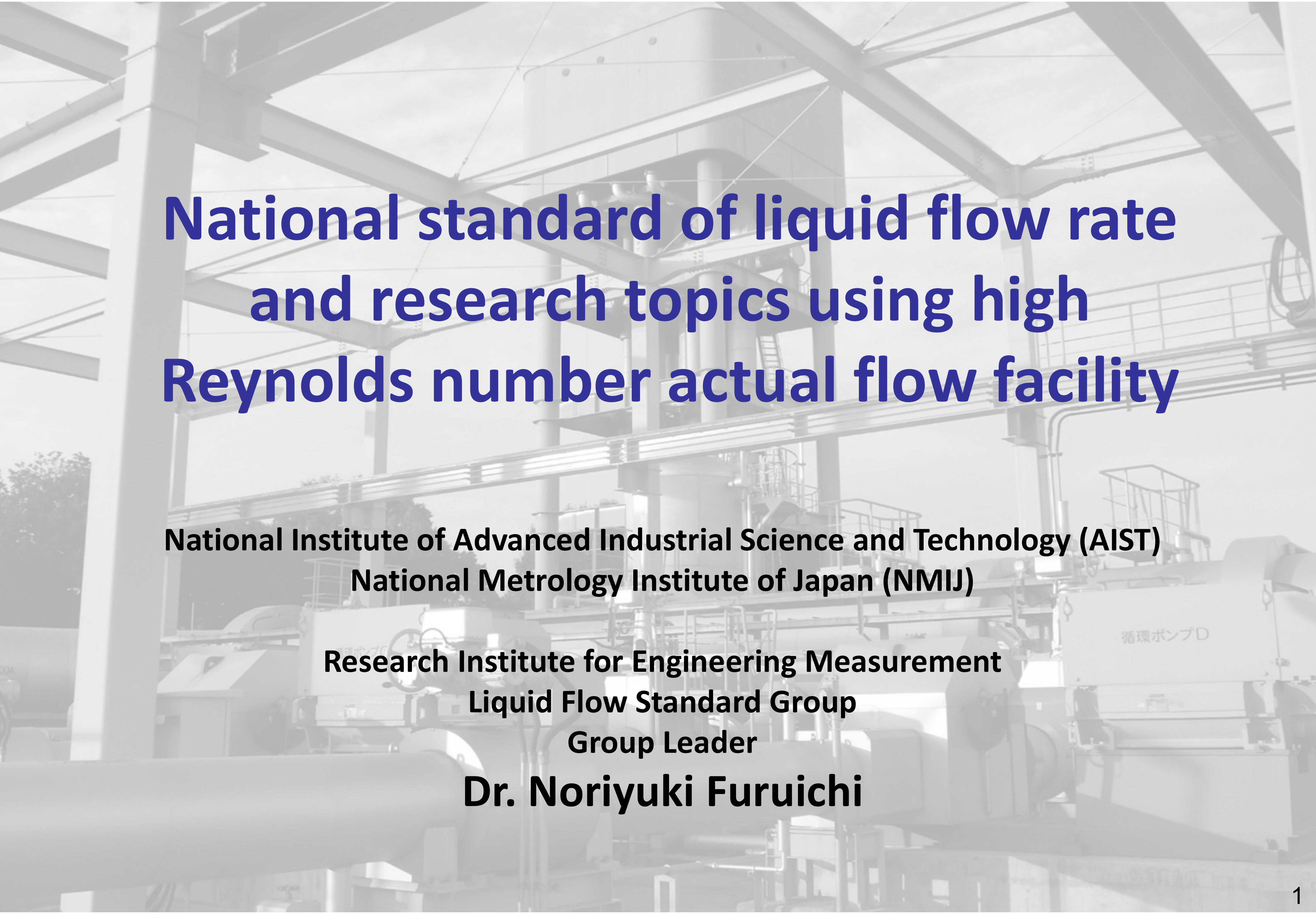

National standard of liquid flow rate and research topics using high Reynolds number actual flow facility

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

Research Institute for Engineering Measurement
Liquid Flow Standard Group
Group Leader
Dr. Noriyuki Furuichi

Biography

1999	Doctor course at Gifu University in Japan
1999 - 2001	Paul Sherrer Institute in Switzerland, Researcher
2001 - 2004	Gifu University in Japan, Assistant, Researcher
2004 - Present	AIST (National Institute of Advanced Industrial Science and Technology), NMIJ (National Metrology Institute of Japan)
2012 – 2013	PTB-Berlin in Germany, Guest researcher

Typical research works

Development of multi-point LDV, Development of flow rate measurement techniques, Fundamental research for separated and reattachment flow, Research work for high Reynolds number turbulent flow and so on…

Today's Contents

- Introduction of institute (AIST, NMIJ) and flow calibration facilities in liquid flow standard group
- High Reynolds number facility
- Examination for throat-tapped flow nozzle
- Novel research works for high Reynolds number turbulent pipe flow

Today’s Contents

- Introduction of institute (AIST, NMIJ) and flow calibration facilities in liquid flow standard group
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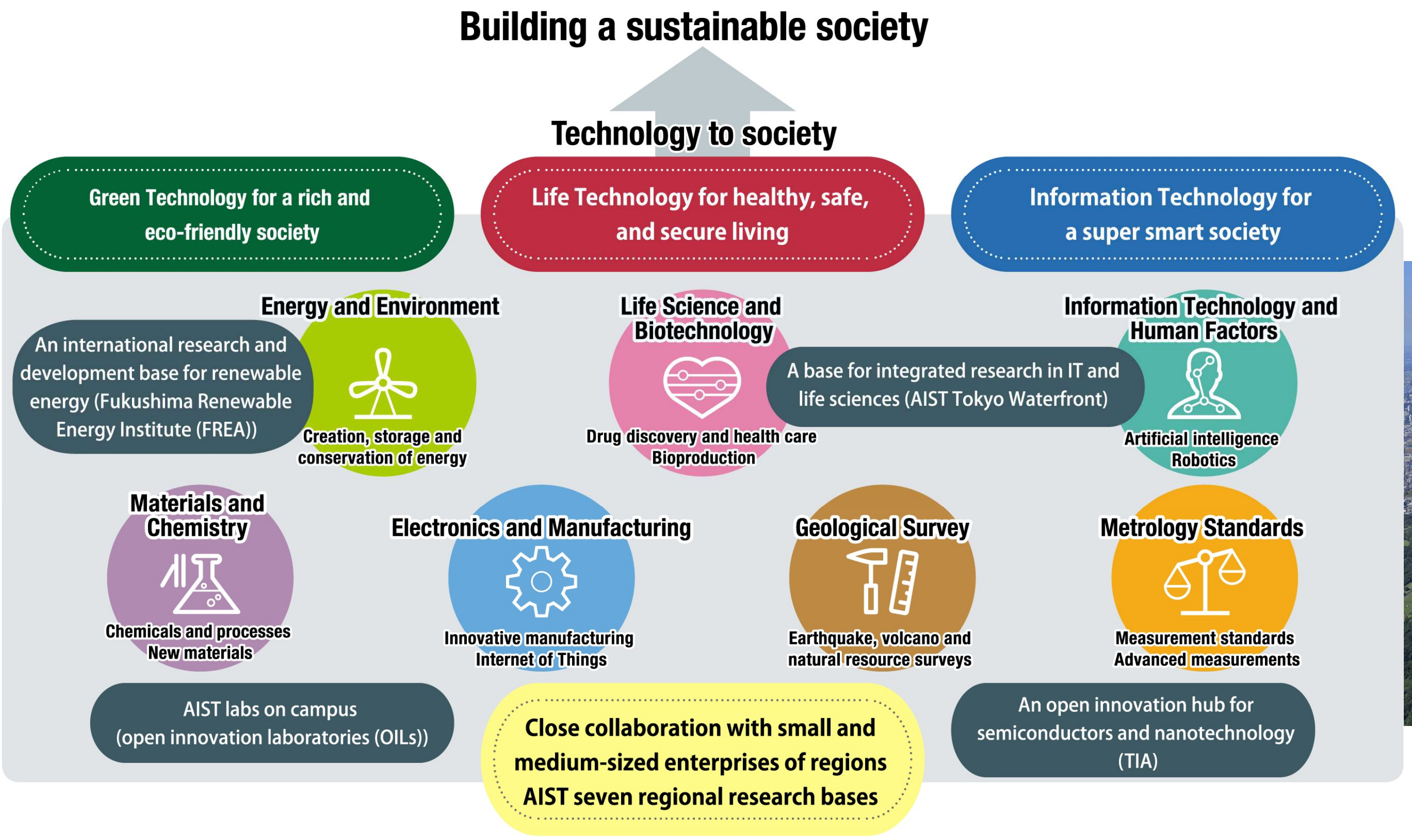
Introduction of AIST

NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

- Energy and Environment
- Life Science and Biotechnology
- Information Technology and Human Factors
- Materials and Chemistry
- Electronics and Manufacturing
- Geological Survey of Japan
- National Metrology Institute of Japan



Building a sustainable society

Technology to society

Green Technology for a rich and eco-friendly society

Life Technology for healthy, safe, and secure living

Information Technology for a super smart society

Energy and Environment
Creation, storage and conservation of energy

An international research and development base for renewable energy (Fukushima Renewable Energy Institute (FREA))

Life Science and Biotechnology
Drug discovery and health care
Bioproduction

A base for integrated research in IT and life sciences (AIST Tokyo Waterfront)

Information Technology and Human Factors
Artificial intelligence
Robotics

Materials and Chemistry
Chemicals and processes
New materials

Electronics and Manufacturing
Innovative manufacturing
Internet of Things

Geological Survey
Earthquake, volcano and natural resource surveys

Metrology Standards
Measurement standards
Advanced measurements

AIST labs on campus (open innovation laboratories (OILs))

Close collaboration with small and medium-sized enterprises of regions
AIST seven regional research bases

An open innovation hub for semiconductors and nanotechnology (TIA)

