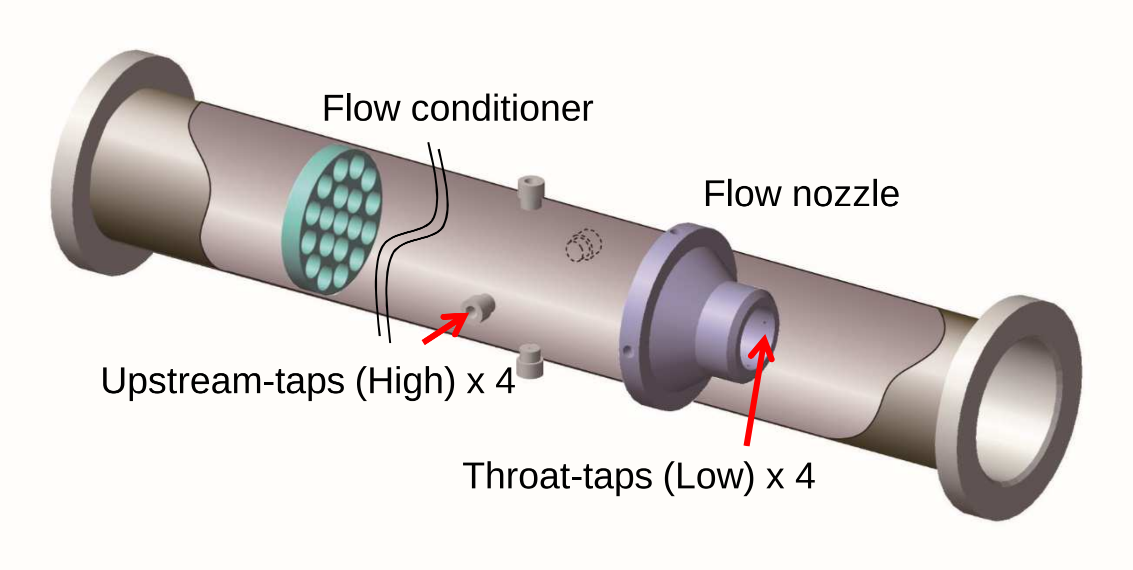
REDEFINITION OF STANDARD EQUATION FOR DISCHARGE COEFFICIENT OF THROAT-TAPPED FLOW NOZZLE

Noriyuki FURUICHI and Yoshiya TERAO

National Institute of Advanced Industrial Science and Technology (AIST)
National Metrology Institute of Japan (NMIJ)

FLOMEKO 2019
June 26-28, 2019, Lisbon, Portugal

Throat-tapped flow nozzle



Major application

Evaluation of steam turbine (ASME PTC 6, IEC 60193 etc.)
Feedwater flowrate measurement in nuclear power plant

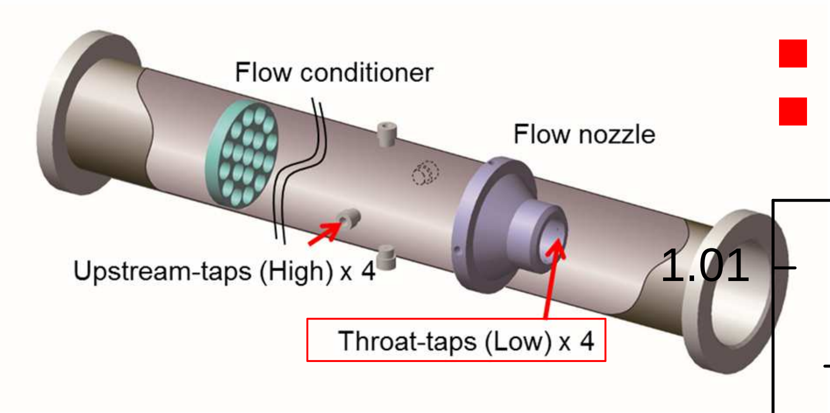
Discharge coefficient defined in ASME PTC 6

$$C_{\mathrm{PTC6}} = k_{\mathrm{t}} - \frac{0.185}{{Re_{\mathrm{d}}}^{0.2}}\left(1 - \frac{361239}{Re_{\mathrm{d}}}\right)^{0.8}$$

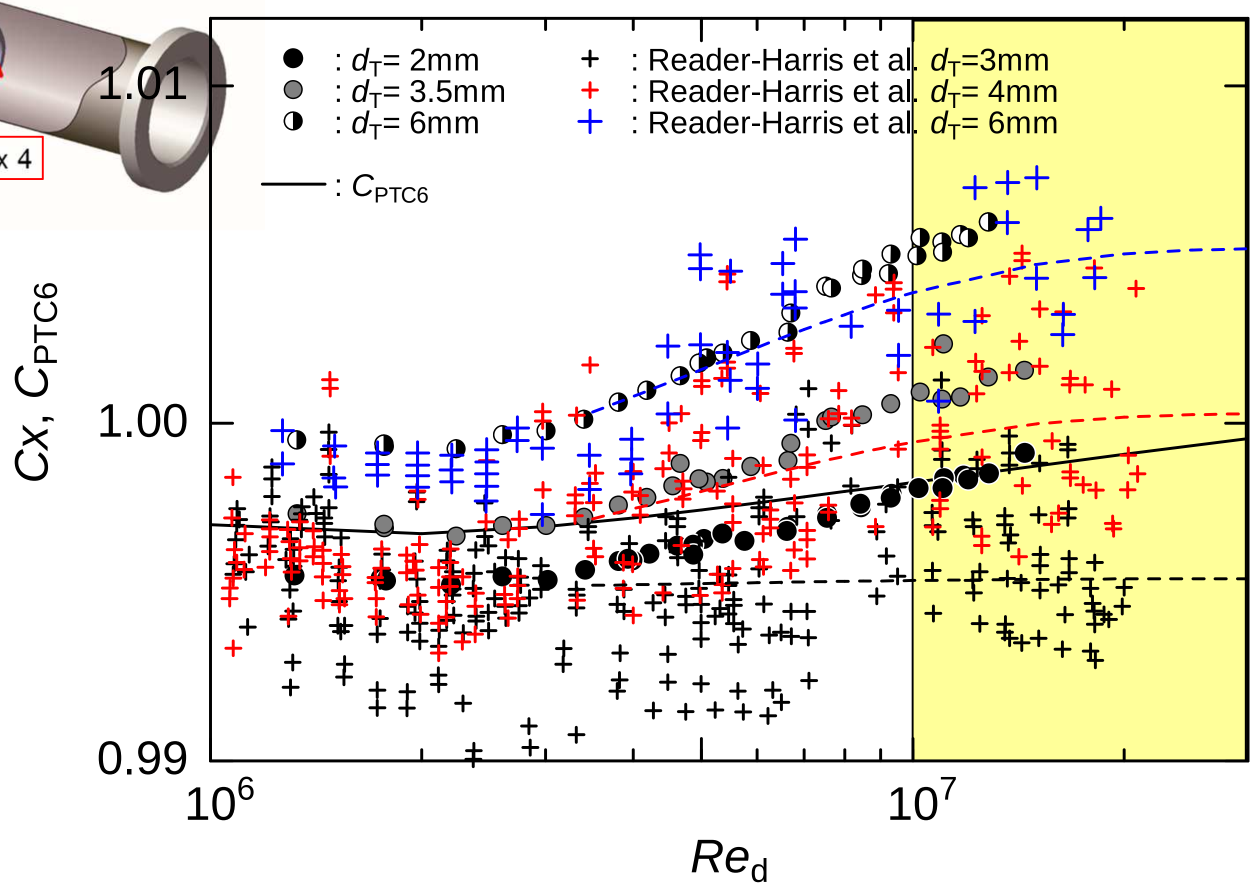
Determined by actual flow calibration, Nominal value = 1.0054

