Experimental Investigation of Discharge Coefficient and Tapping Error of PTC 6 Flow Nozzle using High Reynolds Number Calibration Rig

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Abstract

A tap effect of a discharge coefficient of a throat tap flow nozzle based on PTC 6 is investigated by measuring the discharge coefficient in $1.8\times10^5<Re_d<1.4\times10^7$. The measurement error of the differential pressure, when it is normalized by a wall shear stress including the effect of roughness caused by the hole of a tap, is described as a function of tap Reynolds number based on the friction velocity and the tap diameter. The equation of the discharge coefficient of the flow nozzle is proposed, which consists of the two terms that can be physically evaluated, the theoretical discharge coefficient and the measurement error of differential pressure.

Introduction

Throat tap type flow nozzles (flow nozzle) based on ASME PTC 6 [1] are widely used in engineering fields, especially in electric power plants, to evaluate the efficiency of a steam turbine. In PTC 6, an equation of a discharge coefficient of the flow nozzle is described as a function of throat Reynolds number based on the throat diameter and a bulk velocity in the throat, which is based on the paper of Murdock et al.[2]. The most significant point of PTC 6 is that an extrapolation of that equation is permitted to get the discharge coefficients in higher Reynolds number region, though accuracy on the extrapolation and a theoretical background is unclear. Since capabilities of most calibration facilities is relatively smaller than one required at actual plants, the description of the extrapolation in PTC 6 is very useful.

In recently, discharge coefficients of the flow nozzle of PTC 6 for various throat tap diameters were measured at high throat Reynolds numbers up to 1.4×10^7 for water flow by authors [3] and measured up to 3.0×10^7 for gas flow by Reader-Harris et al. also [4]. Most of their results are deviated from the equation of PTC 6 and show a dependency of the size of tap diameter, namely tap effect, which is not considered in the equation in PTC 6. These results indicate that the equation of discharge coefficient must include the size of the throat tap diameter. Authors have presented the relation between the discharged coefficient and throat Reynolds number for the flow nozzle with the throat diameter of 165.22mm under throat Reynolds number range of $2.4\times10^5<Re_d<1.4\times10^7$ [3], which includes the tap effect as a function of the size of the tap diameter normalized by the throat diameter. In this paper, the discharge coefficients of a flow nozzle with the throat diameter of 99.89 mm, strictly manufactured according to PTC6, are measured to confirm the function developed in the reference [3] using the 5t weighing tank system and the prover system for water flow in AIST,NMIJ.

On the other hand, the function developed in the reference [3] is available only for the throat Reynolds number range examined, $2.4\times10^5<Re_d<1.4\times10^7$ because whether the tap effect evaluated is adequate over Reynolds numbers examined is physically not confirmed. Static pressure measurements that are influenced by the size of tap diameter have been reported in [5]-[7]. These previous papers report that this effect is would be caused by a measurement error of the pressure and is related with the wall shear stress. Taking into account these previous results, the relation between the measurement error of differential pressure and the wall shear stress is investigated to clarify the mechanism of the tap effect in this paper. The analysis shows that the tap effect is explained by the wall shear stress and tap Reynolds number based on the tap diameter and the friction velocity. The general equation proposed in this paper can estimate the discharge coefficient up to $Re_d=5.0\times10^7$, over throat Reynolds number examined.

Flow nozzle and facility

Flow nozzle

Specifications of two flow nozzles are shown in Table.1. Nozzle A is examined newly in this paper and Nozzle B is discussed in previous paper [3]. Nozzle B is manufactured according to PTC 6, but its four taps are different diameters. Nozzle A is manufactured strictly according to PTC 6 with four tap diameters of 3.5 mm. From the top to the clockwise direction, each tap is called as Tap1 - Tap4, respectively. Nozzle B has four taps whose diameter is 2, 3.5, 5, 6 mm. Each tap is also called as Tap1, Tap2, Tap3 and Tap4. The throat diameter of Nozzle A is 99.894 mm and Nozzle B is 165.220 mm. Nozzle A and Nozzle B with the 6 mm diameter tap are roughly similar figure each other. The picture of Nozzle

Table 1. Specifications of flow nozzles

	A	B[3]
Throat diameter d (mm)	99.894	165.220
Upstream pipe diameter D (mm)	199.90	338.96
Diameter ratio β	0.4997	0.4874
Throat tap diameter d_{Tap} (mm)	3.5	2, 3.5, 5, 6
Upstream tap diameter d_U (mm)	4	6

Fig.1 Flow nozzle (Nozzle B)

B is shown in Fig.1. The roughness of the nozzle surface satisfies PTC 6.