AIST Tsukuba Center

Employees and Budget of AIST

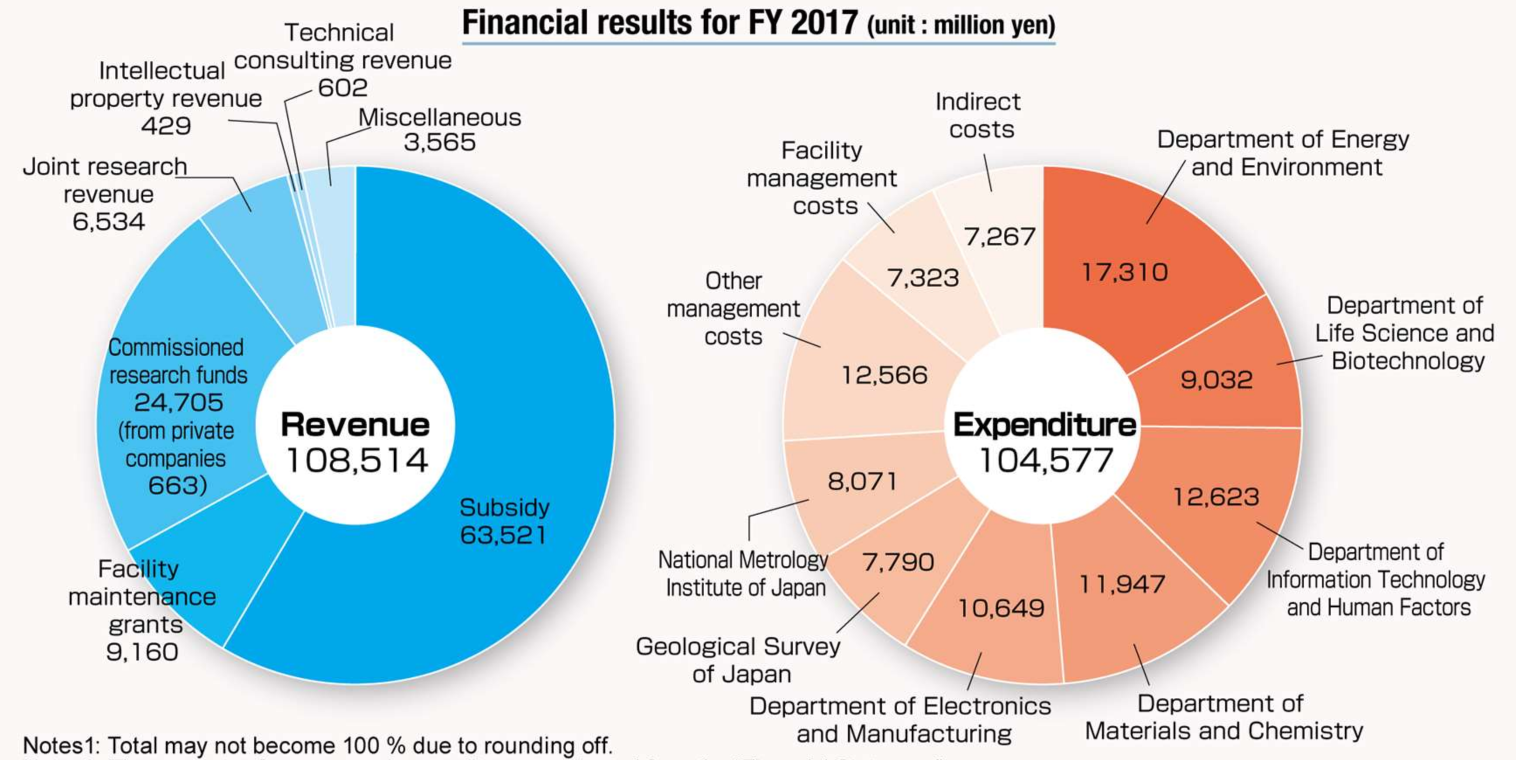
● Researchers (foreign nationals)	2,331(139)
Permanent	1,982
Fixed term	349
● Administrative employees	699
Total number of employees :	3,030
● Executives (full time)	13
● Visiting researchers	233
● Postdoctoral researchers	243
● Technical staff	1,549

(As of July 1, 2018)

Number of researchers accepted through industry/academia/government partnerships

● Companies	1,867
● Universities	2,446
● Public organizations	1,043

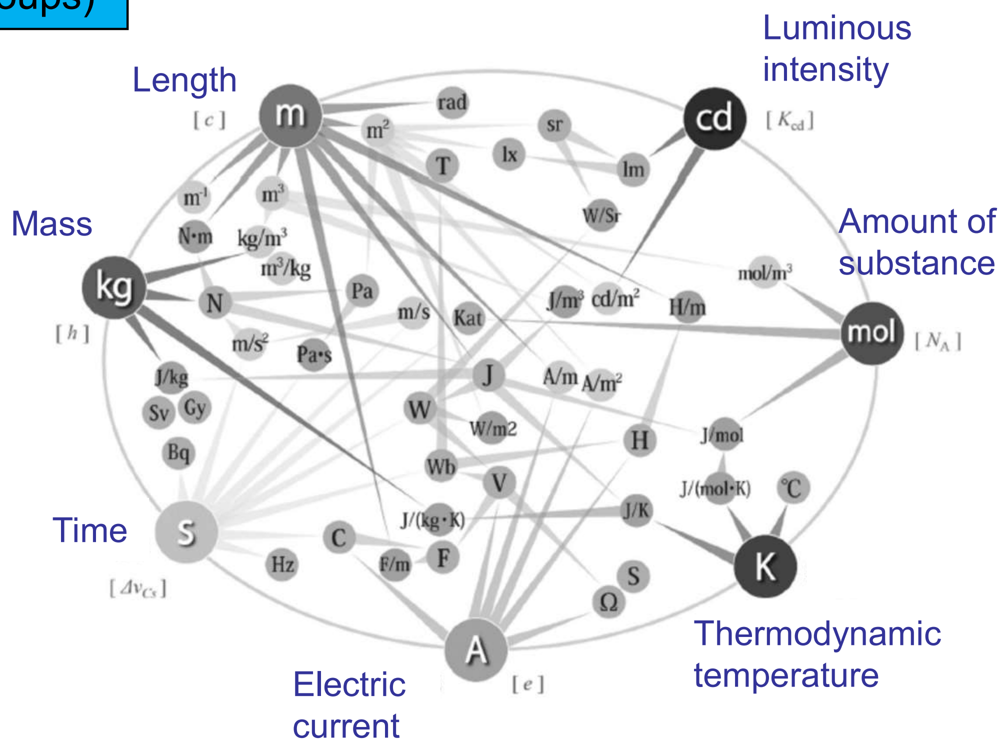
(foreign nationals : 530)
(Total number of researchers accepted in FY 2017)


Financial results for FY 2017 (unit : million yen)

Notes1: Total may not become 100 % due to rounding off.
Notes2: The amounts of revenue and expenditure are adapted from the “Financial Statement” prescribed in Article 38 of the Act on General Rules for Incorporated Administrative Agencies.

What is NMIJ?

- Research Institute of Engineering Measurement (14 Groups)
  - Liquid flow standard group
    Group leader: Furuichi, Researcher 3, Technician 4, Assistant 2
  - Gas flow standard group
    Group leader: Morioka, Researcher 4, Technician 2, Assistant 1
  - Legal metrology group
  - Length, Mass, Torque, Fluid property, Pressure etc.
- Physical Measurement (10 Groups)
  - Time, Temperature, Frequency, Electric power etc.
- Material Measurement (12 Groups)
- Analysis Measurement (8 Groups)



NMIJ is composed of four Research Institutes (Engineering Measurement, Physical Measurement, Material and Chemical Measurement and Analytical Instrumentation Measurement), Center for Quality Management of Metrology and Research Promotion Division of NMIJ. The dissemination of measurement standards, in which a rapid progress has been expected as an infrastructure in industries, is NMIJ's indispensable mission along with research development of measurement technologies. As for activities specifically related to measurement standards, four research institutes in charge of supplying measurement standards, Center for Quality Management of Metrology for processing administrative tasks and Research Promotion Division of NMIJ responsible for planning and coordination, work together and conduct a wide variety of related activities both domestically and internationally to facilitate the dissemination, maintenance and supply of measurement standards.

■ Main works in liquid flow standard group

☐ Liquid flow standard

- Fluids; Water, Kerosene, Light oil, Heavy oil, Gasoline
- Supply national standard of liquid flowrate
- Supply reference value for JCSS accredited companies
- Development of new flow facility


Water flow facility

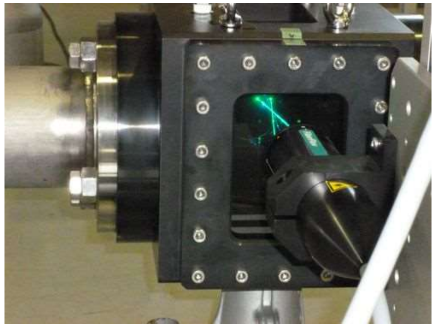
☐ Development/Standardization of flowmeters

- Research work for Coriolis, Ultrasonic flowmeter
- Flowmeter evaluation as collaborative work with private company
- Development of transfusion system in medical field
- Development of ISO of throat-tapped flow nozzle

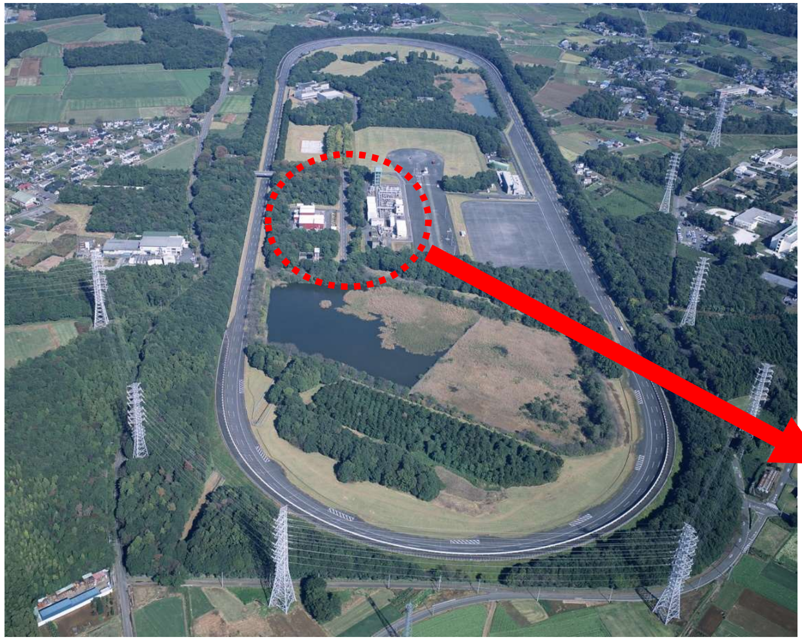

Hydrocarbon flow facility

☐ Fundamental research work using standard facility

- Universal structure of turbulent pipe flow
- Research work of pipe friction factor
- Experimental research work of pulsation flow

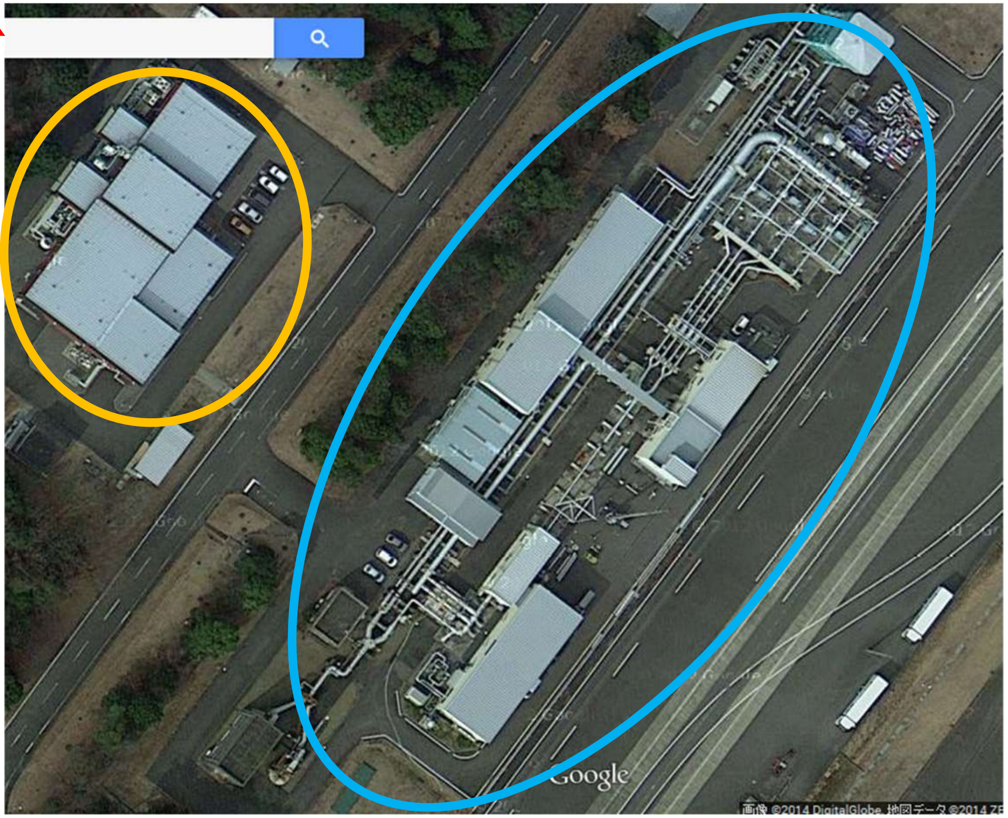

Measurement of pipe flow

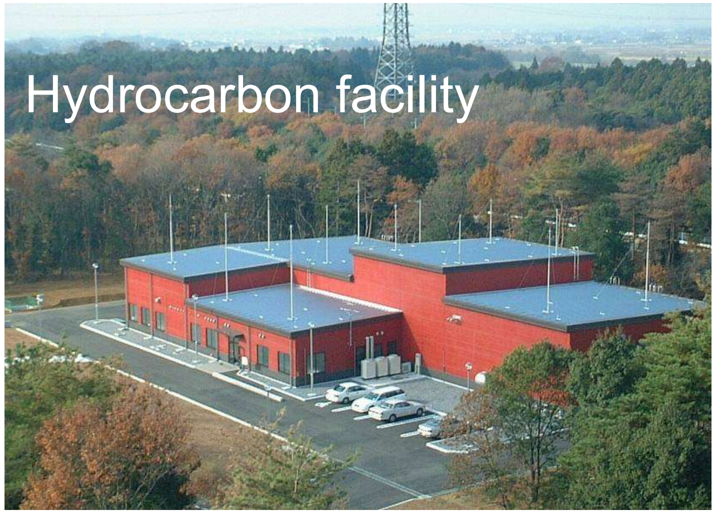
Location and pictures



AIST, Tsukuba North Site


Water flow facility




Hydrocarbon facility

■ Overview of water flow facility

High Reynolds number facility

High Reynolds number facility
Comparison method
BMC 0.08%
750~12000m³/h
20~70°C
400A~600A