Recent experiments for high Reynolds number

by Furuichi et al. and Dr. Reader-Harris et al.



- Influence of the throat-tap diameter; d_T
- Reynolds number dependency



Previous works by author's

- Discharge coefficient behavior at high Reynolds number
- Influence of the throat-tap diameter
- Static pressure measurement error using wall tap
- Theoretical analysis

- Propose new equations for the discharge coefficient

- Comparison with other facility (with PTB)

1) Comparison of high temperature and high Reynolds number water flows between PTB and NMIJ, Furuichi. N., Cordova L., Lederer, T., Terao, Y., *Flow Measurement and Instrumentation*, 52 (2016), 157-162
2) Further investigation of discharge coefficient for PTC 6 flow nozzle in high Reynolds number, Furuichi, N., Terao, Y., Nakao, S., Fujita, K., Shibuya, K., *Journal of Engineering for Gas Turbines and Power*, 138 (2016), 041605-1-11
3) Static pressure measurement error at a wall tap of a flow nozzle for a wide range of Reynolds number, Noriyuki Furuichi, Yoshiya Terao, *Flow Measurement and Instrumentation*, 46 (2015), pp.103-111
4) New Discharge Coefficient of Throat Tap Nozzle Based on ASME Performance Test Code 6 for Reynolds Number From 2.4×10^5 to 1.4×10^7, Furuichi, N, Cheong, KH, Terao Y., Nakao, S., Fujita, K., Shibuya, K., *Journal of Fluid Engineering*, 136(1), 011105 (2013), doi:10.1115/1.4025513
5) Re-definition of discharge coefficient of throat-tapped flow nozzle and investigations on influence of geometric parameters, Furuichi, N., Terao, Y., *Flow Measurement and Instrumentation*, 65 (2019), pp.16-21.

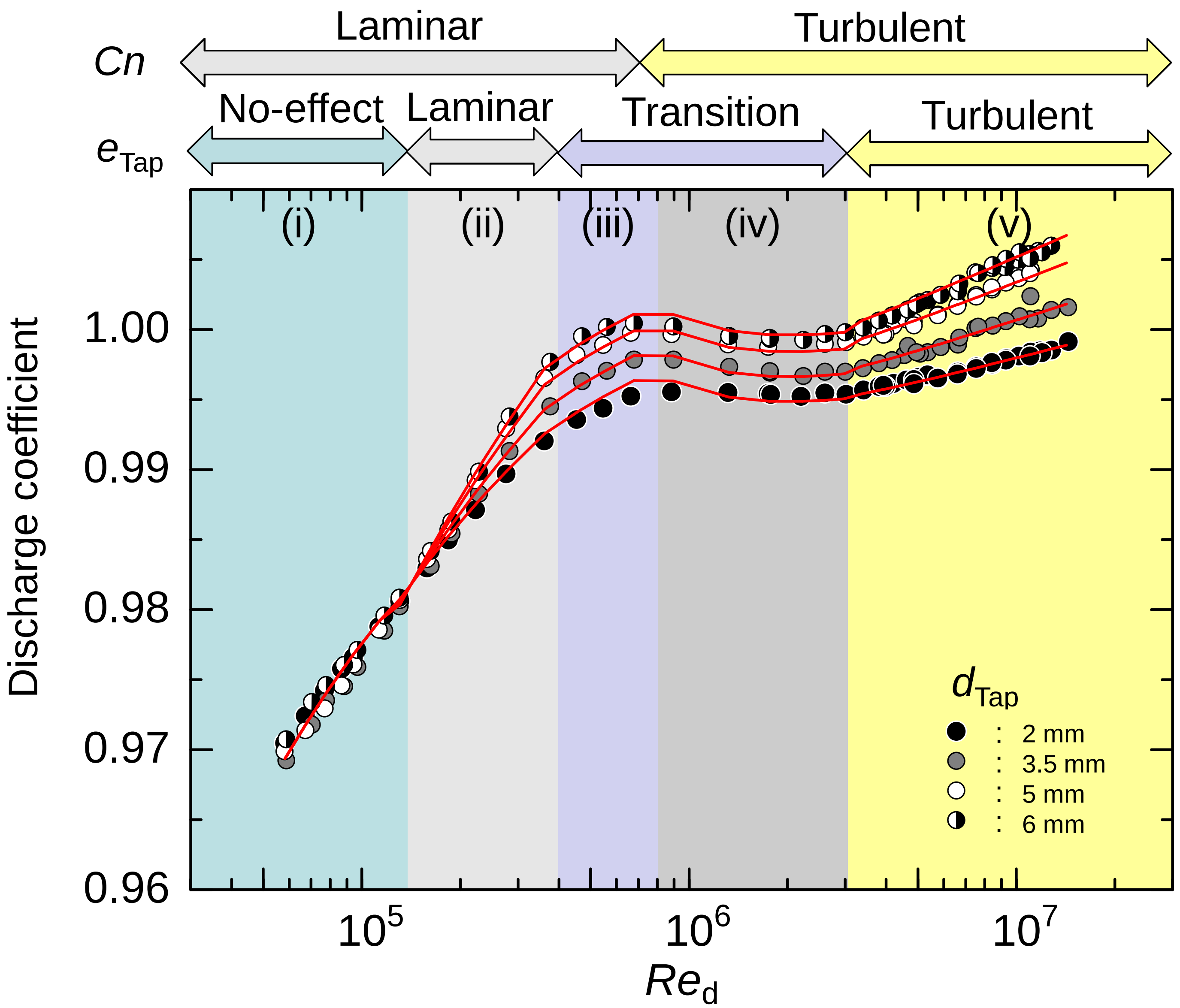
Proposed equation for ideal nozzle

$$C_\mathrm{f} = Cn + e_\mathrm{Tap}$$

C_f : Discharge coefficient
Cn : Ideal discharge coefficient
e_Tap : Static pressure error ➡ Tap effect
d : Diameter of throat
d_Tap : Diameter of wall tap
Re_d : Reynolds number

