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Ultrasound Flow Metering for the Distorted Velocity Distribution by Means of the Parallel Shift Method

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The objective of the study is to improve the accuracy of the ultrasound flow rate measurement for the distorted velocity distribution. Velocity profile after bended pipes and expansion section were firstly calculated by a commercial CFD software. Using the CFD result, the suitable estimation method of acoustic intensity shift was examined and resulted that the three parallel paths is sufficient. From the experimental result, the present flow meter could apply to the measurement of flow rate just after the double-bend and expanded pipes.

Keywords: Flow rate measurement, Ultrasound shift method, distorted flow, CFD, Signal processing

1. Introduction

Precise management and control have been important issue in a large scale energy plant or reaction device using such gaseous fluid as steam and air. In order to obtain the accurate flow rate, longer straight pipe or section, by which the flow is fully developed, must be prepared to stabilize the velocity profile around the following measurement section. However, the space-saving flow rate metering with low pressure drop and high reliability is desired for the industrial and consumer applications. Moreover, transient flow rate determination will contribute to the reliable and real-time operation of the system and enables to control the local fluid behavior with the higher temporal resolution.

Ultrasound flow meter has the significant characteristics that the pressure drop at the measurement section is negligibly small. Higher temporal resolution is one of the other advantages. Conventional ultrasound transit-time or sing-around methods, however, have difficulties in determining the flow rate with distorted velocity profile, which is caused by the various reasons such as a bending, elbow, bulb and sudden change of pipe diameters. Therefore, the numerous number of studies were reported, e.g., non-axisymmetric flow rate determination by means of a time-based ultrasonic flow meter with theoretical velocity profiles [1], developments of the tomographic reconstruction method to obtain the sectional velocity distribution with multi-path flow meter [2,3] and so on.

The objective of the study to develop the novel flow rate measurement method that could be applied to the distorted or nonaxisymmetric velocity profile. In our previous works [4-8], ultrasound shift method were developed and applied to the measurement of the gaseous flow in pipes. In order to improve the accuracy and robustness of the system, multiple beams were employed and various type of the beam alignments were compared. The investigations resulted that the parallel beam alignment enables to improve the accuracy of the flow rate determination in the vicinity of the single elbow. That led us to apply the proposed technique to the practical and more complicated flow fields found in the actual pipe flow systems. In this study, the investigation was extended to the measurement at the downstream of the double elbow section as well as the expansion flow. In the measurement system, the displacement of the acoustic intensity distribution due to the cross-wind effect was determined by means of the ultrasound receiver array. Expected amount of the shift as a function of the velocity distributions as well as the probe beam orientation was firstly predicted by means of a commercial CFD software that is followed by the experimental validation of the measurement accuracy of resultant flow rate.

2. Flow rate measurement by the multi-beam ultrasound shift method

Volume flow rate, Qv, is defined as the following integral equation.

$$Qv = \iint u\, dy\, dz \qquad (1)$$

The equation indicated that the flow rate is the integral of the axial velocity component, $u\ (y, z)$, throughout the area of the test section that is perpendicular to the main flow in a pipe or a duct. In other words, the flow rate determination requires the two dimensional measurement of the axial velocity component. However, non-intrusive multi-dimensional measurement of the velocity distribution within an enclosure or such internal flows as pipe or duct flows is quite difficult. Figure 1 depicts the fundamental principle of the ultrasound shift method [4].

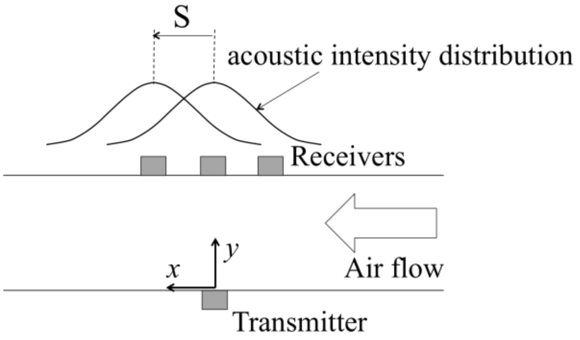

Figure 1 Schematic diagram of the ultrasound shift method.

In contrast to the conventional time-based ultrasound flow meter methods, which employ the inclined ultrasound beams to the pipe axis, the probe beam is emitted and propagates perpendicularly to the axis of the pipe. Ultrasound beam that reached to the opposed side of the transmitter was diverged and was also shifted due to the convection of the fluid flow passing through the test section. Therefore, the intensity profile of the received beam is moved to the downward of mean flow and the degree of the displacement is proportional to the flow rate.