50t system
Weighing tank method
BMC 0.06%
30~3000m³/h
15A~400A

Prover system
BMC 0.08%
100~800m³/h
20~70°C
100A~200A

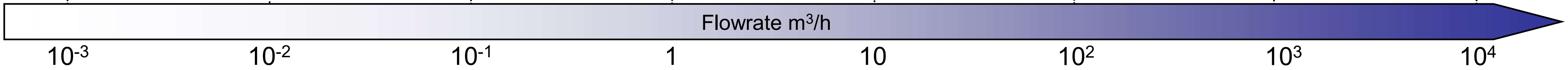
5t system
Weighing tank method
BMC 0.04%
5~300m³/h
15A~400A

500kg system
Weighing tank method
BMC 0.04%
0.3~30m³/h
15A~400A

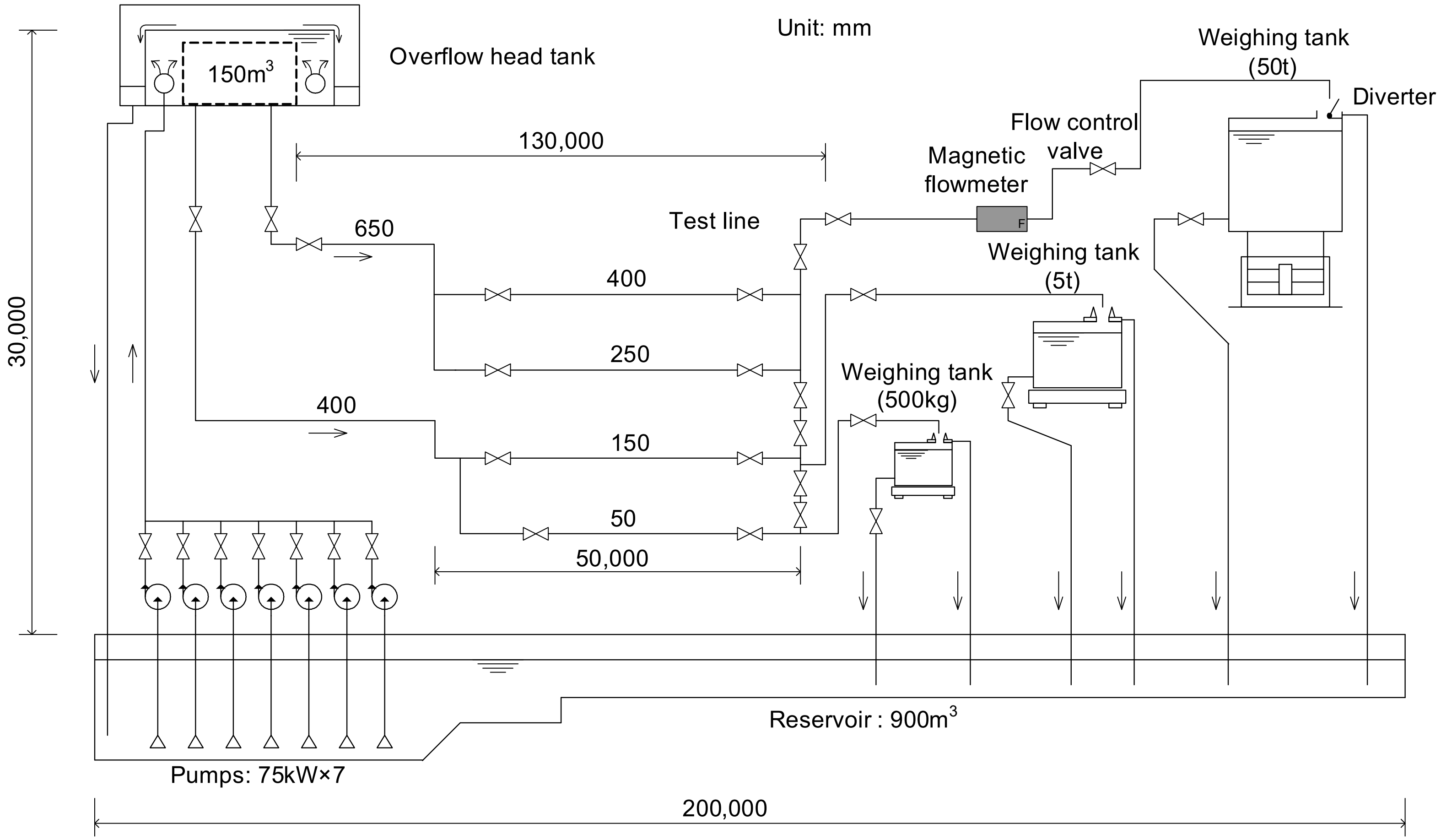
10kg system
Weighing tank method
BMC 0.04%
0.002~1.2m³/h
~25A

5t, 500kg weighing system

Prover system

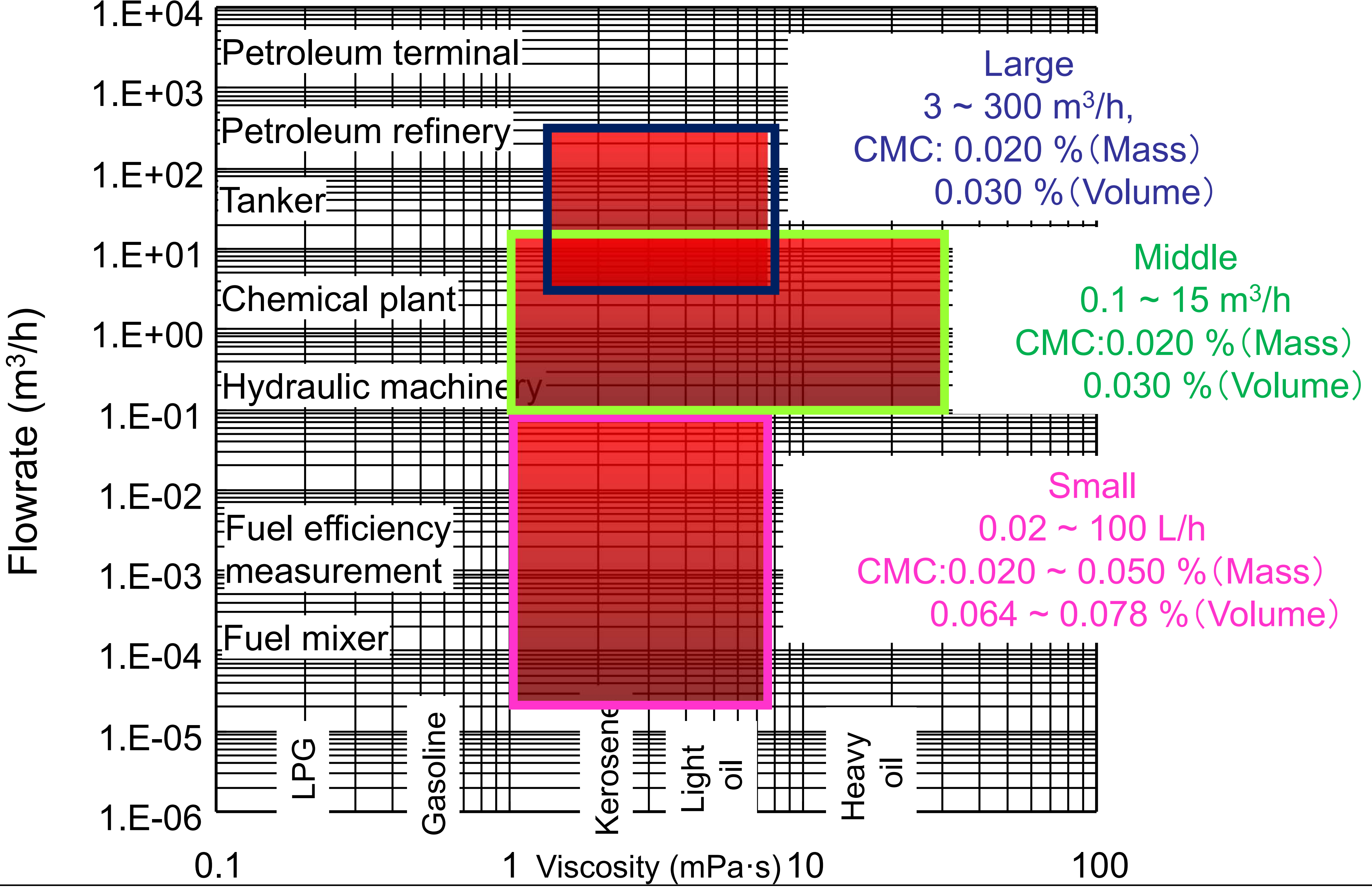


Main facility for water flow



- Flowrate : 0.3 m^3/h – 3000 m^3/h
- Temperature : ambient, ±1 °C/day
- Reference of flow rate : Static gravimetric method using weighing tank
- Uncertainty of flow rate measurement: 0.04% ~ 0.06%