	Equation	Reynolds number range
(i)	$C_\mathrm{f} = 1.0042 - \frac{8.41}{Re_\mathrm{d}^{0.5}}$	$Re_\mathrm{d} < 1.3\times10^5$
(ii)	$C_\mathrm{f} = 1.0042 - \frac{8.41}{Re_\mathrm{d}^{0.5}} + \left(0.2053\ln\left(Re_\mathrm{d}\right) - 2.4344\right)\frac{d_\mathrm{Tap}}{d}$	$1.3\times10^5 < Re_\mathrm{d} < 4.0\times10^5$
(iii)	$C_\mathrm{f} = 1.0042 - \frac{8.41}{Re_\mathrm{d}^{0.5}} + 0.196\frac{d_\mathrm{Tap}}{d}$	$4.0\times10^5 < Re_\mathrm{d} < 8.0\times10^5$
(iv)	$C_\mathrm{f} = 1.0042 - \frac{0.255}{Re_\mathrm{d}^{0.2}}\left(1 - \frac{400000}{Re_\mathrm{d}}\right)^{0.8} + 0.196\frac{d_\mathrm{Tap}}{d}$	$8.0\times10^5 < Re_\mathrm{d} < 3.0\times10^6$
(v)	$C_\mathrm{f} = 1.0042 - \frac{0.255}{Re_\mathrm{d}^{0.2}}\left(1 - \frac{400000}{Re_\mathrm{d}}\right)^{0.8} + \left(0.0746\ln\left(Re_\mathrm{d}\right) - 0.9051\right)\frac{d_\mathrm{Tap}}{d}$	$3.0\times10^6 < Re_\mathrm{d}$

Proposed equation for ideal nozzle



Objective

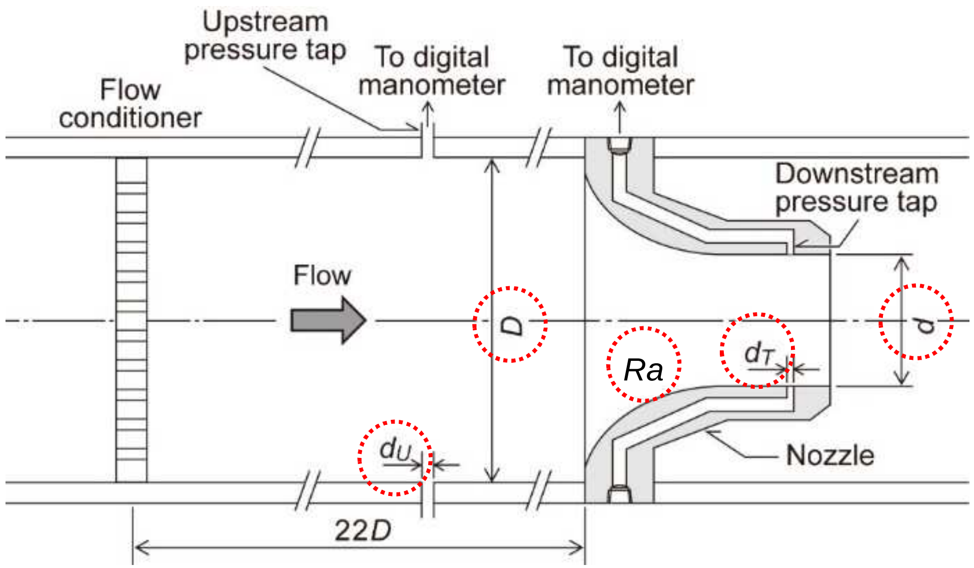
To establish new equations as ISO standard,

- ☐ More detail examinations for d_T/d
- ☐ Influence of upstream-tap diameter
- ☐ Roughness of nozzle surface
- ☐ Influence of upstream condition (flow conditioner)
- ☐ Individuality of manufacturing

↓

Final equations for the throat-tapped flow nozzle are proposed.

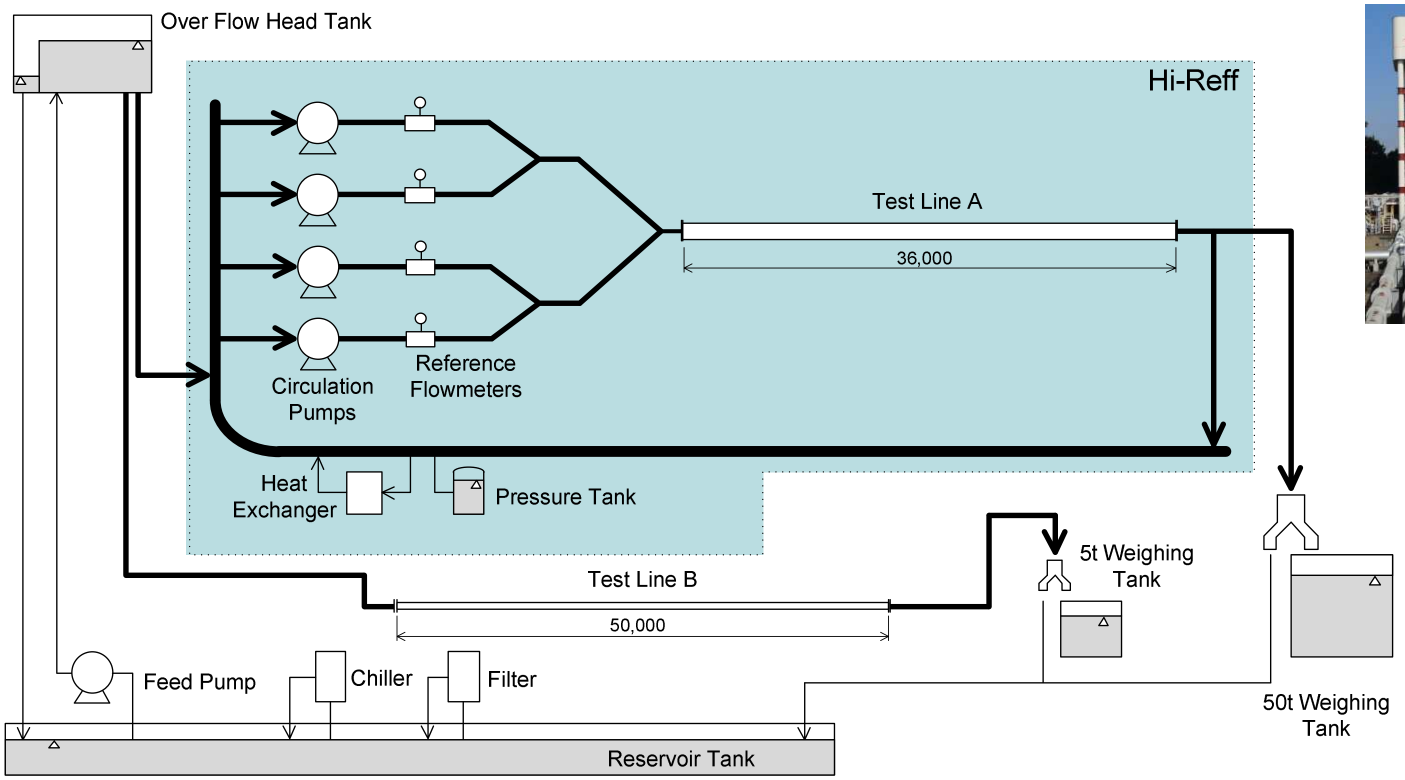
Examined parameters of throat-tapped flow nozzle