The magnitude of the shift of the acoustic intensity distribution, *S*, can be obtained by the following equation.

$$S = \int_0^D \frac{u}{c} dy \tag{2}$$

Where *c* denotes the sound velocity, representative value of *c* is equal to 340 m/s for the air at room temperature and atmospheric pressure, and 1480 m/s for water. *D* denotes the internal diameter of the pipe, $u = u\ (y,\ z)$ is the radial velocity distribution of the flow. For the air flow measurement with the pipe diameter of 160 mm, the magnitude of the shift is a few mm. When the velocity distribution in the test section is assumed to be axisymmetric, the flow rate could be directly obtained by using Abel transform of the amount of the shift. If the flow is distorted due to the bend, elbow, bulb or any kind of the disturbing element in the flow systems, the single path methodology could not be applied or suffered from the terrible measurement error. Since the secondary flow and backward flow after the aforementioned elements generates the distorted velocity profile, it becomes difficult to assume the symmetric velocity profile, i.e., the error will significantly be increased depending on the orientation of the probe beam. In contrast, the multi-path ultrasound shift method have the possibility to reflect the velocity modulation and is effective in reducing the bias error and in improving the accuracy of the resultant flow rate. In our previous works, quad ultrasound shift method at the radial alignments were proposed and applied to the distorted flow after the single 90 deg L-bend section. The investigation resulted that the oversampling effect at the intersection of radial beams causes the bias error of the measured flow rate. In the present study, the parallel beam alignment was employed. By integrating the spatial distribution of shift, *S*, the flow rate could be obtained by the following equation.

$$Qv = c \int_0^D S(z) dz \tag{3}$$

To calculate the flow rate on the basis of Eqn. 3, infinite number of shift values are required. As the distortion of velocity distribution in a pipe flow is not drastic, the distribution of the shift could be approximated by using the lower order polynomials. The order is limited by the number of measured shift values.

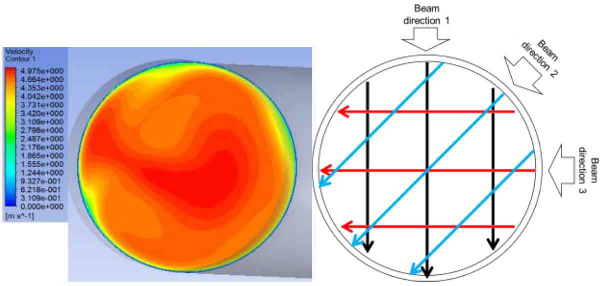

Figure 2 Velocity distribution after the double bended pipe (Z bend) by means of CFD software. The orientation of the parallel ultrasound beams is depicted as well.

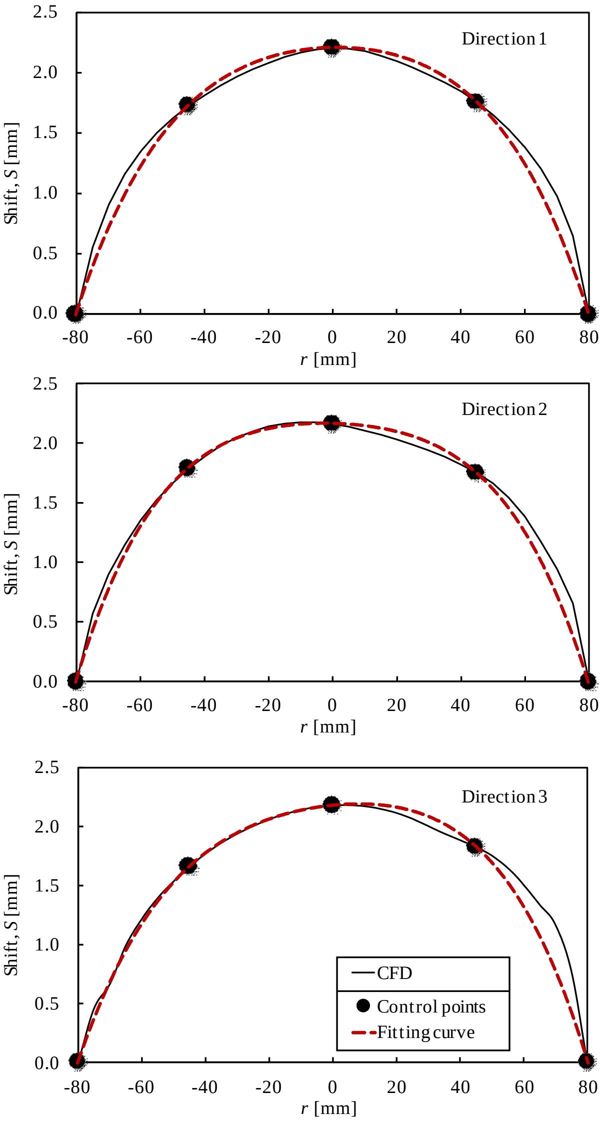

Figure 3 Predicted shift distribution after the double elbow from the CFD result of the velocity distribution. Fitting curve was obtained with the 4th order polynomials using the 3 measuring points as well as the boundary condition (*S*=0) at the pipe surfaces. Solid circular plots corresponds the measurement point. Velocity profile after bended pipes was calculated by CFD software.