■ Flowrate and viscosity range of hydrocarbon flow facility

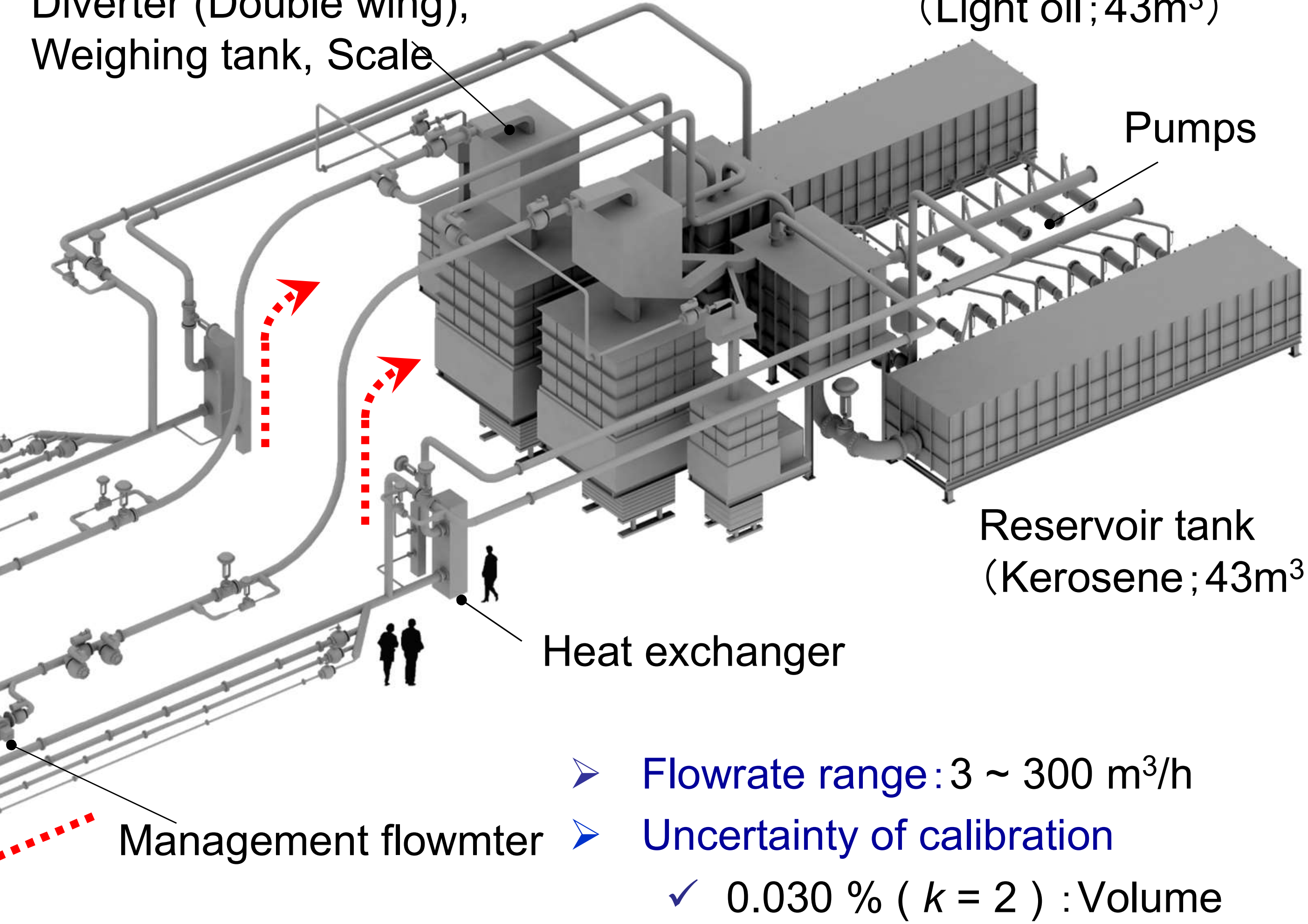


Large
3 ~ 300 m^3/h,
CMC: 0.020 %（Mass）
0.030 %（Volume）

Middle
0.1 ~ 15 m^3/h
CMC:0.020 %（Mass）
0.030 %（Volume）

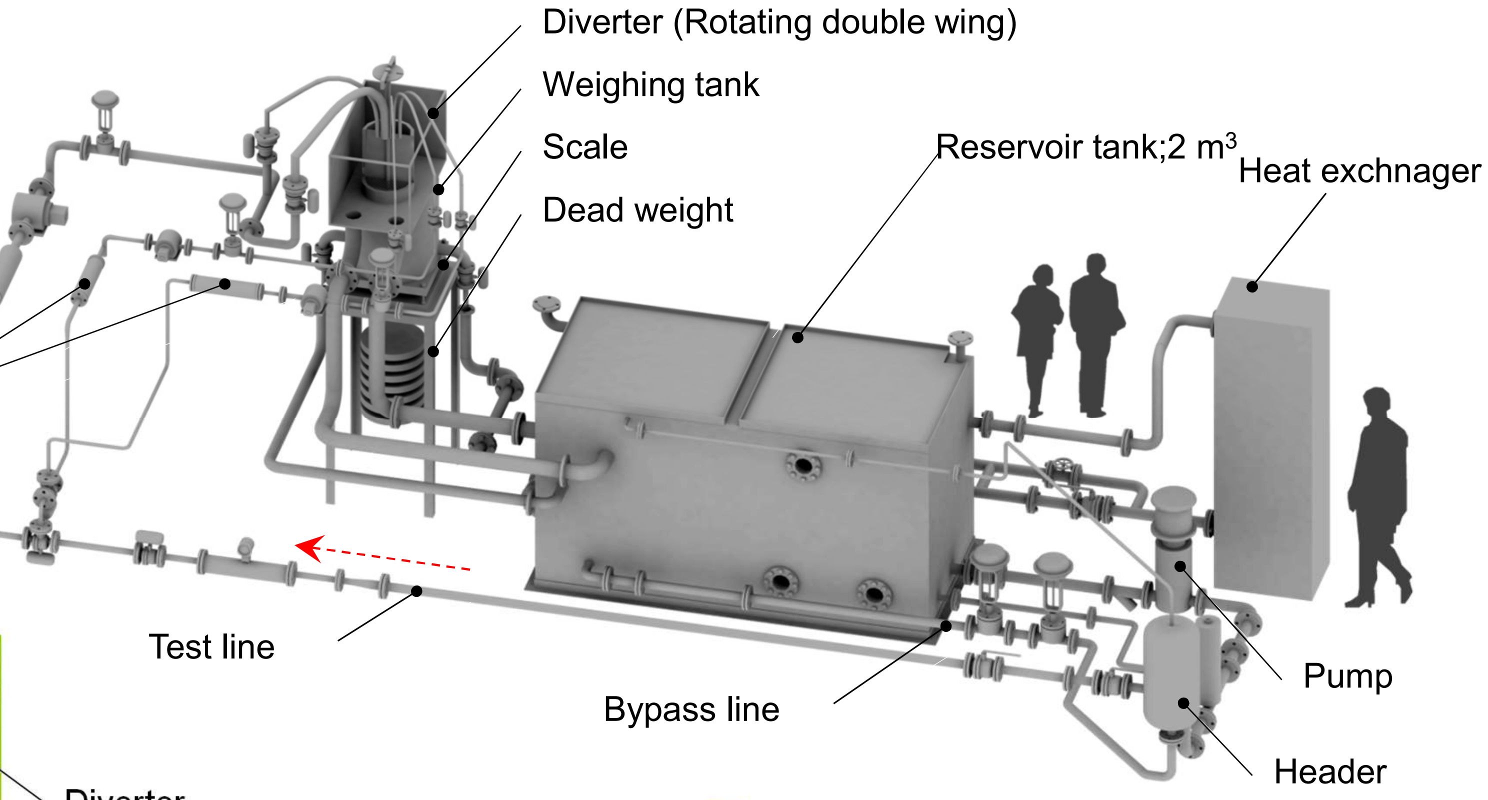
Small
0.02 ~ 100 L/h
CMC:0.020 ~ 0.050 %（Mass）
0.064 ~ 0.078 %（Volume）

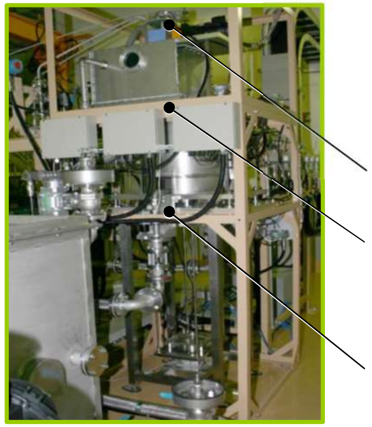
■ Large flowrate facility



- ➢ Flowrate range：3 ~ 300 m^3/h
- ➢ Uncertainty of calibration
  - ✓ 0.030 % (*k* = 2) ：Volume
  - ✓ 0.020 % (*k* = 2) ：Mass
- ➢ Liquids ：Kerosene, Light oil

Middle flowrate facility

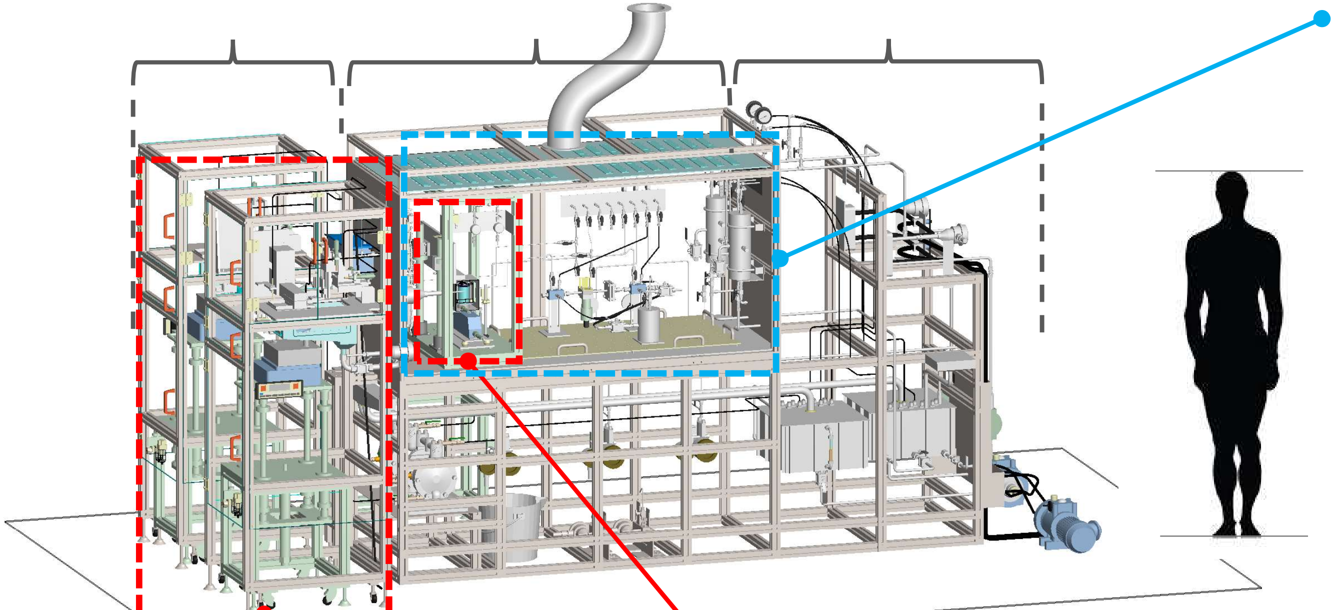




Weighing tank system

- Flowrate range: 0.1 ~ 15 m^3/h
- Uncertainty of calibration
  - 0.030 % (k = 2) : Volume
  - 0.020 % (k = 2) : Mass
- Liquids : Gasoline, Kerosene, Light oil, Heavy oil

Small flowrate facility



Weighing tank

Testing area

Reservoir tank, Pump

Isothermal Chamber
（15℃~35℃）

2kg weighing system
(1 ~ 100 L/h)

100g weighing system
(0.02 ~ 1 L/h)

- Flowrate range : 0.02 ~ 100 L/h
- Uncertainty of calibration
  - ✓ 0.064 ~ 0.078 % ($k = 2$) : Volume
  - ✓ 0.020 ~ 0.050 % ($k = 2$) : Mass
- Liquids : Gasoline, Kerosene, Light oil

■ National standard of liquid flowrate (as summary)

Water flow

	Reference standard	Flowrate range	Uncertainty
Small	10 kg weighing tank	0.002 m^3/h ～ 1.2 m^3/h	0.039 %
Middle, Large	500 kg, 5 t and 50 t weighing tank	0.3 m^3/h ～ 3 000 m^3/h	0.042 % ～ 0.060 %
High Reynolds number	Prover, Reference meter	750 m^3/h ～ 12 000 m^3/h ～ 70 °C	0.081 %

Hydrocarbon flow

	Reference standard	Flowrate ran	Uncertainty
Small	Weighing tank	0.000 02 m^3/h ～ 0.1 m^3/h	0.02%~0.05% (Mass)
Middle	Weighing tank	0.1 m^3/h ～ 15 m^3/h	0.02 % (Mass) 0.03%(Volume)
Large	Weighing tank	3 m^3/h ～ 300 m^3/h	