Experimental facility

Experiments in this paper are carried out using the 5t weighing tank system and the prover system in NMIJ [8][9]. The schematic diagrams of each calibration facility are shown in Fig.2. The 5t weighing tank system is connected to the normal water calibration facility. In this facility, water is supplied to the test section from the over flow head tank whose height is 30 m. Temperature of water is controlled around 20 °C. In this examination, the test line “250A” is used. The length of upstream straight pipe DN200 is over 50*D*.

The prover system is individual calibration facility. The available flowrate range of this facility is from 200 m^3/h to 800 m^3/h and the temperature range is from 20 °C to 80 °C. The test line is consists of DN200 pipe and the length of upstream straight pipe is over 50*D*.

Experimental condition

Experimental condition is shown in Table 2. For the examinations of Nozzle A at low temperature and low flowrate (Exp.1), the 5t weighing tank is used. Exp.1 is carried out for only Tap1 and Tap3. For the examinations at high Reynolds number (Exp.2), the prover system is used. The examinations are carried out under different temperature conditions and maximum throat Reynolds number is 5.8×10^6.

The experimental condition for Nozzle B is also shown in Table.2. The flow nozzle examined is installed different calibration facility whose name is the high Reynolds number calibration facility. Therefore, the reference flowrate is also given by different methods which are the 50t weighing tank and reference

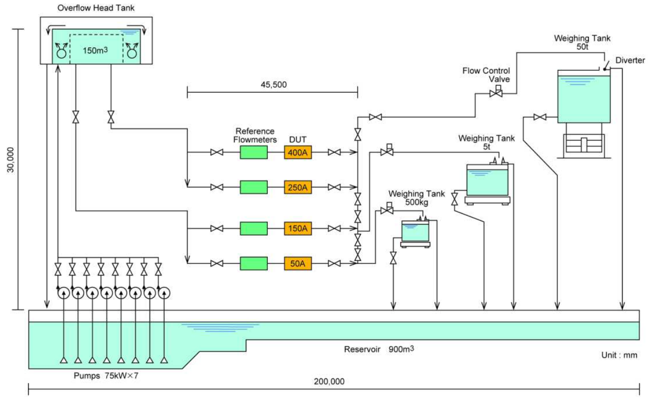

Fig.2(a) Schematic diagram of water flow calibration facility with 5t weighing tank system

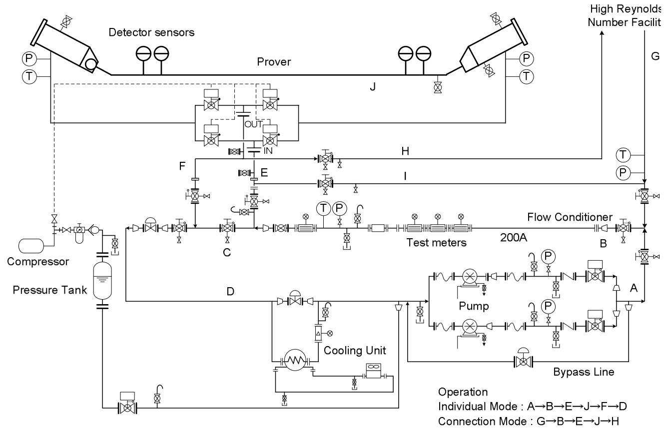

Fig.2(b) Schematic diagram of prover system

flowmeters.

Experimental method

Discharge coefficient *Cx* of the flow nozzle is given by the following equation.

$$Cx = \frac{q}{\pi d^2}\sqrt{8\left(1-\beta^4\right)\frac{\rho}{\Delta p_x}} \qquad (1)$$

where, q is a volumetric flowrate (m^3/h), ρ is a density of water at the test section (kg/m^3) and Δp_x is a differential pressure (Pa).

The differential pressure Δp_x is measured by the digital manometer (DP meter) of Yokogawa Co. Ltd. (MT210). In the experiments, two type manometers are used, which were calibrated before the measurements. The resolution is 10 Pa and 1 Pa. The start and the stop of the differential pressure measurement are completely

Table.2 Experimental condition

Exp. No.	Reference of flowrate	Flowrate (m^3/h)	Temperature (°C)	Pressure (MPa, Gage)	Re number range	Nozzle
Exp.1	Weighing tank (5t)	30 – 300	20 ± 2	0.2 ± 0.10	$1.8\times10^5 – 1.1\times10^6$	A
Exp.2	Prover	250 – 600	20, 30, 40, 53, 65, 79 ± 2	0.5 ± 0.10	$9.0\times10^5 – 5.8\times10^6$	A
Exp.3	Weighing tank (50t)	100 – 800	20 ± 2	0.2 ± 0.03	$2.4\times10^5 – 1.8\times10^6$	B
Exp.4	Ref. Flowmeter	770 – 2270	20 ± 4 70, 75 ± 2	0.3, 0.7 ± 0.10	$1.8\times10^6 – 1.4\times10^7$	B

synchronized with the duration time on the measurement of the reference flowrate. The sampling rate of the digitized differential pressure is 0.5 sec in this examination.