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Figure 2 shows the example of the calculated velocity distribution as well as the angular alignment of the parallel 3 beams through the cross section of pipe. The inner diameter of pipe was 160 mm, distance between the end of the second bend and the test section was 220 mm. Detailed geometry of the pipes will be appeared in the following section. The *k*-*ε* model was used as a turbulent model. Homogeneous inlet velocity and outlet pressure were used as the boundary conditions. Expected shift distributions in terms of the beam orientation were depicted in figure 3. The separation between parallel beams was 45 mm. Fitting with the corresponding three-point shift values as well as the $s = 0$ at the both edges, the fitting curves show good agreement with the shift distribution obtained from the velocity distribution from the numerical simulation.

3. Experiments and results

Figure 4 and figure 5 illustrate the detailed geometry of the experimental set up used in the experiments. Both diameter of pipe and dimension of bended pipe were identical to the previous numerical simulation. In both cases, the test sections were located at 220 mm from the 2nd bend or expanded section in which the conventional single path flowmeters could not be applied. A centrifugal fan was installed at the further downstream from the test section and was controlled with the variable frequency inverter with the shielded enclosure in order not to affect the electrical circuit. Frequency of the emitted ultrasound was 40 kHz, maximum voltage for the ultrasound transmitter was 20 V. The magnitude of the shift of the ultrasound intensity distribution was determined with the 3ch receiver array. Other equipment such as analog circuit, A/D convertor and signal processing software were identical to the previous study [8]. Figure 6 compares the measured flow rate by using the reference orifice flow meter and the present method. Since the angular alignment of the parallel beam will significantly affect the obtained flow rate in practical applications, the effect of the angle was evaluated. Flow rate was varied from 0 to 0.16 m^3/s, which is equal to 576 m^3/h. Re number was 21000. The comparisons show that the linear relation between flow rates were obtained with every angular alignment. Maximum error was 15 % in the worst case at the particular flow rate with the angular alignment of direction 2. The proposed three-parallel paths method could be applied to the flow rate measurement with the distorted velocity profile after the consecutive elbows.

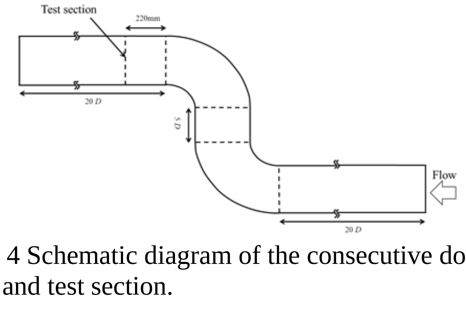

Figure 4 Schematic diagram of the consecutive double-elbow and test section.

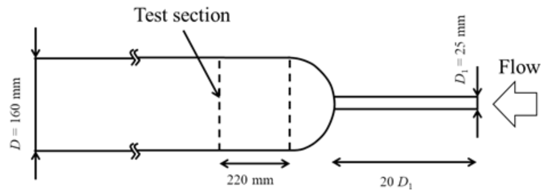

Figure 5 Schematic diagram of the expansion flow and test section.