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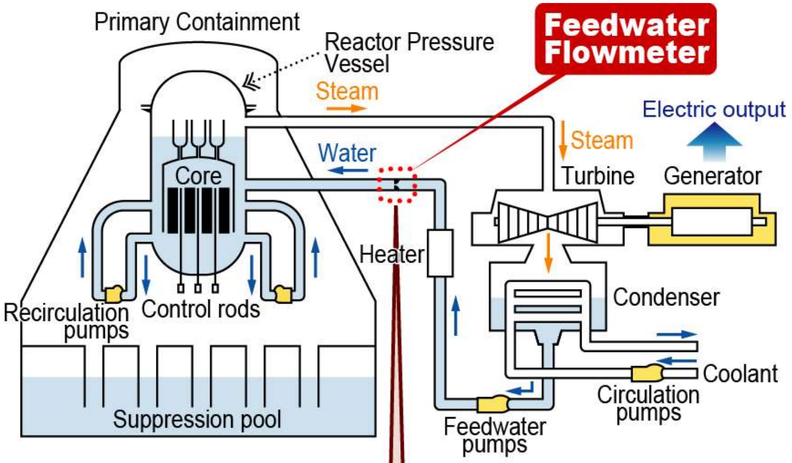
■ Background of development high Reynolds number facility

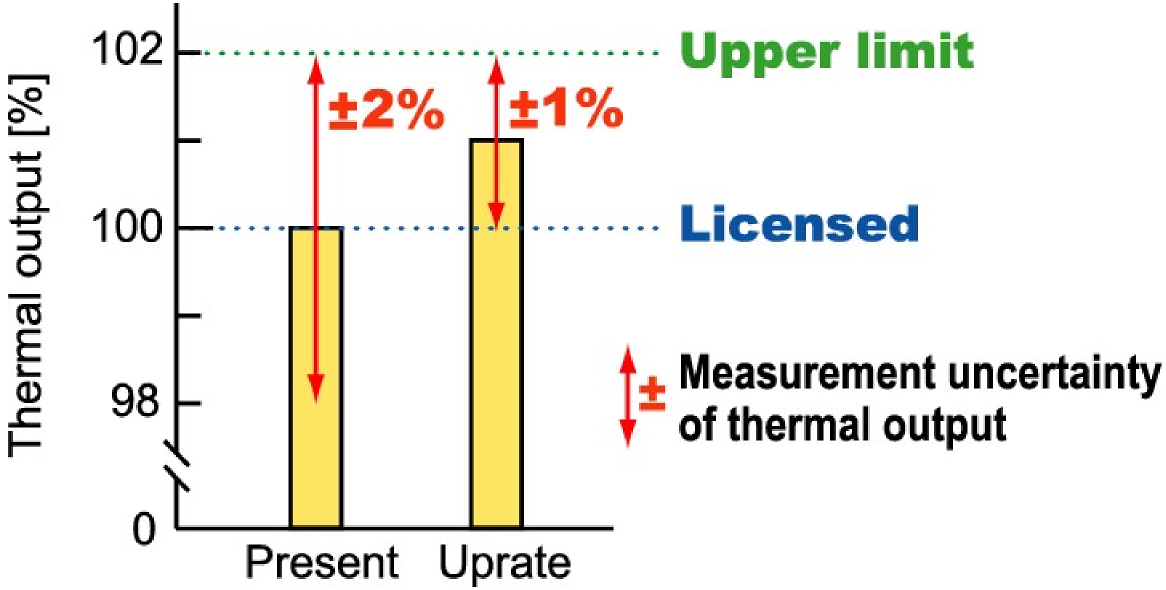
Uprating of nuclear power plant by MUR (Measurement Uncertainty Recapture)

- Thermal output of nuclear power plant is mainly managed by feedwater flowmeter.
- Uprating of thermal output is carried out by replacing feed water flow meter.
- Uprating of thermal out is possible without large modification of power plant and change of regulations.
- App. 1.4% uprating is possible.

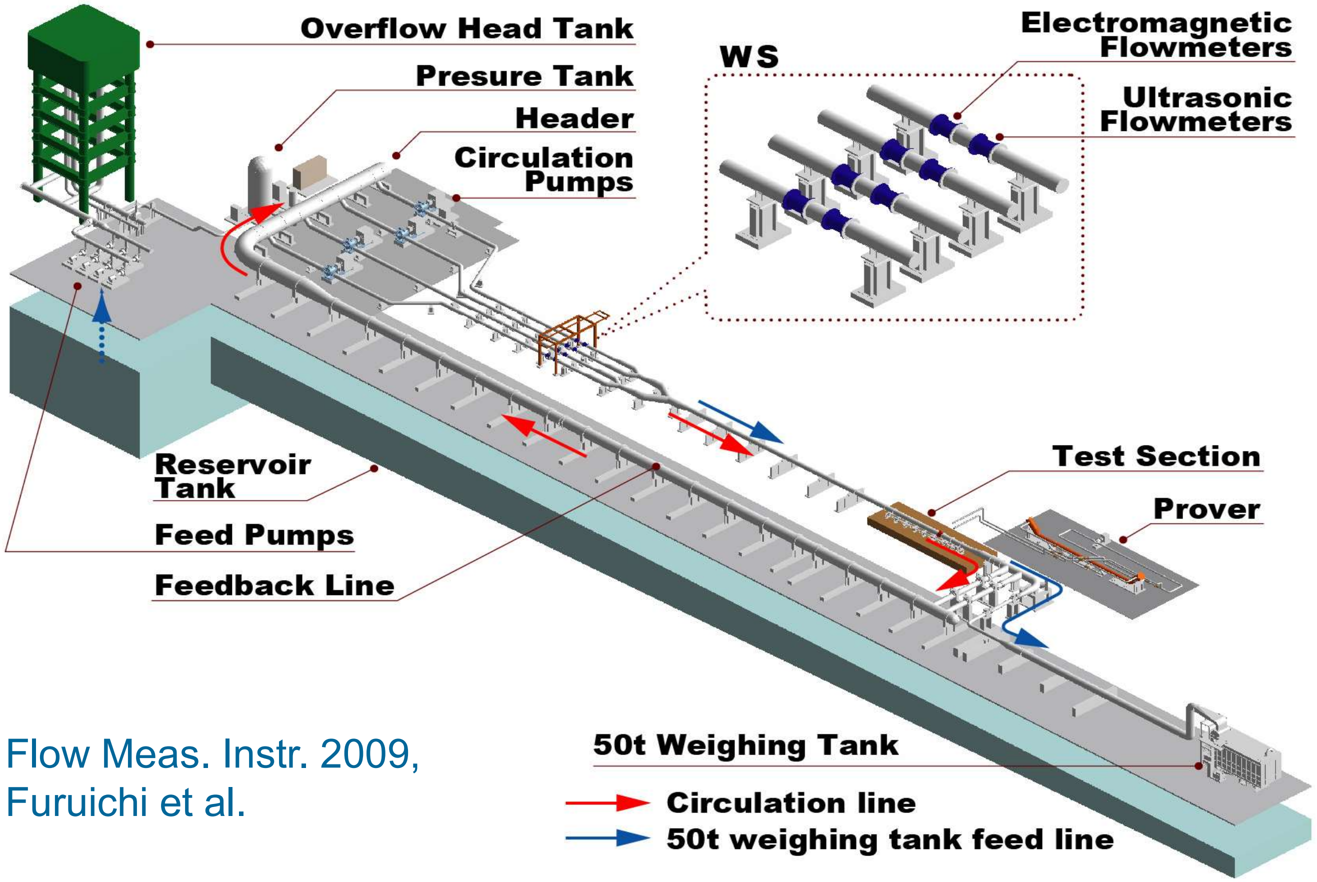


High Reynolds number @ feedwater pipe line

Temperature : 210℃
Pressure : 7MPa
Flow rate : 3000t/h
Pipe diameter : DN400~DN600
Reynolds number : upto 10^7



High Reynolds number facility



Flow Meas. Instr. 2009,
Furuichi et al.

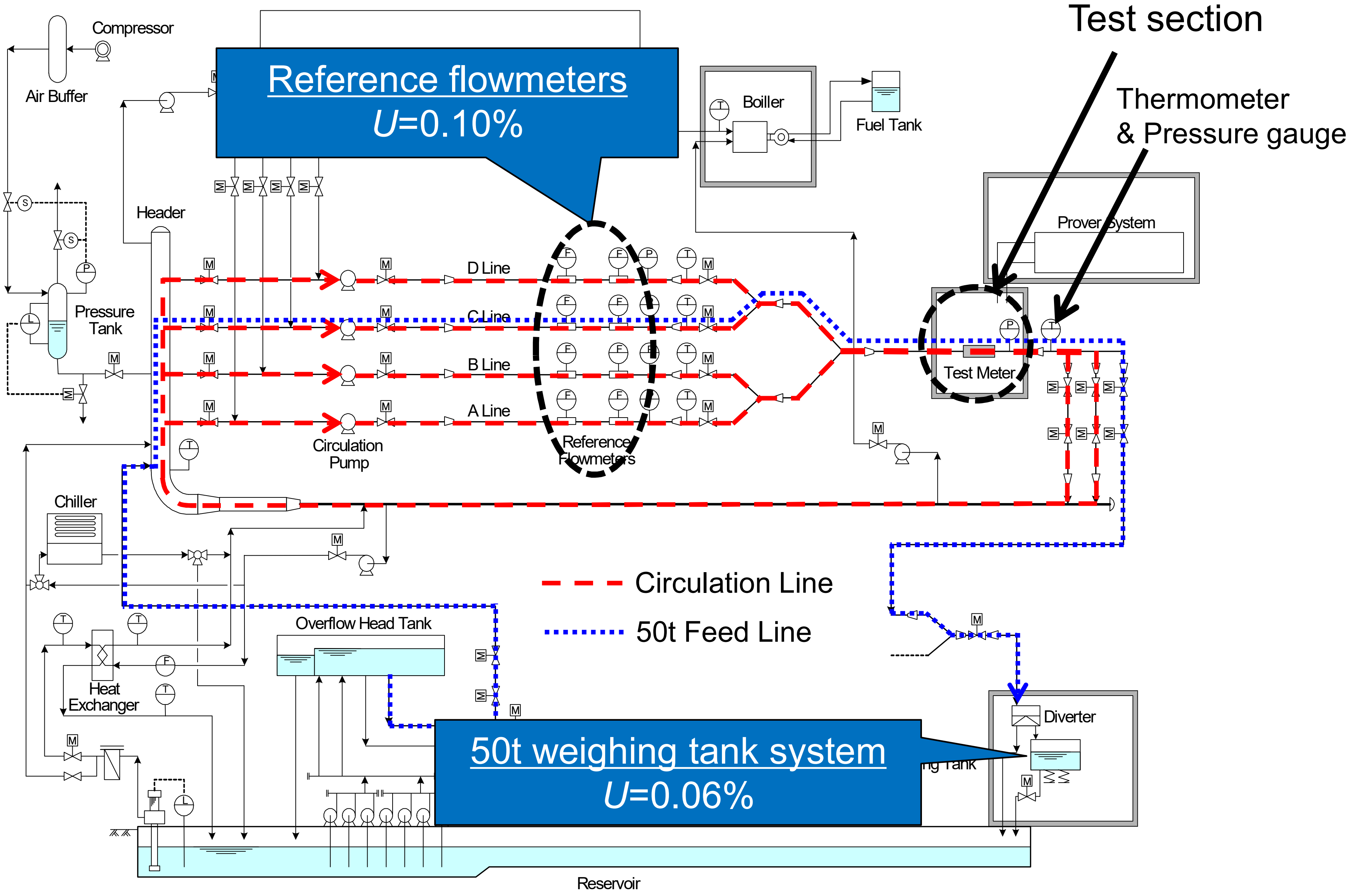
- Equivalent Reynolds number with feedwater of nuclear power plant.
- High accuracy of flow rate measurement
- New facility was constructed at 2004 – 2008.