The density of the pure water ρ_p and the compressibility of water Fp are given by the following equations [10],

$$\rho_p = 999.97495\left\{1 - \frac{(T-3.983035)^2(T+301.797)}{522528.9(T+69.34881)}\right\} \quad (2)$$

$$Fp = 1 + (50.74 - 0.326T + 0.00416T^2)P \quad (3)$$

where, T is temperature at the test section (°C) and P is gauge pressure at the test section (Pa). Equation (2) is valid from 0 °C to 40 °C with the uncertainty less than 0.001%. The difference between the density given by Eq. (2) and Eq. (3) and that of the steam table is less than 0.001% in the present temperature range. The density of these equations is coincident with that of the steam table within 0.008%, even in the temperature range from 40 °C to 80 °C.

The density of water ρ in the calibration facilities is given by the following equation,

$$\rho = Fp_{\mathrm{DUT}}(\rho_P - \rho_c) \quad (4)$$

where, ρ_c is the density correction of water in the calibration facilities which is measured at 20 °C by the density meter of Anton-Paar Inc. (DMA 4500). In this examination, the density correction is -0.17 kg/m^3.

Uncertainty of experiment

Uncertainty analysis of the discharge coefficient is carried out based on ISO GUM. Uncertainty sources of discharge coefficient are differential pressure, density, diameter, flowrate and repeatability of measurement. The largest repeatability of the measurement is 0.01% for Exp.1, 0.05% for Exp.2.

The expanded uncertainty (k=2) for Exp.1 is estimated from 0.05% to 0.70% depending on flowrate. The worst uncertainty is estimated at the lowest flowrate. The most dominant uncertainty source of this case is the resolution of the DP meter. The expanded uncertainty for Exp.2 is estimated at approximately 0.08% for all conditions. The dominant factors in this case are the measurement of flowrates and the repeatability of measurements.

Experimental results

The discharge coefficients obtained from four different taps of Nozzle A are shown in Fig.3. The horizontal axis is throat Reynolds number based on the throat diameter, Re_d. The dashed line is the reference curve of PTC 6. As shown in Fig.3, there is no difference between Exp.1 and Exp.2 so that the influence of the measurement methods does not be found on the discharge coefficients. On the other hand, small differences among taps are observed. The results of Tap3 deviate from others in high Reynolds numbers. This might depend on the manufacturing error of the tap. Therefore, the Tap3 is not treated in later discussions and the results of Tap1 are used as the typical data of Nozzle A in the following discussions.

