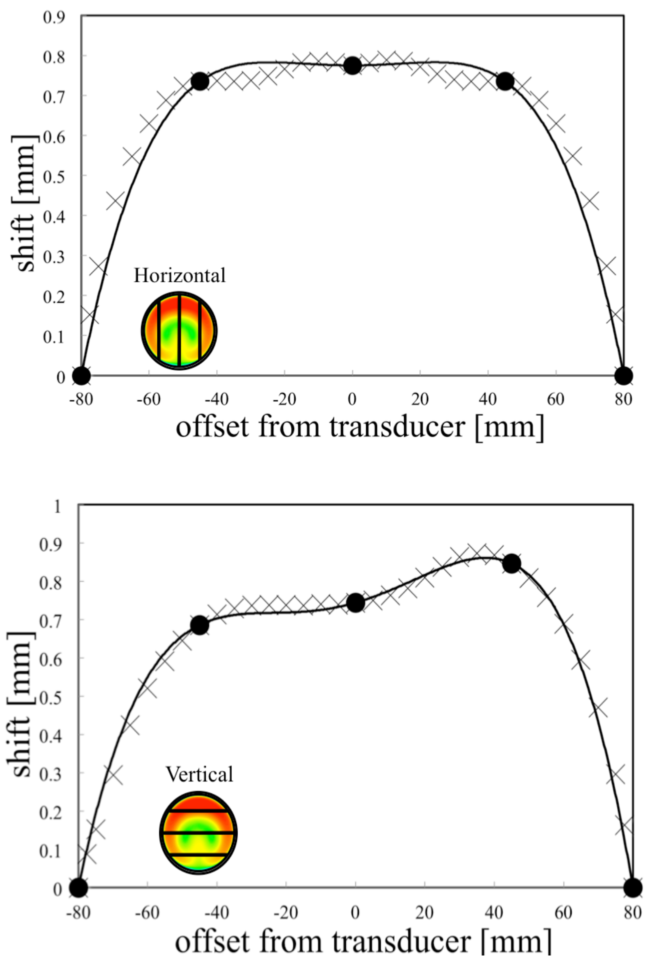

Figure 6: The distribution of shift by simulation

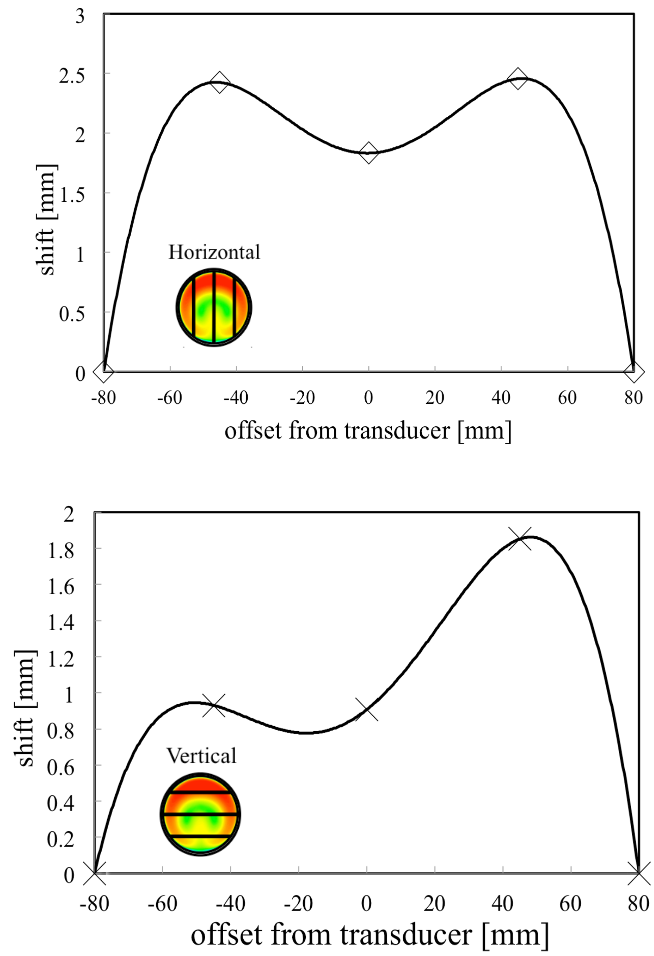

Figure 7: The distribution of shift by experiments

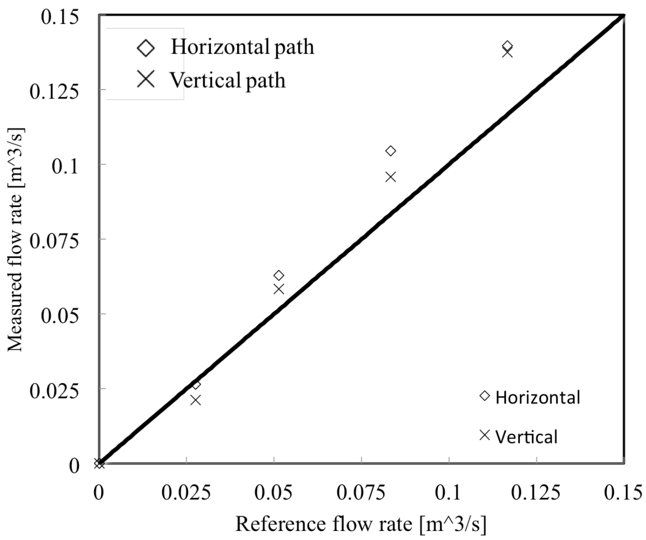

Figure 8: Flow rate versus reference flow rate

measurement paths. The arithmetic mean error of the radial four-path[4] which radical beams was 23.5 %. By comparing the various methods, three-parallel paths measurement could reduce the measurement error in distorted velocity profile.

5. Conclusions

The flow rate measurement after bended pipe using parallel path ultrasound shift method was developed. The axial velocity profile after 90 degrees bended pipe was firstly calculated by commercial CFD software. From the result of calculation, the measurement error by three-parallel paths was estimated to 5 %. By the experiments, it was confirmed that the measurement error of the flow rate was below 20 % even by a distorted velocity profile.

References

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