HiReff
HIGH REYNOLDS NUMBER
ACTUAL FLOW FACILITY

Working fluid : Water
Large flowrate : 3.33 m^3/s (12000 m^3/h)
High temperature : 75 °C
Large pipe : DN600

⇨ $Re_D = 2 \times 10^7$

■ Schematic of Hi-Reff



Test section

Thermometer
& Pressure gauge

Reference flowmeters
U=0.10%

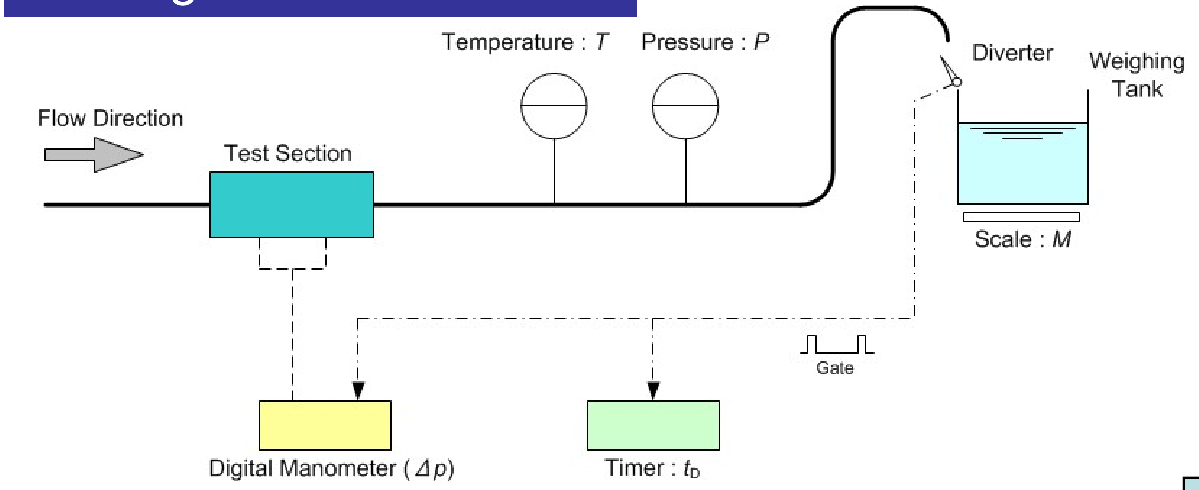
50t weighing tank system
U=0.06%

Circulation Line

50t Feed Line

Calibration method in Hi-Reff

Static gravimetric method

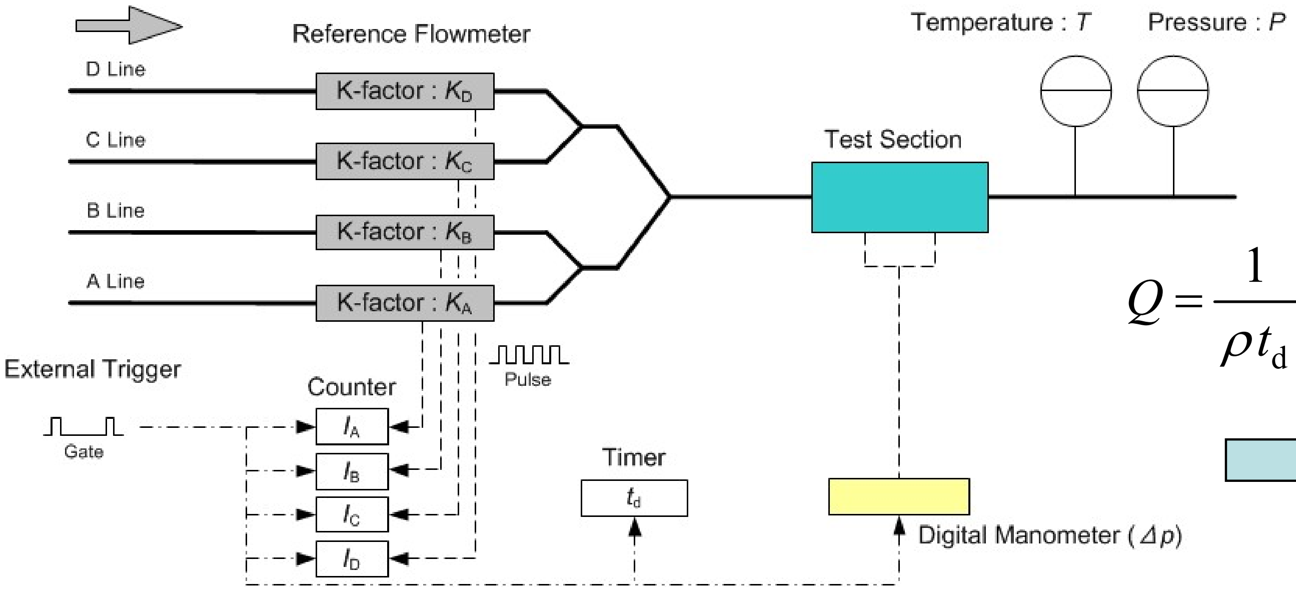


$$Q = \frac{M}{\left(1 - \rho_{\mathrm{air}} / \rho_{\mathrm{wT}}\right) t_{\mathrm{d}} \rho}$$

Q: Flowrate (m^3/s)
M: Weight (kg)
t_d: Duration time (s)
ρ: Density of water in test section (kg/m^3)
$1-\rho_\mathrm{air}/\rho_\mathrm{wT}$: Buoyancy correction

$U(Q)$=0.040%~0.060%

Reference flowmeter method

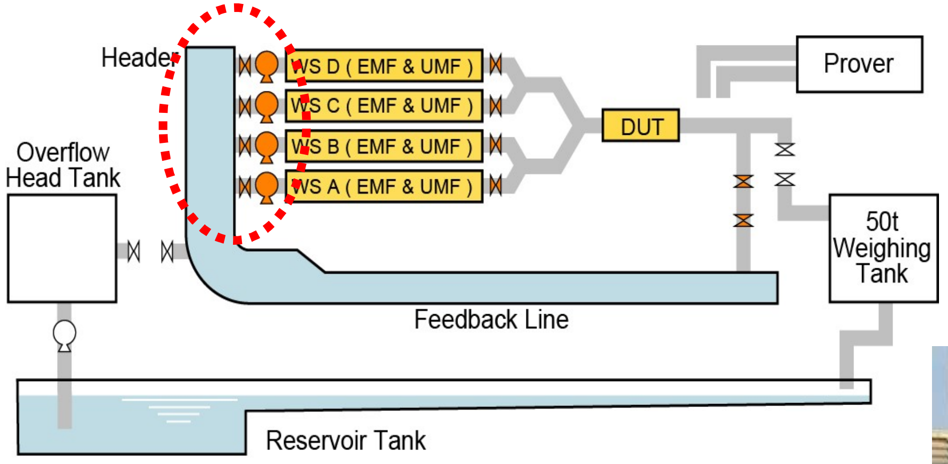


I: Number of pulse (-)
K: K-factor (pulse number/m^3)
Subscripts A-D correspond to lines

$$Q = \frac{1}{\rho t_\mathrm{d}} \left(\frac{\rho_\mathrm{A} I_\mathrm{A}}{K_\mathrm{A}} + \frac{\rho_\mathrm{B} I_\mathrm{B}}{K_\mathrm{B}} + \frac{\rho_\mathrm{C} I_\mathrm{C}}{K_\mathrm{C}} + \frac{\rho_\mathrm{D} I_\mathrm{D}}{K_\mathrm{A}} \right)$$

$U(Q)$=0.10%

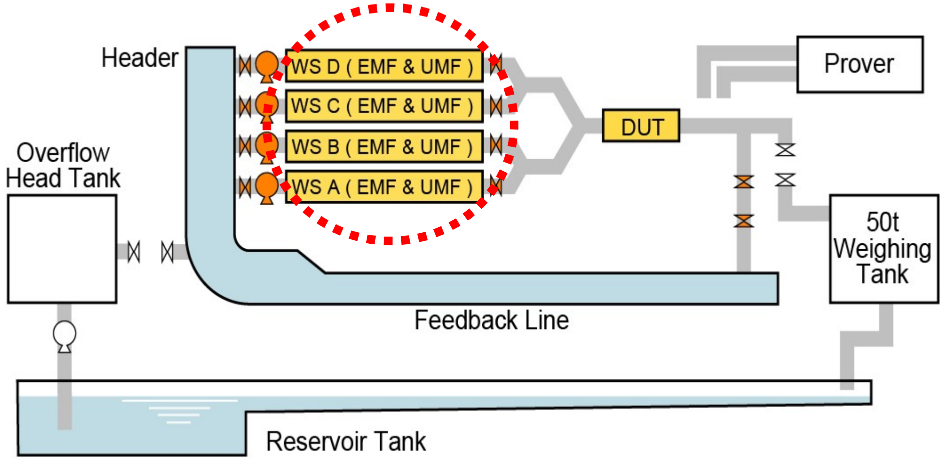
Overview of Hi-Reff



- Pumps
  Type : Double suction volute pump
  Power : 330kW x 4
  Flowrate : 3000m^3/h
  Rotating speed : 900rpm
- Pressure tank
- Heat exchanger
- Chiller

Feed Pumps

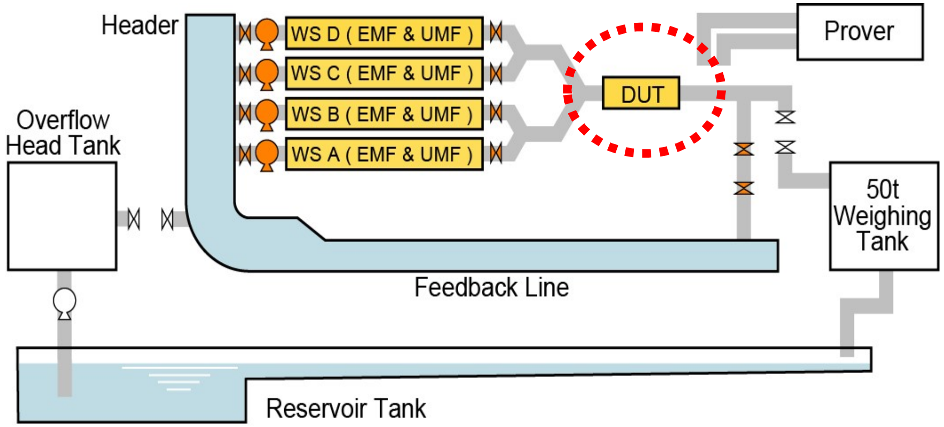
■ Overview of Hi-Reff



WS (Reference flowmeter)

- Electromagnetic flowmeter (Krohne OPTIFLUX)
- Ultrasonic flowmeter (Krohne ALTOSONIC-V)
  Repeatability : less than 0.02%
  Reproducibility : less than 0.04%

■ Overview of Hi-Reff



Testing Area

- Straight pipe length of upstream: over 50*D*
- Applicable pipe diameter: 200 – 600mm
- Condition at testing area
  Temperature : controllable 20~75°C
  Temperature stability : ±0.2°C during calibration
  Pressure : 0.3~0.7MPa depends on flowrate
  Pressure stability : ±0.01MPa
  Fully developed velocity profile
  Room temperature : 15~25°C

■ Summary of Hi-Reff

Hi-Reff
HIGH REYNOLDS NUMBER
ACTUAL FLOW FACILITY

Flowrate range	: ～12000 m^3/h
Maximum velocity	: app. 20 m/s (for DN400)
Water temperature	: 20 °C～75 °C
Pressure range	: 0.1MPa～0.4MPa
Bulk Reynold number	: $Re_D \approx 2.0\times10^7$
Friction Reynolds number	: $Re_\tau \approx 5.0\times10^5$
Straight pipe	: over 30 m (75*D* for DN400)
Pipe diameter	: DN200～DN600 available
Stability of temperature	: less than ±0.2 °C for 40 °C～75 °C
	: less than ±0.1 ° during 5 minutes
Stability of flowrate	: less than 0.4%～1.2%
Stability of pressure	: less than ±0.01 MPa
Accuracy of flowrate	: 0.06%～0.10%

