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# Influence of obstacle plates on flowrate measurement uncertainty based on ultrasonic Doppler velocity profile method

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ABSTRACT

To obtain the specific values of the flowrate measurement uncertainty using the ultrasonic Doppler velocity profile (UVP) method under disturbed flow conditions, experimental measurements were performed. To generate a disturbed flow, obstacle plates were installed upstream of the test section. To estimate which experimental parameter dominates the uncertainty, parametric examinations are conducted for the obstacle plate configuration, the distance between the obstacle plates and the measurement section, the incident angle of the ultrasonic beam, and the flowrate. The maximum deviation of the measured flowrate from the reference flowrate exceeds 2% when the flowrate is measured 8*D* downstream of the obstacle plate. At a distance of 25*D* downstream, the deviation is within the fundamental uncertainty level of the flowrate measurement using the UVP method. Because several uncertainty factors in this examination are cross-correlated with each other, the uncertainties of these factors are evaluated independently using analysis of variance (ANOVA). The total uncertainty is 7.98%, 1.97%, and 1.14% at 8*D*, 16*D*, and 25*D*, respectively.



## 1. Introduction

It is well known that the measured flowrate given by flow meters, such as ultrasonic, electromagnetic, and turbine flow meters, generally depends on the velocity profile in a pipe. This demonstrates that the measurement accuracy of these flow meters is influenced by the upstream pipe configuration even if flow meters are calibrated by a calibration facility. In calibration facilities, the construction of a complete equivalent pipe layout with an actual field is often difficult, and thus an on-site calibration is only the method of checking the accuracy of flowrate measurements. An on-site calibration is a comparison test using a reference flow meter in the actual field. Although the establishment of an on-site flowrate calibration method with high accuracy is expected for actual field measurements, there are a few methods that realize it. For instance, Guntermann et al. [1] proposed an on-site calibration method using a laser Doppler velocimetry (LDV) system. In this method, the reference flowrate in the actual flow field is estimated using the velocity profile measured by the LDV system. However, modifications to the pipe are necessary to use the LDV system.

The ultrasonic Doppler velocity profile (UVP) method [2,3] is a type of flow metering method that is applicable to on-site calibration. The advantages of this flow metering method for on-site calibration are that it can be applied as a clamp-on measurement [4] and that the principle of the flowrate calculation is based on the integration of the measured velocity profile. The former advantage is expected to remove the necessity of modifying the existing pipe, and the latter is also expected not to limit the upstream conditions in principle. Therefore, although reflectors are necessary in the fluid, it is possible that the UVP method can be used as a reference flow metering method for on-site calibration.

To use the UVP method as the reference flow metering method, the measurement uncertainty must be established. The authors performed a fundamental uncertainty analysis for the flow metering method using the UVP method under ideal flow conditions, i.e., an asymmetric velocity profile [5]. In this analysis, the uncertainty of the UVP method is estimated to be approximately 1%. The dominant uncertainty factors are the velocity measurement and the incident angle of the ultrasonic beam. However, to apply the flow metering method to the actual field, it is necessary to establish the uncertainty of flowrate measurements under non-axisymmetric velocity profile fields. As past studies have shown, parametric tests to estimate the uncertainties of flowrate measurements are required for general flow meters [6], and thus such experiments and uncertainty analysis for the UVP method should be performed.

The purpose of this paper is to obtain specific values of the uncertainty of flowrate measurements using the UVP method under disturbed flow conditions. Experimental measurements

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**Nomenclature**

| | |
|---|---|
| $D$ | inner diameter of pipe (mm) |
| $L$ | distance between obstacle plate and test section (m) |
| $f_0$ | fundamental frequency of ultrasound (MHz) |
| $\alpha$ | Incident angle of ultrasonic transducer (deg) |
| $Q_{UVP}$ | flowrate using ultrasonic Doppler velocity profile (UVP) method ($m^3$/h) |
| $Q_{ref}$ | reference flowrate using static gravimetric method ($m^3$/h) |
| $v_b$ | mean velocity (m/s) |
| $r$ | radial position (m) |
| $k$ | coverage factor (dimensionless) |
| $U_P$ | uncertainty of the flowrate measurement with respect to the pipe layout (%) |
| $U_F$ | uncertainty of the flowrate measurement with respect to the flowrate (%) |
| $U_{F\times P}$ | uncertainty of the flowrate measurement with respect to the interaction between the pipe layout and the flowrate (%) |
| $U_A$ | uncertainty of the flowrate measurement with respect to the incident angle of the ultrasound (%) |
| $U_{A\times P}$ | uncertainty of the flowrate measurement with respect to the interaction between the incident angle of the ultrasound and the pipe layout (%) |
| $U_R$ | uncertainty of the flowrate measurement with respect to repeatability (%) |
| $U_{UVP}$ | uncertainty of the flowrate measurement with respect to the UVP method (%) |
| $U_{CMC}$ | uncertainty of the national standard calibration facility (%) |
| $U_T$ | total uncertainty of the flowrate measurement (%) |
| $e$ | deviation of the flowrate given by the UVP method from the reference flowrate (%) |