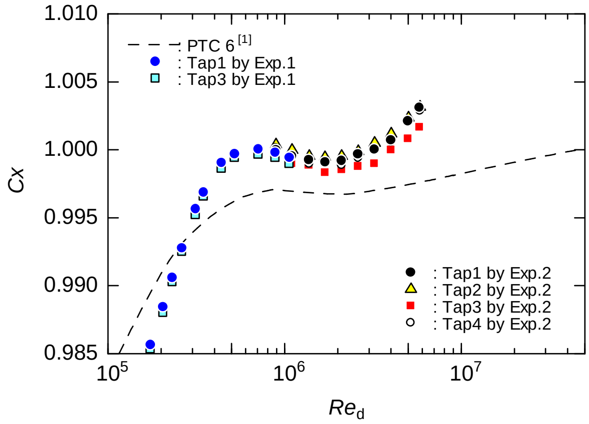

Fig.3 Variations of discharge coefficient of Nozzle A

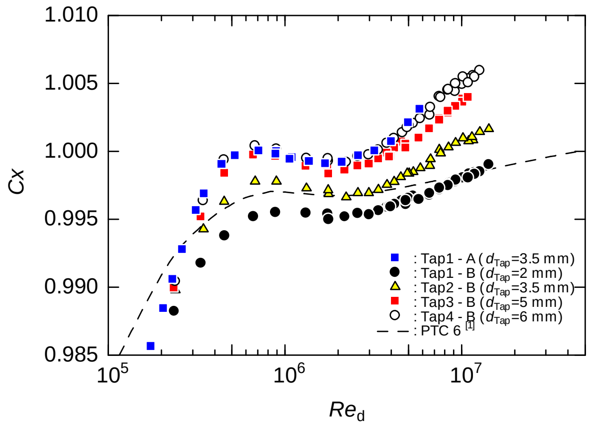

Fig.4(a) Variations of discharge coefficient with Re_d

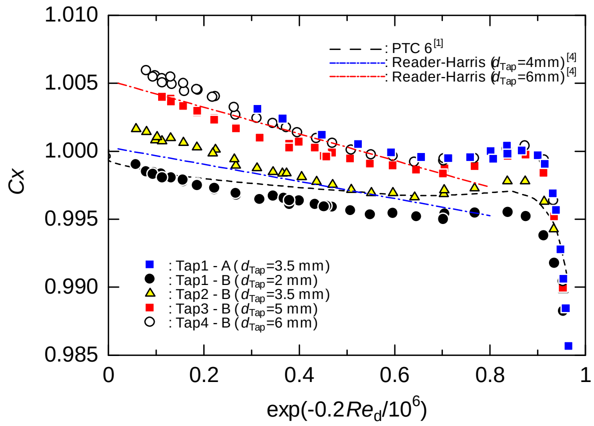

Fig.4(b) Variations of discharge coefficient with $\exp(-0.2Re_d/10^6)$

Experimental results are shown in Fig.4. The horizontal axis of Fig.4(a) is throat Reynolds number and that of Fig.4(b) is $\exp(-0.2Re_d/10^{-6})$ proposed by Reader-Harris[4]. As discussed in previous paper [3], Fig.4 indicates an important point, namely the discharge coefficients being influenced by the size of the tap diameter. The larger the size of the tap diameter is, the larger the discharge coefficient is. The difference between the discharge coefficients obtained from Tap 1 (d_{Tap}=2mm) and that obtained from Tap 4 (d_{Tap}=6mm) of Nozzle B is about 0.55% at Re_d=4.5×10^5 and 0.69% at Re_d=1.0×10^7. The influences of the tap diameter on the discharge coefficient are also reported by Reader-Harris et al [4]. The blue dotted line (d_{Tap}=4mm) and the red dotted line (d_{Tap}=6mm) in Fig.4(b) are fitting lines for the

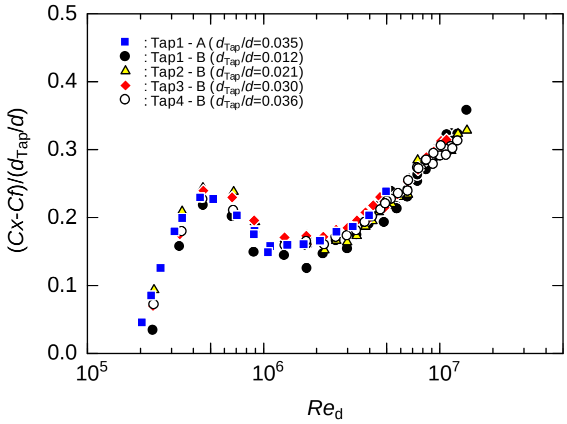

Fig.5 Relation between (Cx-Cf)/(d_{Tap}/d) and Re_{d}

discharge coefficient of flow nozzles with different throat diameters of the reference [4].

In Fig.4, the discharge coefficients for Tap1 of Nozzle A (d_{Tap}=3.5mm) does not agree with one for Tap2 of Nozzle B (d_{Tap}=3.5mm), though their tap diameter is the same. On the other hand, the discharge coefficients for Tap1 of Nozzle A agrees with one of Tap4 of Nozzle B (d_{Tap}=6mm). These nozzles have approximately the same value of d_{Tap}/d, which is called the normalized tap diameter, the normalized tap diameter being 0.35 for Tap 1 of Nozzle A and 0.36 for Tap4 of Nozzle B. Therefore, a following function including the normalized tap diameter is proposed to estimate the discharge coefficient.

$$Cx = Cf + \frac{d_{\mathrm{Tap}}}{d} f\left(Re_{\mathrm{d}}\right) \qquad (5)$$

where, Cf is the discharge coefficient of the flow nozzle without tap, and the second term of the right hand side means the tap effect, which corresponds to a deviation of discharge coefficient caused by taps from Cf. The discharge coefficients without taps of Eq.(5), Cf, are given in theoretically as the following equations for the laminar and the turbulent region [3].

$$Cf = Ct = 1 - \frac{5.9610}{Re_{\mathrm{d}}^{0.5}}, \quad (Re_{\mathrm{d}} < 1.0\times10^{6}) \qquad (6)$$

$$Cf = Ct = 1 - \frac{0.185}{Re_{\mathrm{d}}^{0.2}}\left(0.75 - \frac{337500}{Re_{\mathrm{d}}}\right)^{0.8}, \quad (Re_{\mathrm{d}} > 1.0\times10^{6}) \qquad (7)$$

where, Ct means the theoretical discharge coefficient without tap. Fig.5 shows the relation between (Cx-Ct)/(d_{Tap}/d)=$f(Re_{\mathrm{d}})$ and throat Reynolds number. All results of Nozzle A and of Nozzle B are nearly on the same line, independently on tap diameter. This result indicates that the tap effects can be described as a function of the normalized tap diameter and throat Reynolds number. On the other hand, the physical meaning of the second term of the right hand side in Eq.(5) is not sufficient in over examined Reynolds number region, unlike Cf.