Pipe diameter ***D*** (mm)		100, 200, 350
Throat diameter ***d*** (mm)		50, 99, 165
Diameter ratio β		app. 0.5
Throat-tap diameter d_T (mm)		2, 3.5, 4, 5, 6, 7
d_T/d		0.012 ─ 0.1
Upstream-tap diameter d_U (mm)		2, 4, 5
Surface roughness	***Ra*** (μm)	0.10, 0.80
	Rt (μm)	0.60, 2.5

Experimental facility

High Reynolds number actual flow facility at NMIJ, AIST (Hi-Reff)



Testing condition

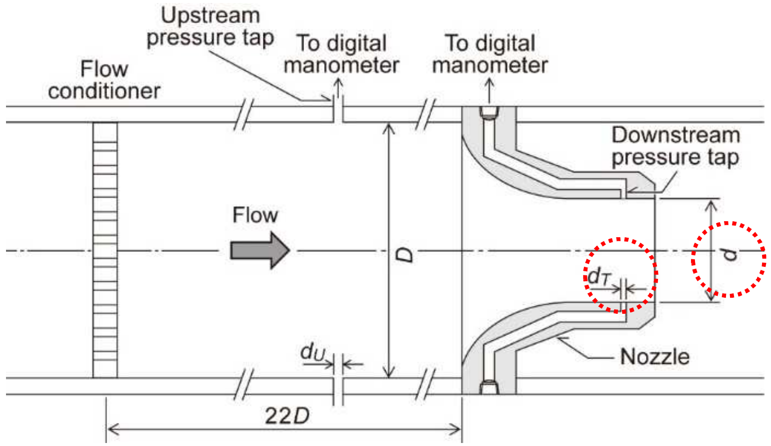
Water temperature : T=20 °C ~ 75 °C