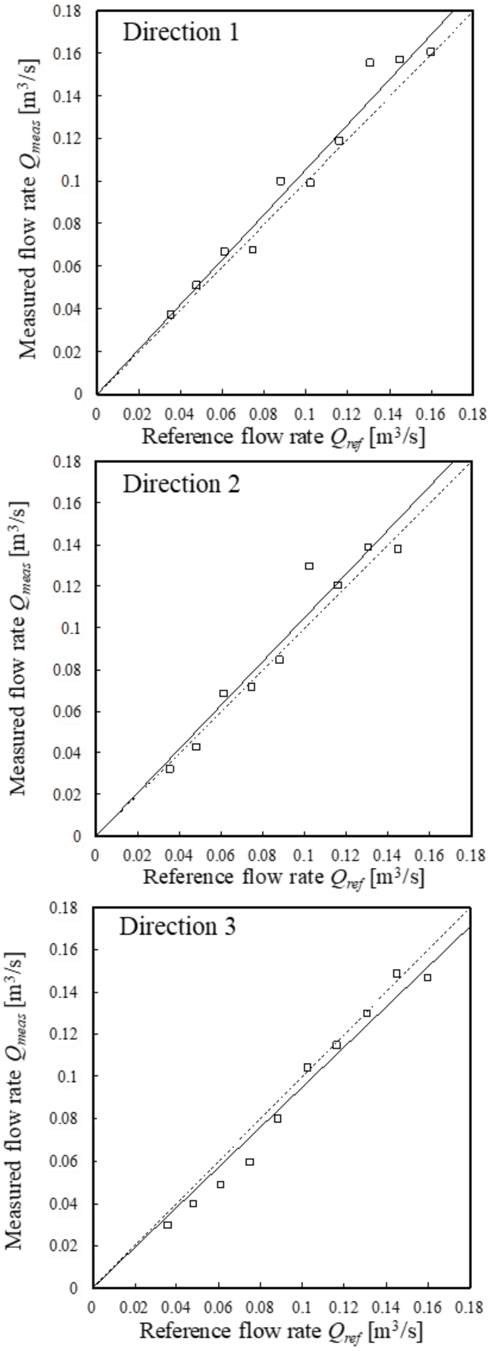

Figure 6 Comparison of results by means of the present shift method and the orifice flow meter as a reference. Flow rate and the angular beam alignment was varied.

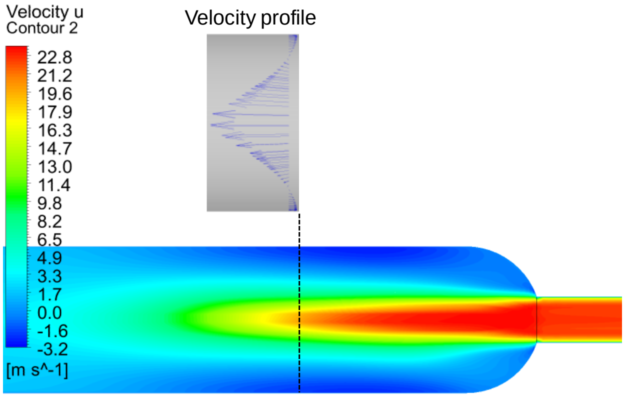

Figure 7 Contour map of the axial velocity distribution at the expansion flow. Corresponding velocity profile at the ultrasound beam path is extracted and depicted.

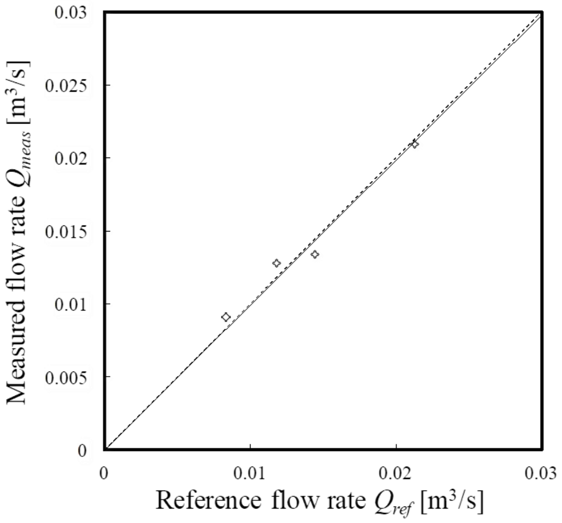

Figure 8 Flow rate measurement just after the expansion section. Orifice flow meters.

Figure 7 depicts the CFD result in the vicinity of the expansion section. At the section, pipe diameter was expanded from 25mm to 160 mm. Contour map of the axial velocity component was described in the figure. Corresponding velocity profile at the ultrasound beam path was also shown in the figure. In the expanding section, width of the radial velocity distribution was rapidly increased due to the higher shear rate at the boundary layer. That is the reason why the higher spatial resolution is desired, especially for the direction of the pipe axis. Moreover, the symmetric recirculation flow is occurred after the backward facing step due to the larger expansion ratio at the section. Figure 8 compares the measured flow rates just after the expansion section. The comparison demonstrated that the present technique could also be applied to the flow rate measurement with the significant velocity distortion. In this case, gradient error was negligible, and the maximum value of the resultant error was 5%.

5. Conclusion

The flow rate measurement after a pair of bended pipes as well as the expansion section was developed that employed the ultrasound shift method with parallel beams. The detailed velocity profiles after the disturbing sections were firstly calculated by a commercial CFD software. From the numerical analysis, the three-point shift measurement enables to obtain the coefficients of the fitting curve of the shift distribution and is sufficient for the determination of the volume flow rate under the present configurations. From the experiments results, it was confirmed that the measurement error of the flow rate with the consecutive double bend system was 15%, that with the expansion flow was 5 %.

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