Discussion

In general, a static pressure measurement is influenced by the tap dimension, in other words, the measurement error of the pressure depends on the size of a tap. The larger the tap diameter is, the larger pressure measurement error is, as shown by Shaw [5]. Shaw indicates that the pressure measurement error normalized by a wall shear stress is a function of tap Reynolds number Re_{t} based on a friction velocity and the tap diameter. However, the results of Shaw cannot be directly applied to the analysis of the flow nozzle because their analysis is carried out for the fully developed flow and Reynolds numbers is too small for the analysis of the flow nozzle. On the other hand, McKeon et al. [6] report the measurement results of the pressure measurement error for higher Reynolds numbers and their results is inconsistent with the function reported by Shaw. As Shaw said in his paper, it is impossible correctly to know the true pressure and pressure measurement error separately, and therefore, Shaw and McKeon et al. propose the way to estimate the pressure measurement error from the measurement results of the pressure by the extrapolation methods.

The differential pressure in the flow nozzle can be theoretically estimated using the theoretical discharge coefficient, Eq.(6) and Eq.(7), and Eq.(1). On the assumption that the discharge coefficient of the flow nozzle without tap is consistent with the theoretical one, Eq.(1) can be replaced to the relation between the differential pressure theoretically estimated and the theoretical discharge coefficient, and resultantly, the next equation is obtained,

$$\Delta p_{\mathrm{T}} = 8\rho\left(1-\beta^{4}\right)\left(\frac{q}{\pi d^{2} Ct}\right)^{2} \qquad (8)$$

where, Δp_{T} is the theoretical differential pressure and the theoretical discharge coefficient Ct is given by Eq.(6) and Eq.(7). The differential pressure measured, Δp_{x}, consists of the actual pressure p and the pressure measurement error e as the following equation.

$$\Delta p_{\mathrm{x}} = \left(p_{\mathrm{H}} + e_{\mathrm{H}}\right) - \left(p_{\mathrm{L}} + e_{\mathrm{L}}\right) \qquad (9)$$

where, subscripts H and L mean a measurement at the upstream tap and the throat tap of the flow nozzle respectively. Equation (9) can be modified to the next equation.

$$\Delta e_{x} = \Delta p_{\mathrm{x}} - \Delta p_{\mathrm{T}} \qquad (10)$$

where, (e_{H}-e_{L}) is replaced to Δe_{x} which means a measurement error of the differential pressure in experiments. Thus, the measurement error of the differential pressure can be estimated from the theoretical discharge coefficient. In the following section, the relation between the measurement error of the differential pressure and the wall shear stress is discussed to investigate the physical meaning about the tap effect in high Reynolds number region, in the turbulent region Re_{d}>3.0×10^{6}.

Figure 6 shows the measurement error of the differential pressure for the results of Tap4 of Nozzle B at different temperature, according to Eq.(8) – Eq.(10). It is found from Fig.6 that the measurement error of the differential pressure depends strongly on the temperature and the contribution of the measurement error of the differential pressure to the differential pressure measured is found to be 1.5%~2.3% in this experiment.

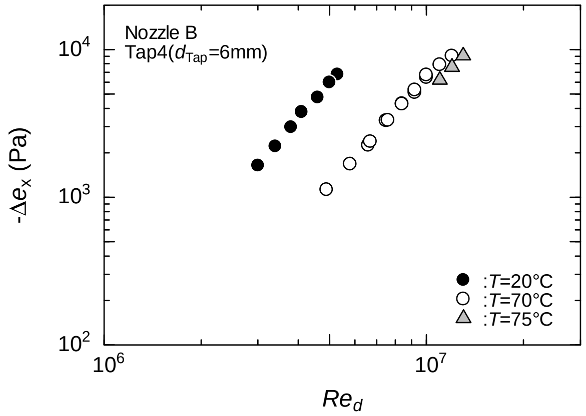

Fig.6 Measurement error of differential pressure

The wall shear stress τ_0 is given by the next equation.

$$\tau_0 = \frac{1}{2} c_f \rho U^2 \tag{11}$$

where, c_f is the local skin friction coefficient. With considering the developing of the boundary layer on the flow nozzle, the local skin friction coefficient is given by the next equation [11].

$$c_f = \{2\log_{10}(Re_x) - 0.65\}^{-2.3} \tag{12}$$

where, $Re_x = Ux/\nu$, x is the distance between a transition point from the laminar to turbulence and the tap position. The distance x is defined by the next equation [3].

$$x = \left(0.75 - \frac{337500}{Re_d}\right) d \tag{13}$$

Figure 7(a) and (b) show the relation between the measurement error of the differential pressure normalized by the wall shear stress and tap Reynolds number, Re_t. Tap Reynolds number is given by the following equation using the friction velocity.

$$Re_t = \frac{\sqrt{\tau_0 / \rho}}{\nu} d_{Tap} \tag{14}$$

The results for Tap4 of Nozzle B are shown in Fig.7(a). In this figure, the measurement error of the differential pressure for different temperatures is completely on the same line since the effect of temperature difference is taken into the change of the density. So that the measurement error of the differential pressure is found to be a function of the wall shear stress and tap Reynolds number.