Flowrate : q=30 m^3/h ~ 2500m^3/h

Reynolds number : Re_d=5.8x10^4 ~ 1.4x10^7

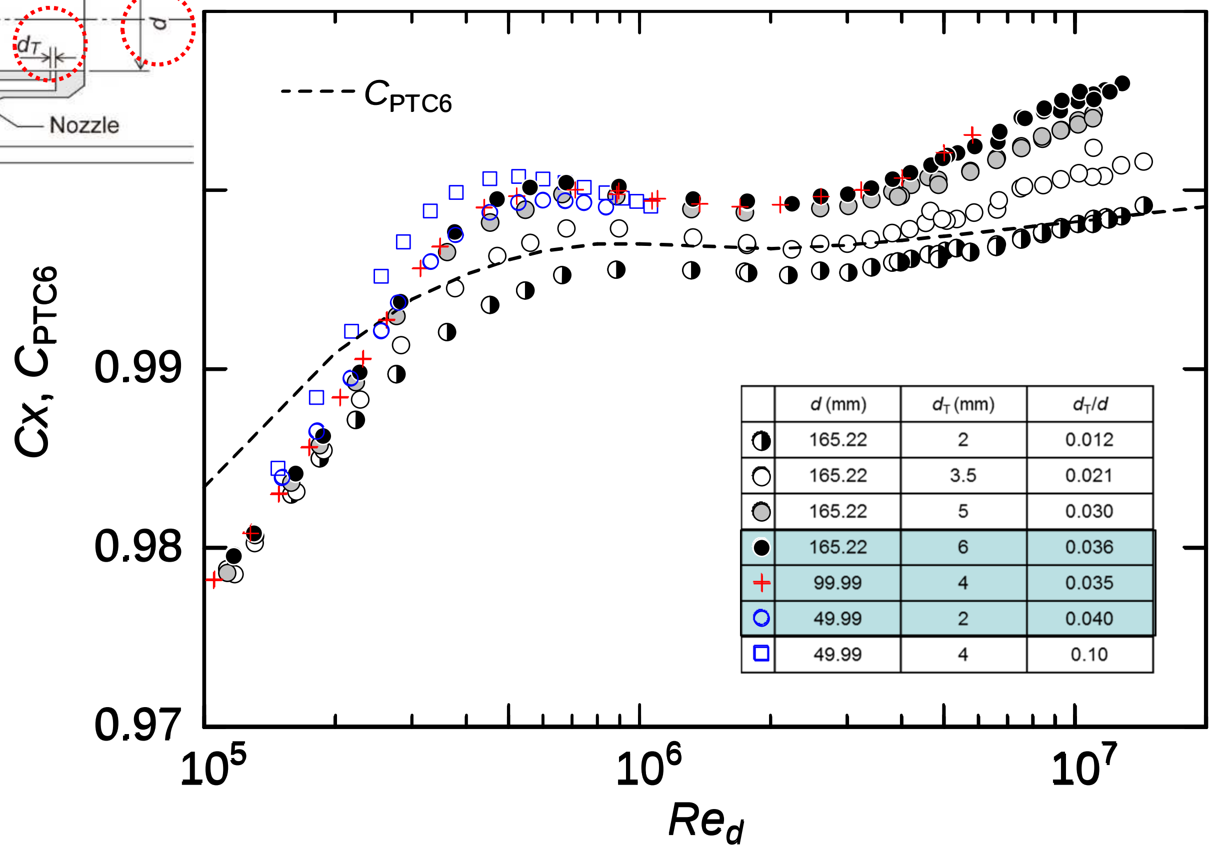
Experimental result I

For variable d_T/d



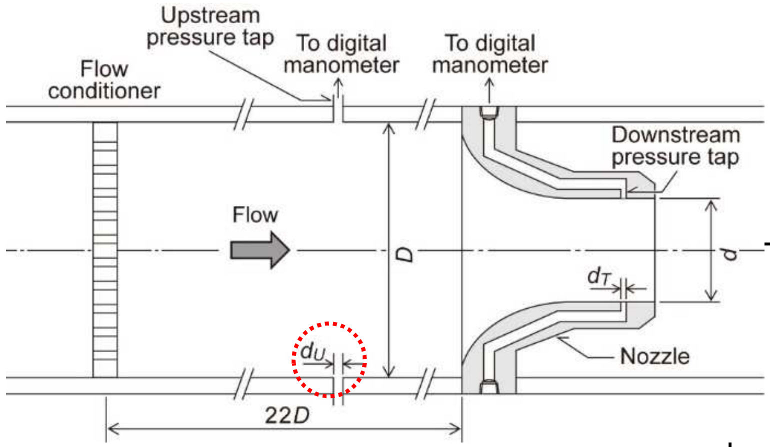
- Discharge coefficient is given as

$$Cx = f\,(Re_d,\ d_T/d)$$

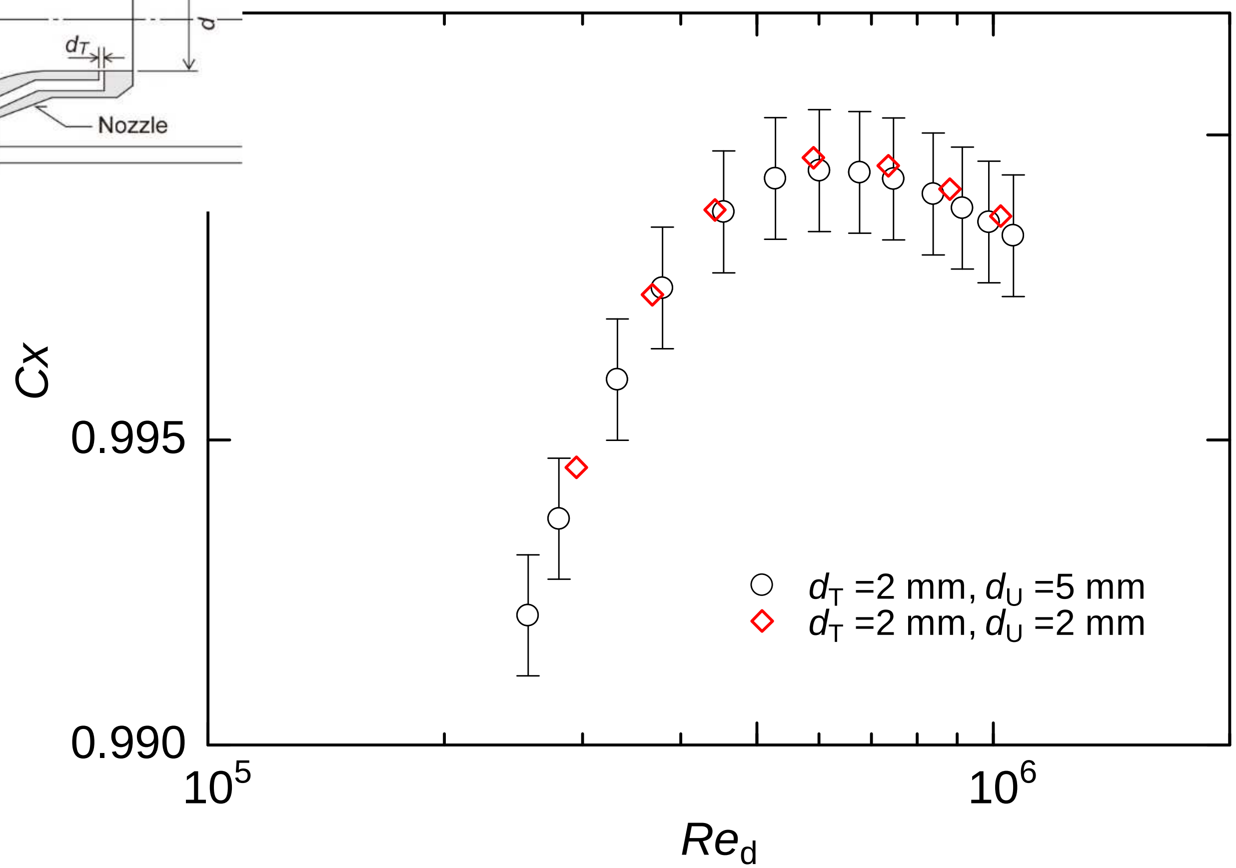


Experimental result II

Upstream-tap effect

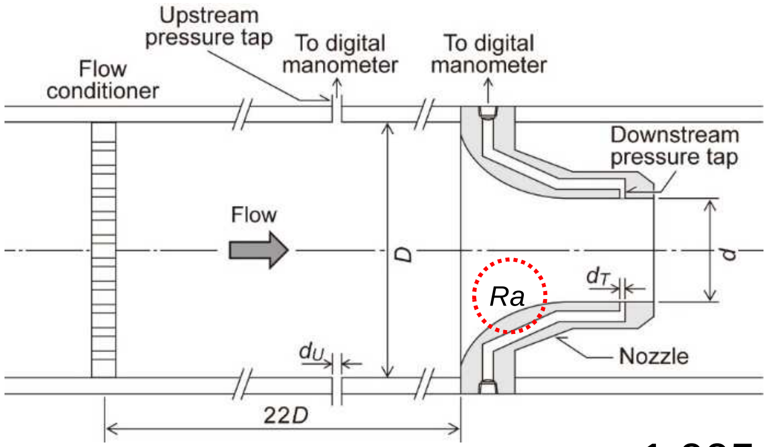


- Influence of upstream-tap diameter is relatively smaller than uncertainty of measurement.



