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Static pressure measurement error at a wall tap of a flow nozzle for a wide range of Reynolds number

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ABSTRACT

The static pressure measurement error at a wall tap of a flow nozzle is examined for a wide range of Reynolds number. The static pressure measurement error is obtained using the measured discharge coefficient for the flow nozzle. The static pressure measurement error is influenced by the diameter of the wall tap and the viscosity of the working fluid. This paper presents several relations between the static pressure measurement error normalized by the wall shear stress and the tap Reynolds number, which is based on the diameter of the wall tap and the friction velocity. The best relation to reasonably explain the static pressure measurement error is proposed in this paper.

1. Introduction

The static pressure measurement error for a wall tap is a classical and important subject in fluid dynamics. In general, it is caused by the secondary flow in the hole, which is induced by the wall shear stress. Since the 1960s, many researchers have studied this subject, and Shaw [1] first reported a universal relation between the Reynolds number based on the diameter of the wall tap and the static pressure measurement error, which is given by

$$\frac{e}{\tau_w} \propto Re_t, \tag{1}$$

where e is the static pressure measurement error and τ_w is the wall shear stress. Re_t is defined as $Re_t = u_\tau d_t/\nu$, where u_τ is the friction velocity, d_t is the diameter of the wall tap, and ν is the kinematic viscosity. The left-hand side of Eq. (1) is called the dimensionless pressure measurement error, and the right-hand side, Re_t, is called the tap Reynolds number. Shaw reported that the dimensionless pressure measurement error increases with increasing Reynolds number and reaches an asymptotic value at $Re_t \approx 800$. Therefore, it is expected that the dimensionless pressure measurement error is constant for $Re_t > 800$.

After Shaw's report, experimental results at higher tap Reynolds number regions up to $Re_t \approx 2000$ were reported by Rainbird [2] and Franklin and Wallace [3]. Their results show that the dimensionless pressure measurement error does not reach an asymptotic value but continues to increase with increasing tap Reynolds number, although the slope in the high tap Reynolds number region is smaller than that in the low tap Reynolds number region. Moreover, in a recent publication, McKeon and Smits [4] performed an experiment with high tap Reynolds numbers up to $Re_t \approx 8000$, and they indicated that the universal curve obtained by Shaw is applicable to only low tap Reynolds numbers ($Re_t < 1000$). Moreover, they reported that the dimensionless pressure measurement error in the higher tap Reynolds number region is influenced by the tap diameter relative to the pipe diameter.

The static pressure measurement error at the wall tap significantly influences the discharge coefficient of a throat-tap flow nozzle, hereafter flow nozzle, which is a type of differential pressure flowmeter. The wall tap to measure the static pressure is located on the upstream pipe wall and at the throat region of the flow nozzle, as shown in Fig. 1. Because the wall shear stress on the wall at the throat is larger than that at the upstream pipe, the static pressure measurement error at the wall tap at the throat is larger than that at the upstream pipe. This difference induces an error in the differential pressure between two wall taps and influences the discharge coefficient. Some previous studies on the flow nozzle have already taken into account the static pressure measurement error [5–7]. However, previous analyses are based on Shaw's experimental results and are limited to only the low Reynolds number region, even though most flow nozzles are used in the high Reynolds number region. In particular, previous reports

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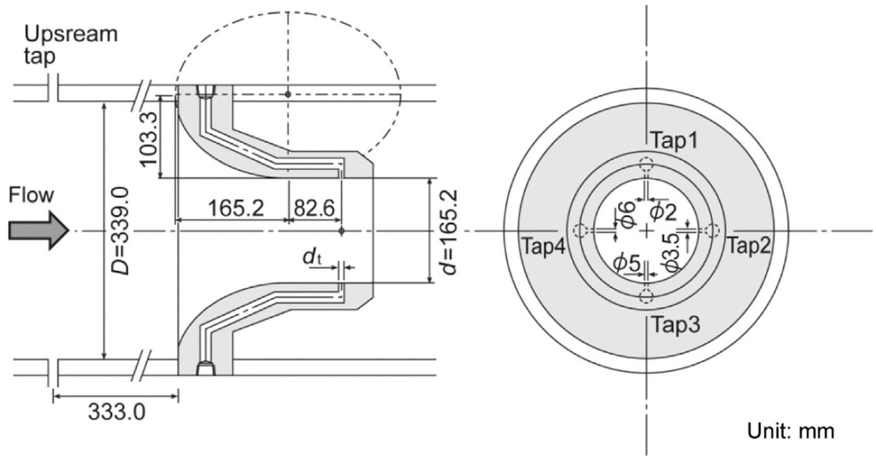

Fig. 1. Geometry of the flow nozzle examined in this experiment.

do not take into account the influence of the diameter of the wall tap for the discharge coefficient. Moreover, the diameter of the wall tap at the throat of the flow nozzle is larger than the previous fundamental analysis by Shaw, McKeon and Smits. Because the large diameter of the wall tap is suitable to use in the actual engineering field. Thus, the influence of the static pressure measurement error on the discharge coefficient of the flow nozzle has not been sufficiently clarified.