The relation between the normalized differential pressure error and tap Reynolds number for Tap1 of Nozzle A and all taps of Nozzle B are shown in Fig.7(b). Fig.7 (b) includes the normalized pressure errors of McKeon et al.[6] for d_{Tap}/d =0.018 under fully developed flow, by the blue dashed line, and of Reader-Harris et al.[7] for the tap in Venturi flowmeter, by the red dashed line. They carry out measurements for d_{Tap}/d =0.026~0.13, and their results show the similar characteristics to the present results, but they do not consider the influences of d_{Tap}/d on the pressure measurement.

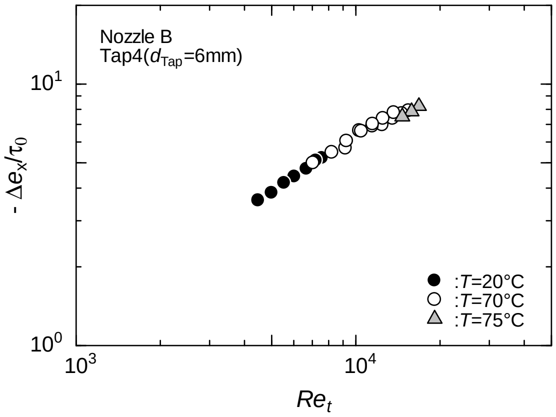

Fig.7(a) Relation between normalized differential pressure error and tap Reynolds number for Tap4 of Nozzle B

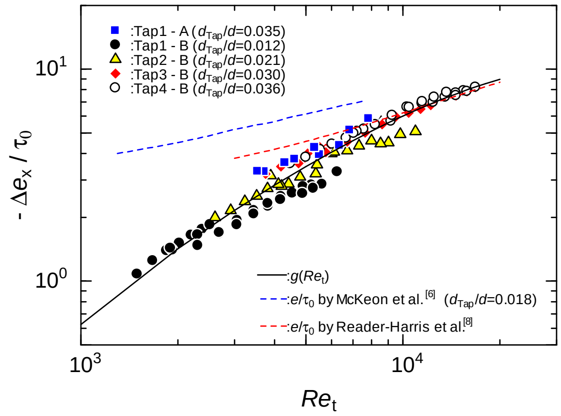

Fig.7(b) Relation between normalized differential pressure error and tap Reynolds number for all tap

The solid line in Fig.7 (b) is the approximation curve for whole results in this experiment. Figure 7(b) shows that the normalized differential pressure error increases with the size of the tap diameter and its increasing rate with tap Reynolds number is slightly different for the size of the tap diameter. Therefore, the approximation curve in Fig.7(b) is not sufficient to explain the measurement error of the differential pressure. Eq.(12) is the local skin friction coefficient is for the flow on the smooth surface, but the holes of the tap exist on the surface of the flow nozzle so that the holes must be regarded as the roughness of the surface. Therefore, the next equation considering the surface roughness is proposed to estimate the local skin friction coefficient for the turbulent region, which is called the modified local skin friction coefficient.

$$c_f^{\ *} = \{2\log_{10}(0.75Re_d - 337500) - 0.65\}^{-2.3} + k\frac{d_{Tap}}{d} \tag{15}$$

where, Re_x in Eq.(12) is replaced to Re_d using Eq.(13) and k is defined as the value when J given by the next equation is the smallest value to minimize the deviation of $-\Delta e_x/\tau_0^*$ from $g(Re_t^*)$.

$$J = \sum\left\{\left(-\frac{\Delta e_x}{\tau_0^{\ *}} - g\left(Re_t^{\ *}\right)\right) / g\left(Re_t^{\ *}\right)\right\}^2 \tag{16}$$

where, τ_0^* is the wall shear stress calculated from Eq.(11) with the modified local skin friction coefficient of Eq.(15) and Re_t^* is tap Reynolds number using τ_0^*. Finally, k in Eq.(15) is decided as 0.055 and the