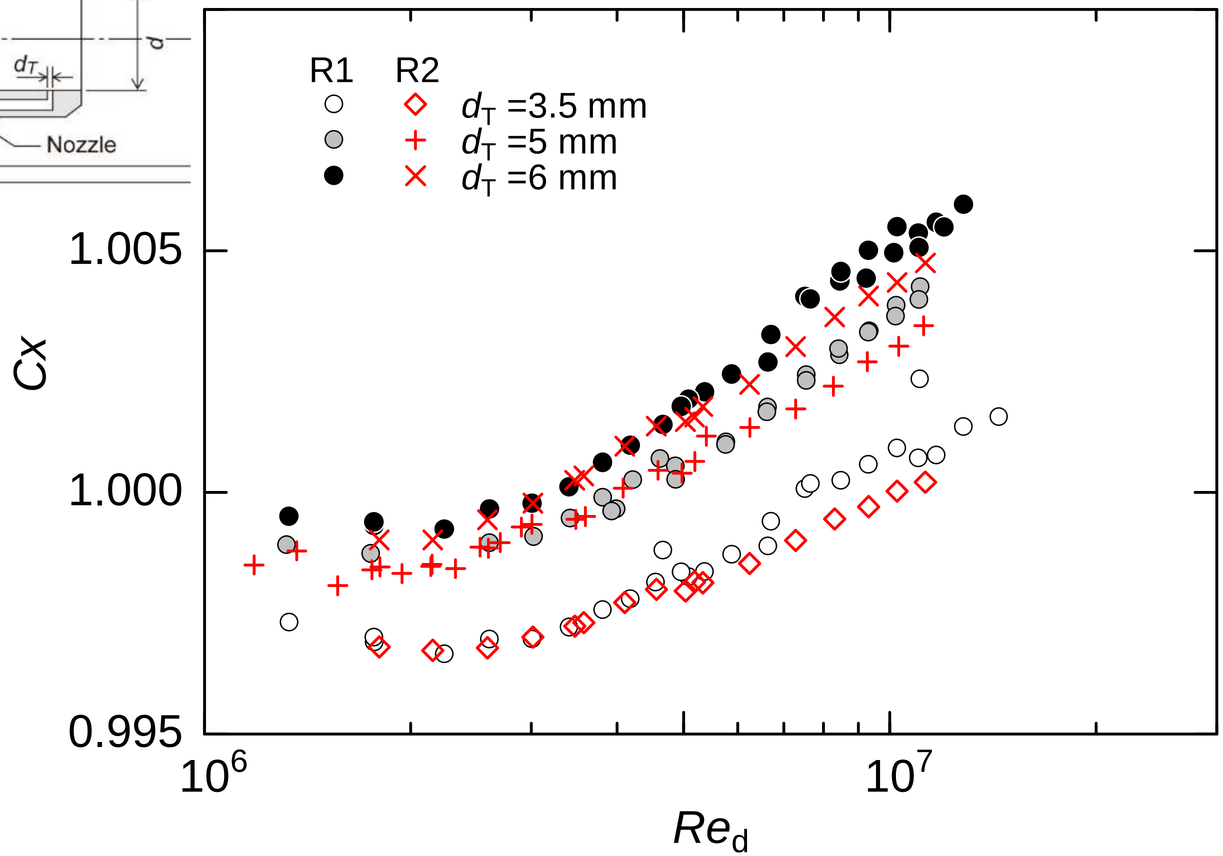
Experimental result III

Surface roughness



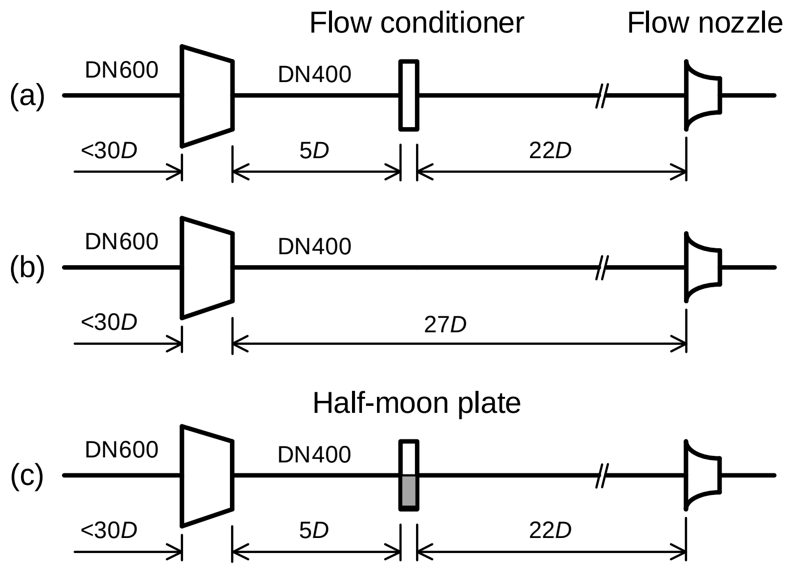
R1 : *Ra* = 0.1 µm
R2 : *Ra* = 0.8 µm

- Influence of roughness is observer for $Re_d > 6 \times 10^6$.
- Discharge coefficient is decreasing with increasing roughness.