In this paper, the static pressure measurement error for the wall tap at the throat of the flow nozzle is estimated using the discharge coefficient results, which are obtained over a wide range of Reynolds numbers. The diameter of the wall tap in this experiment is from 2 mm to 6 mm. The influence of the static pressure measurement error is analyzed using the wall shear stress in accordance with previous studies. The purpose of this paper is to determine a universal relation between the static pressure measurement error at the wall tap of the flow nozzle and the Reynolds number. This relation would also be useful in the estimation of the static pressure measurement error for inlet pipe flows and the wall tap with large diameter.

2. Experiment

2.1. Flow nozzle

The flow nozzle, which is shown in Fig. 1, is manufactured according to ASME PTC 6 [8] except the wall taps. The diameters of the upstream pipe and the throat are $D=339.0$ mm and $d=165.2$ mm, respectively. The diameter ratio β is 0.4874. To measure the pressure, wall taps are installed in the upstream pipe and the straight part of the flow nozzle. The geometries of the wall taps are given in Table 1. Four wall tap sets are installed at 90° intervals in the azimuthal direction. The diameter and depth of the wall taps at the upstream pipe are $d_t=6$ mm and $l_t=20$ mm, respectively. At the throat of the flow nozzle, each wall tap has a different diameter; these diameters are $d_t=2$, 3.5, 5 and 6 mm for Tap1, Tap2, Tap3, and Tap4, respectively. The depth of these wall taps is $l_t=16.7$ mm. The ratio l_t/d_t influences the static pressure measurement error as reported by Shaw [1], Livesey et al. [9], and McKeon and Smits [4]. In the results obtained by Shaw, the effect of l_t/d_t appears to be negligible for $l_t/d_t>2$ in the relation between the dimensionless pressure measurement error and the tap Reynolds number. McKeon and Smits [4] also conclude that $l_t/d_t>2$ is necessary to ensure the dimensionless pressure measurement is independent of the diameter of the wall tap. The diameters and depths of the wall taps in this study satisfy this criterion.

Table 1
Geometries of wall taps.

	Upstream pipe	Tap1	Tap2	Tap3	Tap4
Pipe diameter; D or d (mm)	339.0	165.2	165.2	165.2	165.2
Tap diameter; d_t (mm)	6	2	3.5	5	6
Tap depth; l_t (mm)	20	16.7	16.7	16.7	16.7
d_t/D or d_t/d	0.018	0.012	0.021	0.030	0.036
l_t/d_t	3.33	8.35	5.57	3.34	2.78

On the other hand, the description for the geometry of the wall tap can be found in ISO5167-3 [10]. This ISO does not describe the throat tapped flow nozzle. However, the criteria for the wall tap of the Venturi nozzle of which the geometry is similar with the throat tapped flow nozzle is defined. In ISO5167-3, the diameter of the wall tap is less than 0.04d and is from 2 mm to 10 mm. The depth of the wall tap is over 2.5d_t. As shown in Table 1, the geometries of the wall taps in this experiment satisfy the criterion defined in ISO5163-3. This means that the result in this experiment is also useful to estimate the pressure measurement error for the Venturi nozzle.

2.2. Experimental facility

The experiments are performed using actual flow facilities at the National Institute of Advanced Industrial Science and Technology (AIST), National Metrology Institute of Japan (NMIJ). Schematics of the facilities are shown in Fig. 2. These facilities have the national standard equipment for flow rate measurement in Japan.

2.2.1. Hi-Reff (high Reynolds number actual flow facility)

The high Reynolds number actual flow facility, which is called Hi-Reff, is shown in Fig. 2(a) [11]. The feed water line is represented by the solid arrows labeled “Circulation line” in Fig. 2(a). Water is supplied to the test section by four circulation pumps at a maximum flow rate of 0.83 m^3/s. The four lines are combined upstream from the test section. The length of the test section is 35 m, and the straight pipe length is over 50D for a DN600 pipe. The specifications of the high Reynolds number facility are as follows: the flow rate range is 0.21–3.33 m^3/s, the temperature range is 20–80 °C, the pressure range is 0.3–0.7 MPa, and the maximum possible Reynolds number is 2.0×10^7. The pipe diameter of the tested device can range from 200 to 800 mm. In this experiment, the reference flow rate at the test section is given by the reference flowmeters installed in each line downstream from the pumps. This reference flowmeters are calibrated using a 50 t