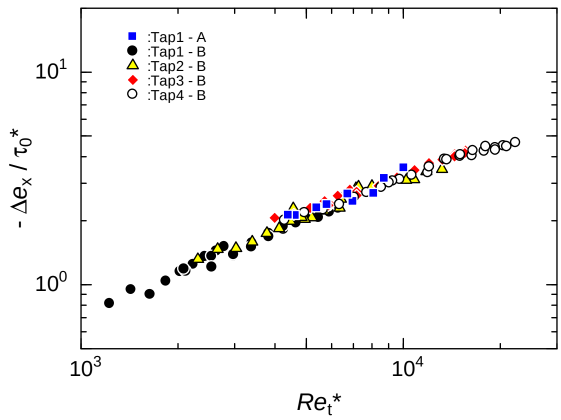

Fig.8 Relation between normalized differential pressure error and modified tap Reynolds number

approximation curve $g(Re_t^*)$ is decided as the next equation.

$$g\left(Re_t^*\right) = -\frac{\Delta e_f}{\tau_0} = 5.36 - 5.02\exp\left(-8.8\times10^{-5} Re_t^*\right) \qquad (17)$$

where, Δe_f means that the measurement error of the differential pressure obtained by the approximation curve $g(Re_t^*)$. The relation between the differential pressure error normalized by τ_0^* and tap Reynolds number Re_t^* based on τ_0^* is plotted in Fig.8. This figure shows that the whole results of Fig.7(b) are on the same line and the measurement error of the differential pressure can be explained by the wall shear stress considering the roughness of the nozzle wall surface. The tap Reynolds number range of the data plotted in Fig.8 is $1.2\times10^3 < Re_t^* < 2.3\times10^4$, which is the tap Reynolds number range that Eq.(17) can be applied to.

Here, it is important to refer the influences of the upstream tap diameter on the measurement error of pressure, because Eq.(17) mentions nothing about the influences of the upstream tap diameter. The upstream tap diameter is 4mm for Nozzle A and 6mm for Nozzle B, and d_u/D is 0.020 for Nozzle A and 0.018 for Nozzle B. The results of Nozzle A and B are almost coincident in Fig.8. Therefore, d_u/D is considered to be one of important factors to the measurement error of the pressure. Although the contribution of d_u/D to the measurement error of the differential pressure might be relatively smaller than one of the throat tap, the evaluation of the influences of the upstream tap diameter is necessary to develop the general relation between the normalized differential pressure and tap Reynolds number in the future work.

The equation of the discharge coefficient considering a measurement error of the differential pressure is derived from Eqs.(1),(8) and (10). The discharge coefficient measured, Cx, of Eq.(1), the differential pressure measured, Δp_x, of Eq.(10) and the measurement error of the differential pressure Δe_x are replaced to the general notation, C, Δp and Δe.

$$C = \frac{q}{\pi d^2}\sqrt{8\left(1-\beta^4\right)\frac{\rho}{\Delta p}} \qquad (18)$$

$$\Delta e = \Delta p - \Delta p_T \qquad (19)$$

Δp calculated from Eq.(18) and Δp_T of Eq.(8) are substituted into Eq.(19), and after simple calculations, C is given as the next equation.

$$C = \left[\left(\frac{1}{Ct}\right)^2 + \left(\frac{\pi d^2}{q}\right)^2 \left\{\frac{1}{8\rho\left(1-\beta^4\right)}\right\}\Delta e\right]^{-0.5} \qquad (20)$$

where, theoretical discharge coefficient Ct is defined by Eq.(7) and the measurement error of the differential pressure Δe is Δe_f defined by Eq.(17). Substituting Δe_f of Eq.(17) in Eq.(20), the general equation is expressed by the next equation.

$$C = \left[\left(\frac{1}{Ct}\right)^2 + \frac{c_f^*}{1-\beta^4}\left\{5.36 - 5.02\exp\left(-8.8\times10^{-5} Re_t^*\right)\right\}\right]^{-0.5} \qquad (21)$$

Here, tap Reynolds number can be related to throat Reynolds number as shown in the next equation.

$$Re_t^* = \frac{d_{Tap}}{d}\sqrt{\frac{c_f^*}{2}} Re_d \qquad (22)$$

Since c_f^* is a function of throat Reynolds number and d_{Tap}/d, the discharge coefficient is decided by the following three parameters, throat Reynolds number Re_d, diameter ratio β and normalized tap diameter d_{Tap}/d. As shown in Eq.(21), the discharge coefficient is described by the theoretical discharge coefficient and the tap effect, and these terms can be physically and correctly determined. Moreover, this equation can be applied adequately to over examined throat Reynolds number range by the following reasons.