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- Introduction of institute (AIST, NMIJ) and flow calibration facilities in liquid flow standard group
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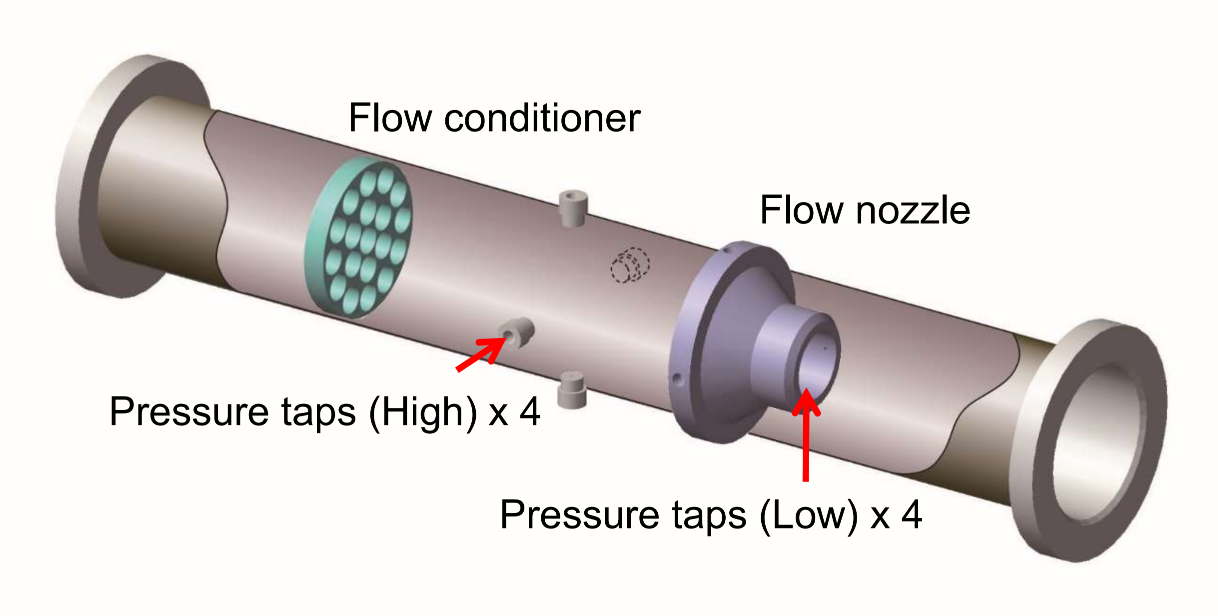
- Novel research works for high Reynolds number turbulent pipe flow

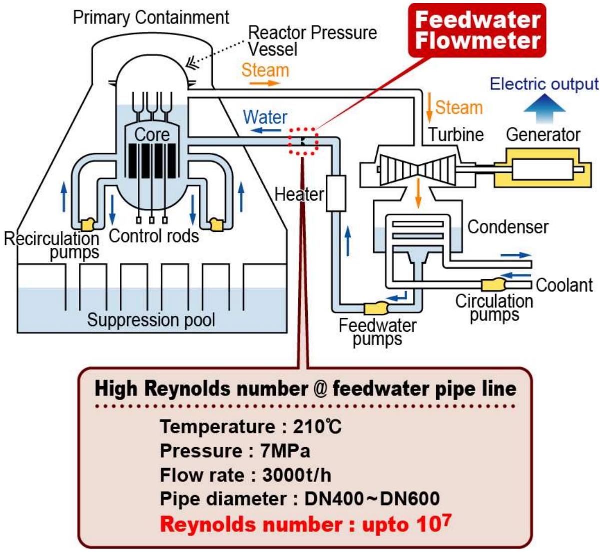
■ Throat-tapped flow nozzle (Differential pressure flow meter)



Throat-tapped flow nozzle is widely used in power plants
to evaluate a steam turbine
as a feed water flow meter in nuclear power plant.

Existing Standard

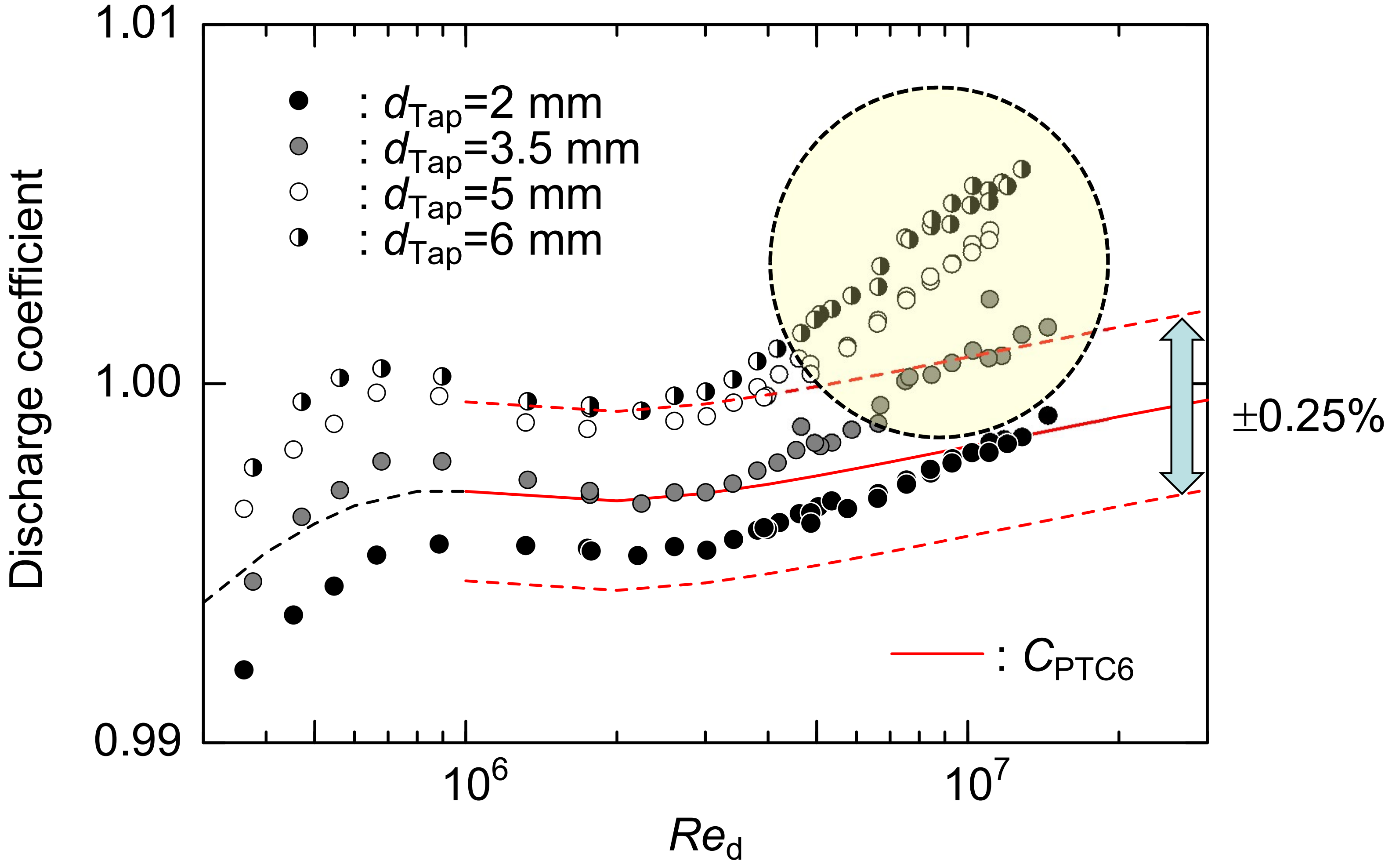
ASME PTC 19.5 – 2004, Flow Measurement
ASME PTC 6 – 2004, Steam Turbine



High Reynolds number @ feedwater pipe line

Temperature : 210℃
Pressure : 7MPa
Flow rate : 3000t/h
Pipe diameter : DN400~DN600
Reynolds number : upto 10^7

Difference between PTC equation and actual data



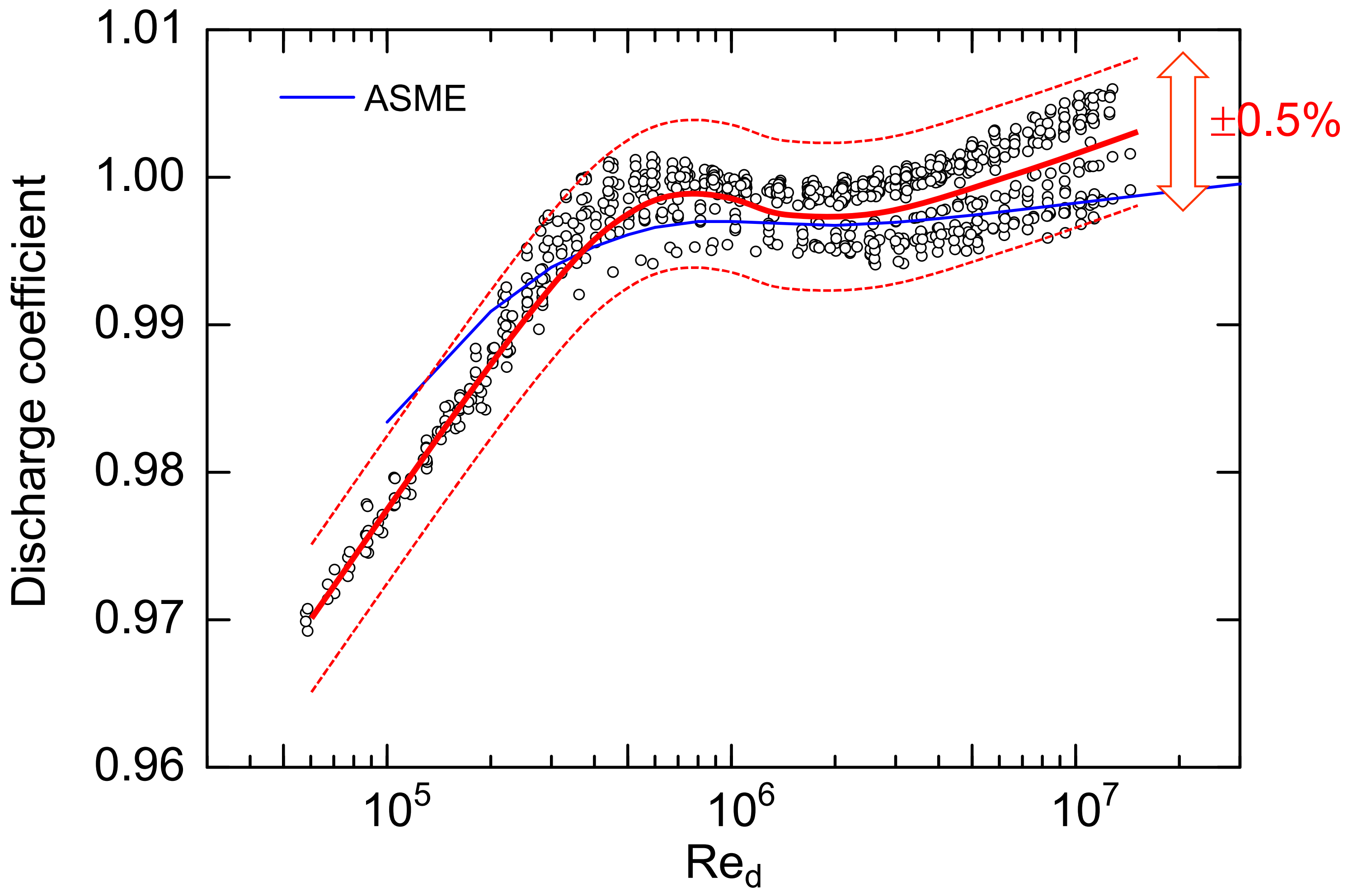
- Tap diameter defined in PTC 6 ; d_{Tap}=1/8"~1/4" (3.175 mm~6.35 mm)

■ Previous research works in NMIJ (2013-2017)

- ☐ Discharge coefficient behavior at high Reynolds number
- ☐ Influence of the diameter of pressure tap and upstream tap
- ☐ Static pressure measurement error using wall tap
- ☐ Individuality of the nozzle
- ☐ Influence of roughness
- ☐ Influence of flow conditioner
- ☐ 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.