were performed at the national standard calibration facility of water flowrate in Japan. Flowrate measurements were based on a multi-path measurement method [7,8] using three ultrasonic transducers. To generate the disturbed flow, obstacle plates were installed upstream of the test section. To determine which experimental parameter is the dominant factor of the uncertainty, parametric examinations were conducted for the obstacle plate configuration, the distance between the obstacle plate and the measurement section, the incident angle of the ultrasonic beam, and the flowrate. Because several uncertainty factors in this examination are cross-correlated with each other, the uncertainties of these factors are evaluated independently using analysis of variance (ANOVA).

## 2. Experiments

### 2.1. Experimental apparatus

Overhead and cross-sectional views of the test pipe are shown in Fig. 1. Three ultrasonic transducers are installed in the test pipe at regular intervals, and their sensors are placed in direct contact with the water. Hereafter, the transducers are called TDX1, TDX2, and TDX3, and their positions around the pipe are shown in Fig. 1. The investigated incident angles of these transducers are $\alpha \approx 8°$ ($\alpha_1 = 8.53°$, $\alpha_2 = 7.46°$ and $\alpha_3 = 8.19°$) and $\alpha \approx 17°$ ($\alpha_1 = 17.3°$, $\alpha_2 = 16.9°$ and $\alpha_3 = 16.6°$). These angles are obtained from actual measurements. The fundamental frequency of the ultrasonic transducers is $f_0 = 2$ MHz, and the diameter of the piezoelectric element is 10 mm. The inner diameter of the test pipe is $D = 199.0$ mm.

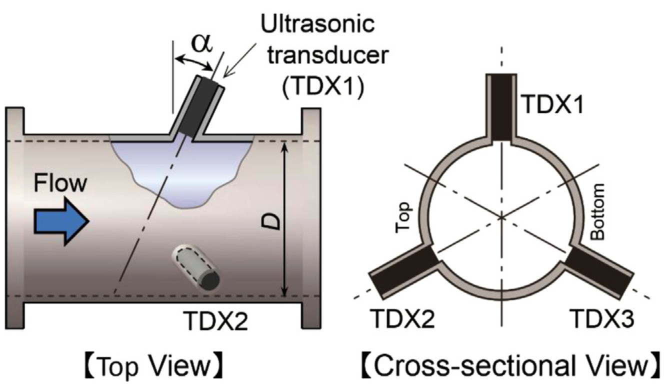


**Fig. 1.** Test pipe.

The velocity profile was measured with a Doppler-based ultrasound velocity profiling instrument (UVP-DUO, Model: MX, Met-Flow SA). The details of this instrument is shown in the reference [5]. The measurement paths were changed in sequence using the multiplexer installed in the equipment. The measurement interval of the velocity profile at each path was approximately 350 ms. The flowrate of each path was calculated by integrating the velocity profile over the pipe diameter [5]. The averaged flowrate which is discussed in the following section, is the arithmetic mean of the flowrate of 3 paths. Additionally, the average flowrates using arbitrary numbers of paths (0.5, 1, and 1.5 paths) were also calculated to evaluate the effect of the number of paths. The cases with 0.5 and 1.5 paths correspond to paths with lengths of 1 and 3 radii, as shown in Fig. 2. The number of samples measured for each path is 610. The distance between measurement points along the path is 1.48 mm. In this experiment, the same parameters determined by the measurement equipment are used for all measurements. This means that the measurement uncertainty of the velocity might increase with decreasing flowrate due to the resolution of the velocity measurements.

### 2.2. Experimental facility and pipe layout

The experiments were performed at the water flowrate calibration facility of the National Institute of Advanced Industrial Science and Technology, National Metrology Institute of Japan (AIST, NMIJ). This facility is the national standard calibration facility of water flow in Japan. The flowrate given by the UVP method is evaluated with respect to the reference flowrate given by the static gravimetric method using a tank system weighing 50 t. The uncertainty of the reference flowrate given by the 50 t weighing tank system is 0.060% ($k = 2$). For the details of the system, see reference [9]. The flowrate range of this experiment is 300–600 $m^3$/h, and the water temperature range is 14.2–21.9 °C. The temperature variation is within 0.1 °C during one measurement. The Reynolds number range is $Re = 4.66 \times 10^5$–$9.68 \times 10^5$. The basic pipe layout with the bubble generator is the same as in a previous study by Furuichi [5]. The flow conditioner is installed a distance of 55$D$ upstream of the test section. Small bubbles that act as reflectors are inserted upstream of the flow conditioner [10].

To generate a disturbed (non-axisymmetric) flow, obstacle plates are installed upstream of the test section, as shown in Fig. 3. This type of plate is frequently used in performance tests of flow