Eq.(7) of the theoretical discharge coefficient can be applied to the throat Reynolds numbers range from $Re_d = 1.0\times10^6$ to Re_d in practical field, for example $Re_d = 5.0\times10^7$, because Eq.(7) is derived according to the boundary layer theory. Eq.(22) provides the relation between throat Reynolds number and tap Reynolds number, which is shown by the solid lines for each tap examined in Fig.9. For example, the measurement error of differential pressure for Tap1 of Nozzle A estimated at $Re_t^* = 2.3\times10^4$ corresponds to that at $Re_d = 5.0\times10^7$. Thus, Eq.(21) can be applied to over examined throat Reynolds number range, though it depends on d_{Tap}/d. The hatching area in Fig.9 is the applicable range of Eq.(21). As mentioned, the higher limit Re_t of Eq.(18) is 2.3×10^4. Substituting this value to Eq.(22), the maximum value of Re_d, $Re_{d\text{-Max}}$ is obtained by the next equation.

$$Re_{d\text{-Max}} = 2.3\times10^4 \frac{d}{d_{Tap}}\sqrt{\frac{2}{c_f^*}} \qquad (23)$$

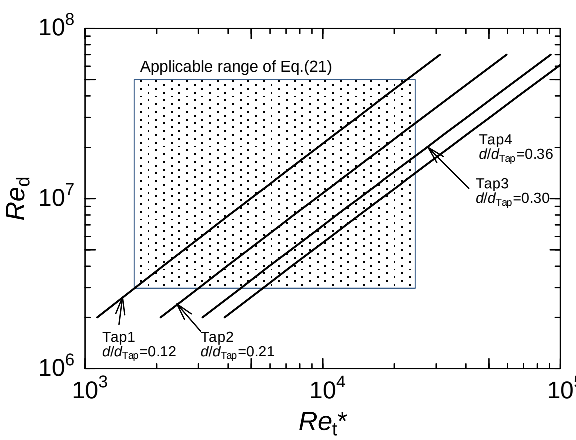

Fig.9 Relation between throat Reynolds number and tap Reynolds number, and applicable range of Eq.(21)

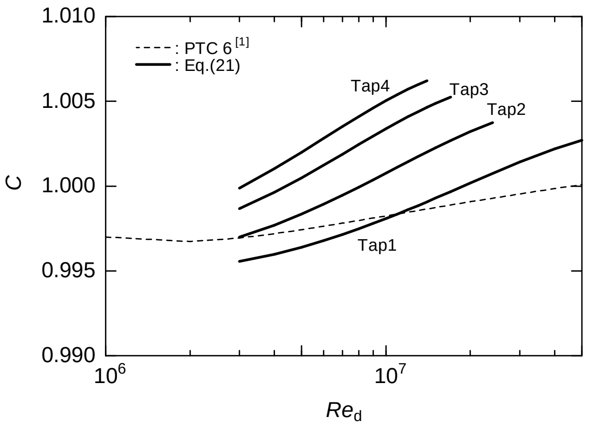

Fig.10 Discharge coefficients of Nozzle A obtained by Eq.(21)

Therefore, the $Re_{d\text{-}Max}$ can be calculated from Eq.(23) by providing d_{Tap}/d.

The discharge coefficients estimated from Eq.(21) for the each tap examined are shown in Fig.10 by the solid lines within Reynolds number range that Eq.(21) can be used. As shown in this figure, the discharge coefficient for Tap1 can be estimated up to Re_d=5.0×10^7. The deviation between the discharge coefficient measured by the present experiments and Eq.(21) for all tap of Nozzle A is less than 0.06%.

Conclusion

In this paper, the tap effect of the discharge coefficient of the flow nozzle based on PTC 6 is investigated in detail through the discussion about the measurement error of the differential pressure. The measurements of the discharge coefficient of flow nozzles with the throat diameters of 99.89 mm and 165.22 mm are carried out by the calibration facilities in AIST,NMIJ, $1.8\times10^5<Re_d<1.4\times10^7$. The results indicate that the discharge coefficient is a function of the tap diameter normalized by the throat diameter and throat Reynolds number in the throat Reynolds number range examined.

The physical meaning of the tap effect is investigated from a point of view of the measurement error of differential pressure in detail. The measurement error of the differential pressure is evaluated by the wall shear stress modified with the local skin friction coefficient considering the surface roughness and the function of the normalized tap diameter. The measurement error of differential pressure divided by the modified wall shear stress is described as a function of tap Reynolds number based on the friction velocity and the tap diameter. The function of the measurement error of differential pressure developed can be applied in tap Reynolds number range, $1.2\times10^3<Re_t^*<2.3\times10^4$.

The equation proposed to estimate of discharge coefficient consists of the two terms of the theoretical discharge coefficient and the measurement error of the differential pressure. This equation described by only three parameters which are throat Reynolds number Re_d, diameter ratio β and normalized tap diameter d_{Tap}/d, especially, d_{Tap}/d is the most significant parameter to decide the characteristics of the discharge coefficient. Since the terms of theoretical discharge coefficient and the measurement error of the differential pressure in the equation can be physically and correctly determined, the discharge coefficient of the flow nozzle based on PTC 6 can be estimated higher Reynolds number region up to 5.0×10^7 by providing the above three parameters.

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