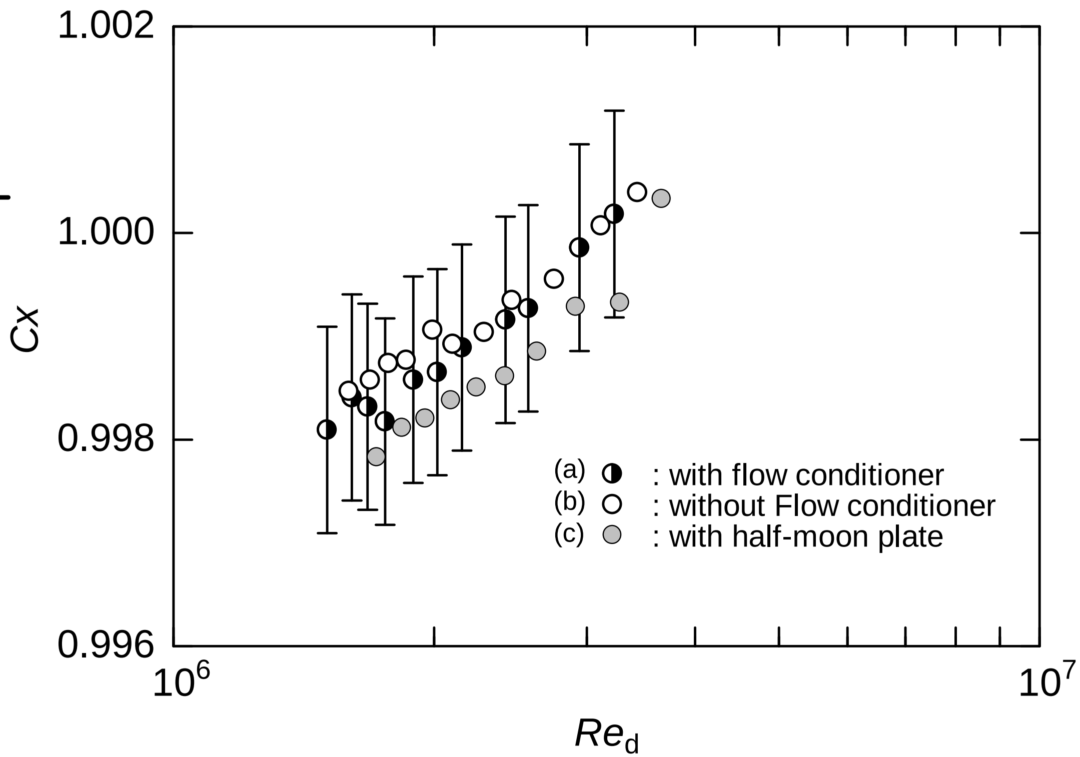


Experimental result IV

Influence of upstream condition



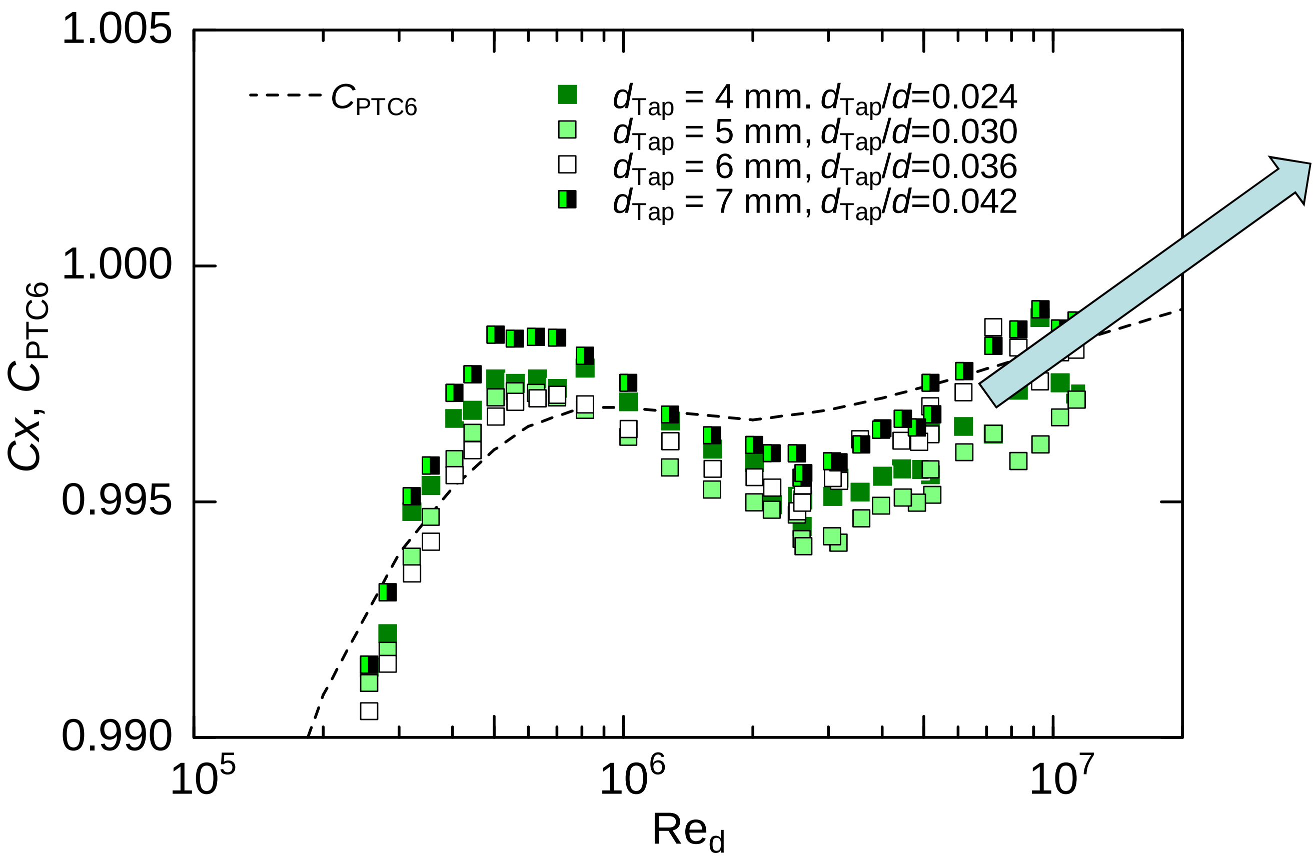
- With over 22*D* straight upstream pipe, the influence of upstream condition is less than 0.05%.



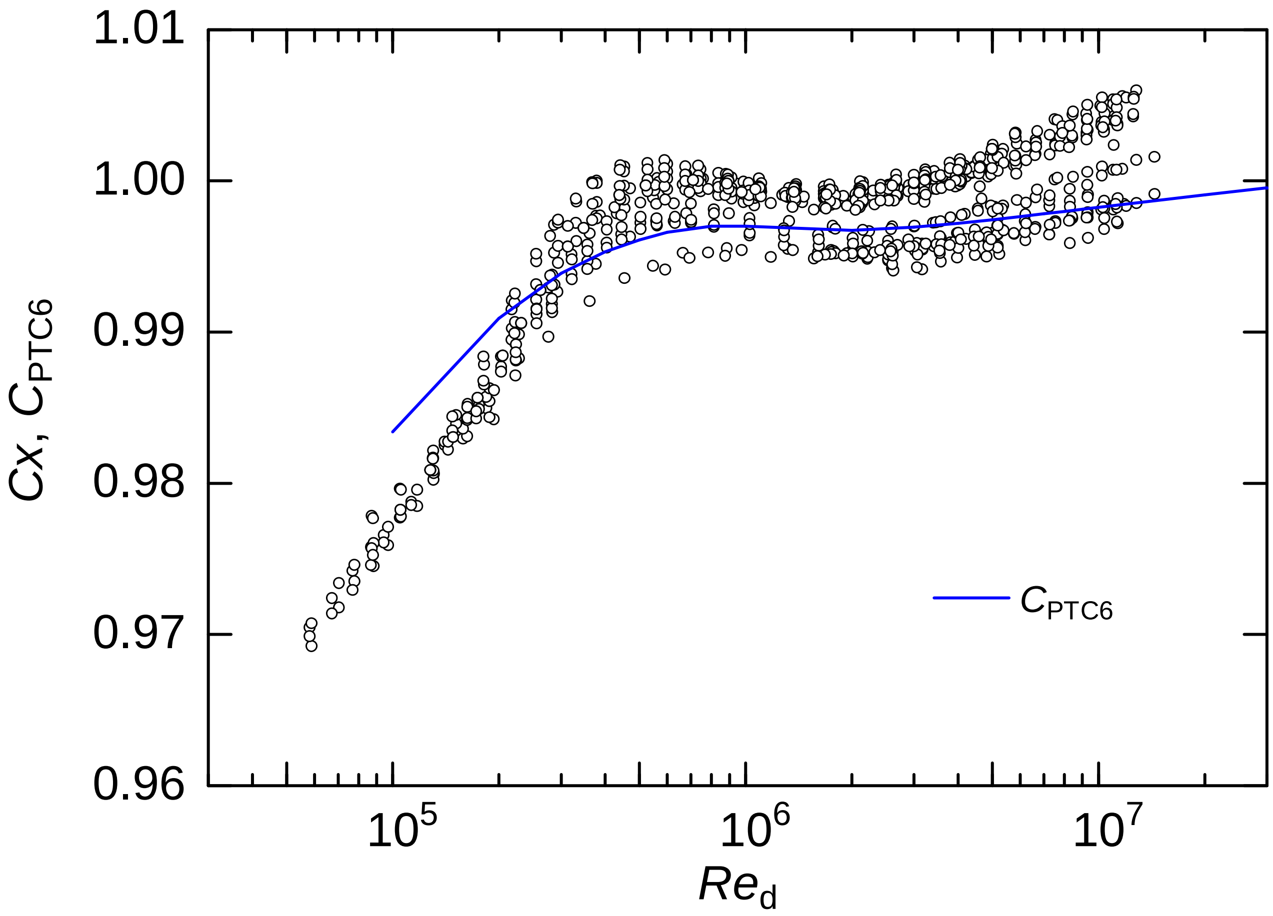
Experimental result V

Individuality of nozzle manufacturing

- Absolute discharge coefficient value is different.
- Tap effect is not according to the physics.
- However, the trend at high Reynolds number is similar.



Summary of experiments



Proposed equation for ideal nozzle

$$C_f = Cn + e_{Tap}$$

	Equation	Reynolds number range
(i)	$C_f = 1.0042 - \frac{8.41}{Re_d^{0.5}}$	$Re_d < 1.3\times10^5$
(ii)	$C_f = 1.0042 - \frac{8.41}{Re_d^{0.5}} + \left(0.2053\ln(Re_d) - 2.4344\right)\frac{d_{Tap}}{d}$	$1.3\times10^5 < Re_d < 4.0\times10^5$
(iii)	$C_f = 1.0042 - \frac{8.41}{Re_d^{0.5}} + 0.196\frac{d_{Tap}}{d}$	$4.0\times10^5 < Re_d < 8.0\times10^5$
(iv)	$C_f = 1.0042 - \frac{0.255}{Re_d^{0.2}}\left(1 - \frac{400000}{Re_d}\right)^{0.8} + 0.196\frac{d_{Tap}}{d}$	$8.0\times10^5 < Re_d < 3.0\times10^6$
(v)	$C_f = 1.0042 - \frac{0.255}{Re_d^{0.2}}\left(1 - \frac{400000}{Re_d}\right)^{0.8} + \left(0.0746\ln(Re_d) - 0.9051\right)\frac{d_{Tap}}{d}$	$3.0\times10^6 < Re_d$

$d_t/d = 0.024$

Summary of experiments

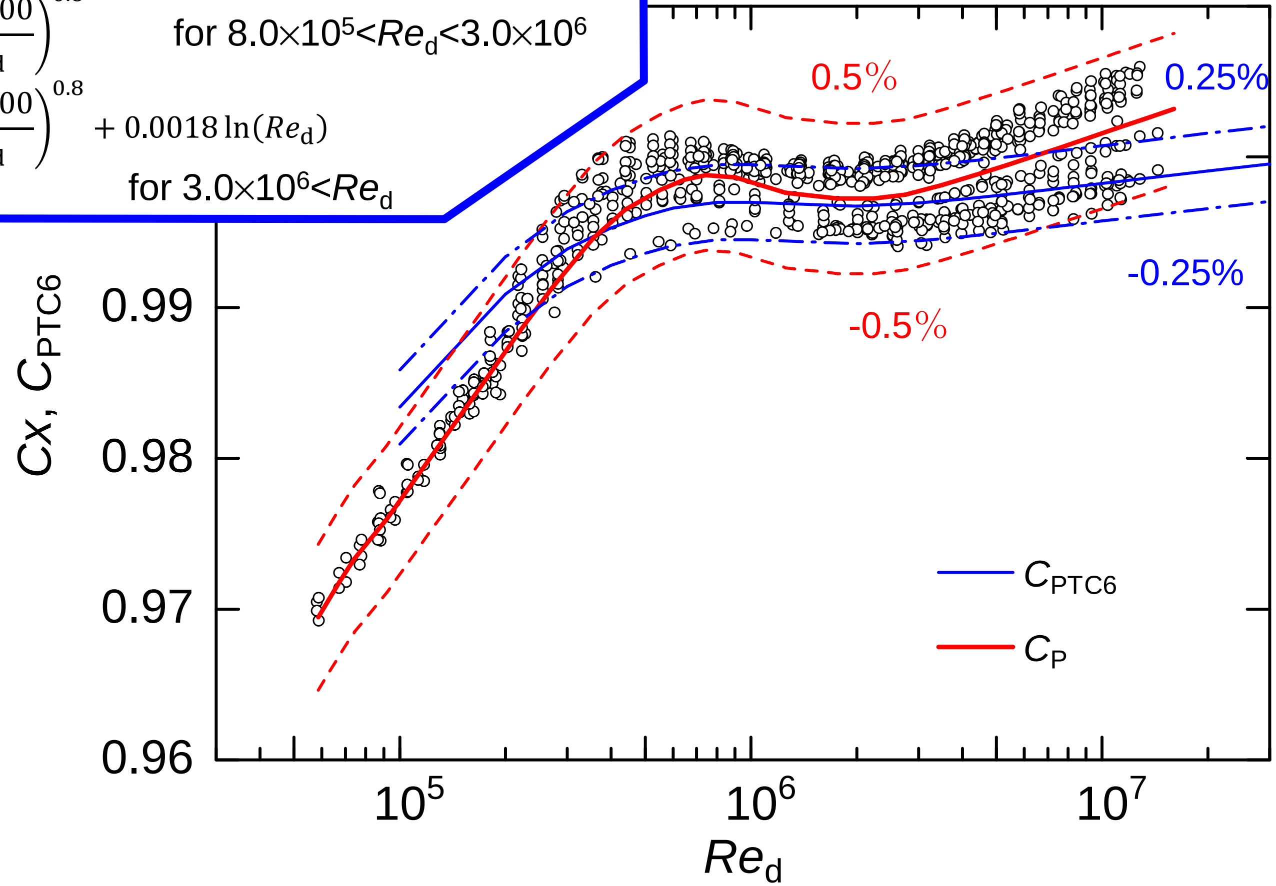
$$C_{P-1} = 1.0042 - \frac{8.41}{{Re_d}^{0.5}}$$ for $Re_d < 1.3\times10^5$

$$C_{P-2} = 0.9558 - \frac{8.41}{{Re_d}^{0.5}} + 0.00492\ln(Re_d)$$ for $1.3\times10^5 < Re_d < 4.0\times10^5$

$$C_{P-3} = 1.0090 - \frac{8.41}{{Re_d}^{0.5}}$$ for $4.0\times10^5 < Re_d < 8.0\times10^5$

$$C_{P-4} = 1.0090 - \frac{0.255}{{Re_d}^{0.2}}\left(1 - \frac{400000}{Re_d}\right)^{0.8}$$ for $8.0\times10^5 < Re_d < 3.0\times10^6$

$$C_{P-5} = 0.9823 - \frac{0.255}{{Re_d}^{0.2}}\left(1 - \frac{400000}{Re_d}\right)^{0.8} + 0.0018\ln(Re_d)$$ for $3.0\times10^6 < Re_d$



Conclusion

- This paper presents experimental discharge coefficient for the several geometric parameters; throat-tap diameter, upstream-tap diameter, roughness of surface of nozzle and flow conditioner.

- The most influence parameter for the discharge coefficient is throat-tap diameter d_T/d and the influence of the other parameters is generally negligible small.

- According to this result, new equations of the discharge coefficient for the throat-tapped flow nozzle is proposed. Although they are separated for five Reynolds number range, all experimental data in NMIJ is **within ±0.5%** of them.