■ All experimental data in NMIJ



New proposed equation

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

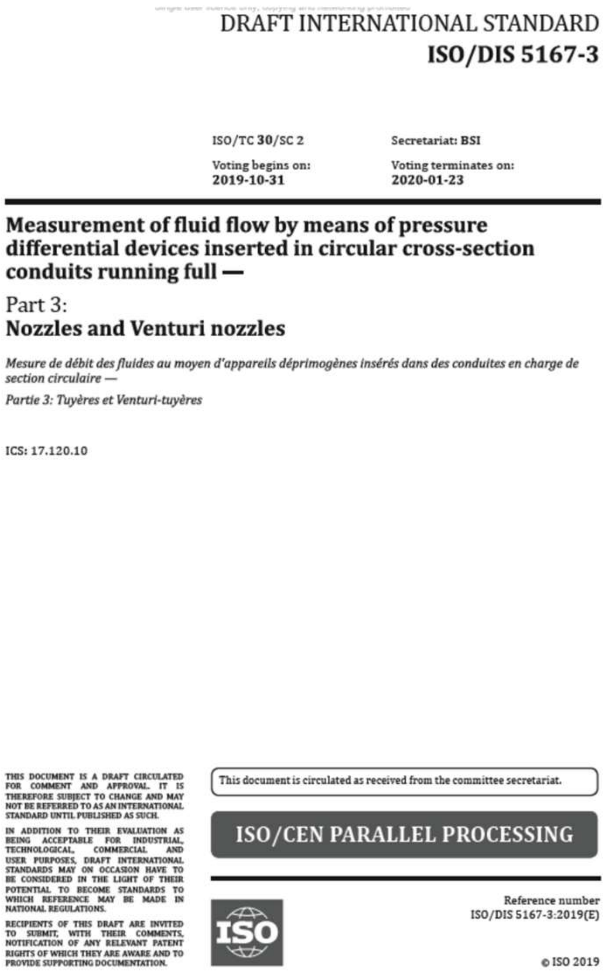
C_f : Discharge coefficient
Cn : Theoretical discharge coefficient
e_Tap : Static pressure error

d : Diameter of throat
d_Tap : Diameter of wall tap
Re_d : Reynolds number

	Equation	Reynolds number range
(i)	$C_\mathrm{F} = 1.0042 - \dfrac{8.41}{{Re_\mathrm{d}}^{0.5}}$	$Re_\mathrm{d} < 1.3\times10^5$
(ii)	$C_\mathrm{F} = 0.9558 - \dfrac{8.41}{{Re_\mathrm{d}}^{0.5}} + 0.00492\ln(Re_\mathrm{d})$	$1.3\times10^5 < Re_\mathrm{d} < 4.0\times10^5$
(iii)	$C_\mathrm{F} = 1.0090 - \dfrac{8.41}{{Re_\mathrm{d}}^{0.5}}$	$4.0\times10^5 < Re_\mathrm{d} < 8.0\times10^5$
(iv)	$C_\mathrm{F} = 1.0090 - \dfrac{0.255}{{Re_\mathrm{d}}^{0.2}}\left(1 - \dfrac{400000}{Re_\mathrm{d}}\right)^{0.8}$	$8.0\times10^5 < Re_\mathrm{d} < 3.0\times10^6$
(v)	$C_\mathrm{F} = 0.9823 - \dfrac{0.255}{{Re_\mathrm{d}}^{0.2}}\left(1 - \dfrac{400000}{Re_\mathrm{d}}\right)^{0.8} + 0.0018\ln(Re_\mathrm{d})$	$3.0\times10^6 < Re_\mathrm{d}$

Summary for throat-tapped flow nozzle

- The revise of ISO 5167-3 has been done including the new term for throat-tapped flow nozzle（ISO/TC30/SC2/WG18；Convenor: Furuichi）
- The project has been started since June, 2018. The revise version of ISO 5167-3 has been approved by DIS ballot.
- Final version will be finished and the revise will be published during 2020 year.



DRAFT INTERNATIONAL STANDARD
ISO/DIS 5167-3

ISO/TC **30**/SC 2
Secretariat: BSI

Voting begins on:
2019-10-31

Voting terminates on:
2020-01-23

Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full —

Part 3:
Nozzles and Venturi nozzles

Mesure de débit des fluides au moyen d'appareils déprimogènes insérés dans des conduites en charge de section circulaire —

Partie 3: Tuyères et Venturi-tuyères

ICS: 17.120.10

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ISO/CEN PARALLEL PROCESSING

Reference number
ISO/DIS 5167-3:2019(E)

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Today's Contents

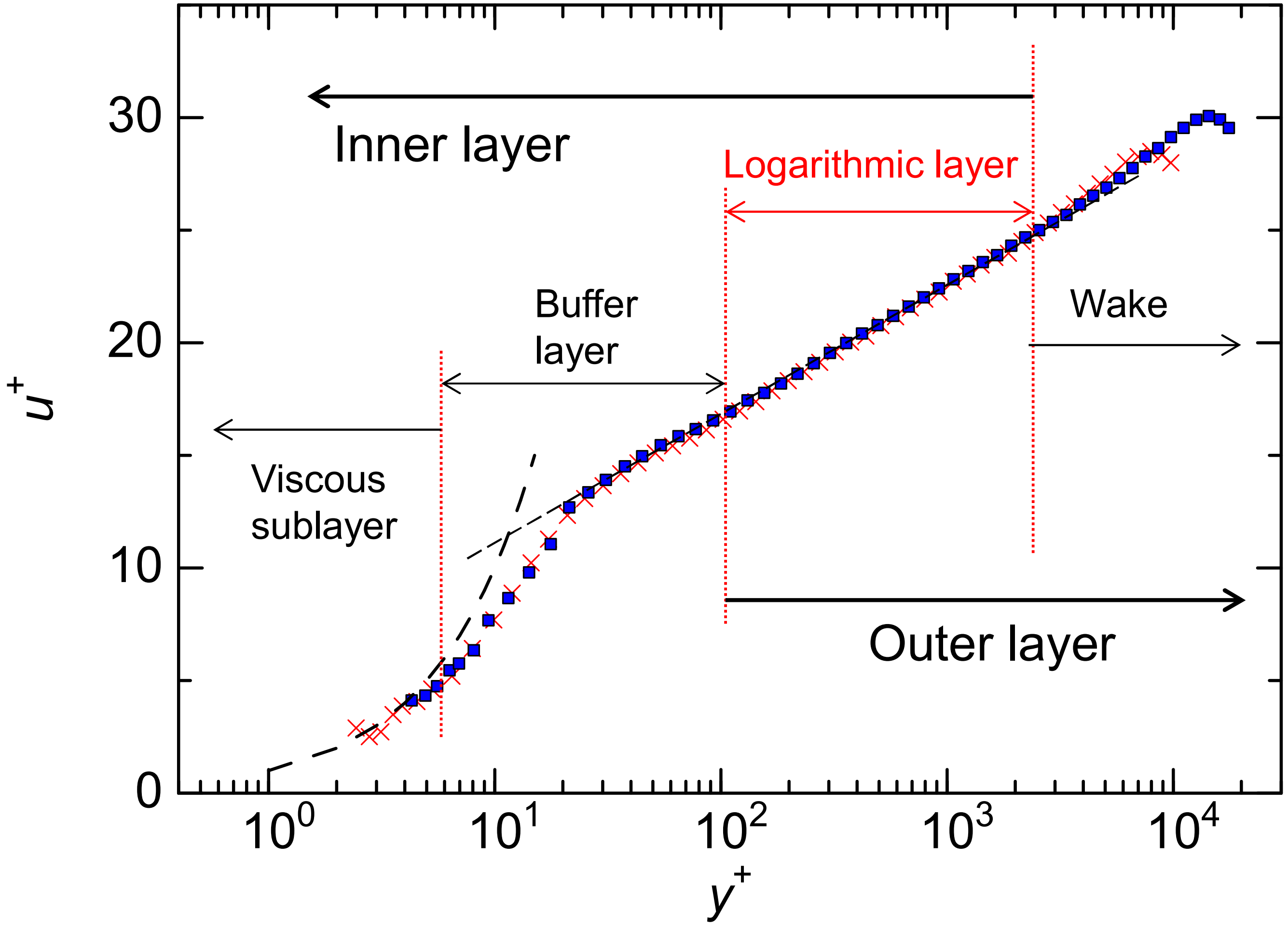
- Introduction of institute (AIST, NMIJ) and flow calibration facilities in liquid flow standard group
- High Reynolds number facility
- Examination for throat-tapped flow nozzle
- Novel research works for high Reynolds number turbulent pipe flow

■ Introduction for issues of wall-bounded flow

Mean velocity profile for wall-bounded flow

$$u^+ = \frac{1}{\boxed{\kappa}} \ln y^+ + B$$

κ: Karman constant
B: Additive constant



- ✓ Is Karman constant universal?
- ✓ If it is universal, which value is correct?

■ High Reynolds number facilities for pipe flow

SuperPipe (Princeton Univ.)

- Working fluid ：Air
- Pressure：24 MPa
- Pipe diameter：0.13 m
- Upstream straight pipe length：200*D*
- Maximum Reynolds number：3.8×10^7

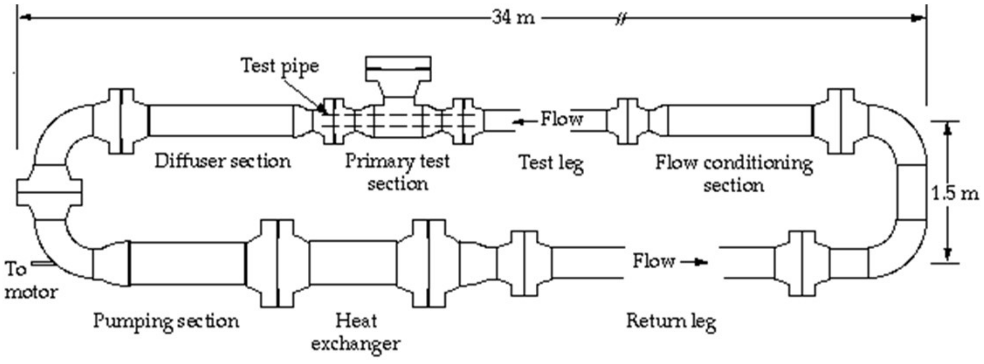
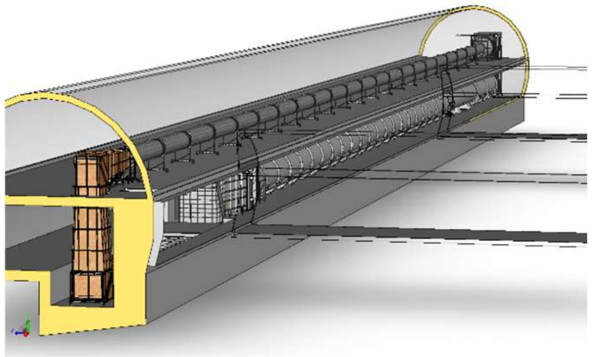


Figure 1: Diagram of the experimental facility.

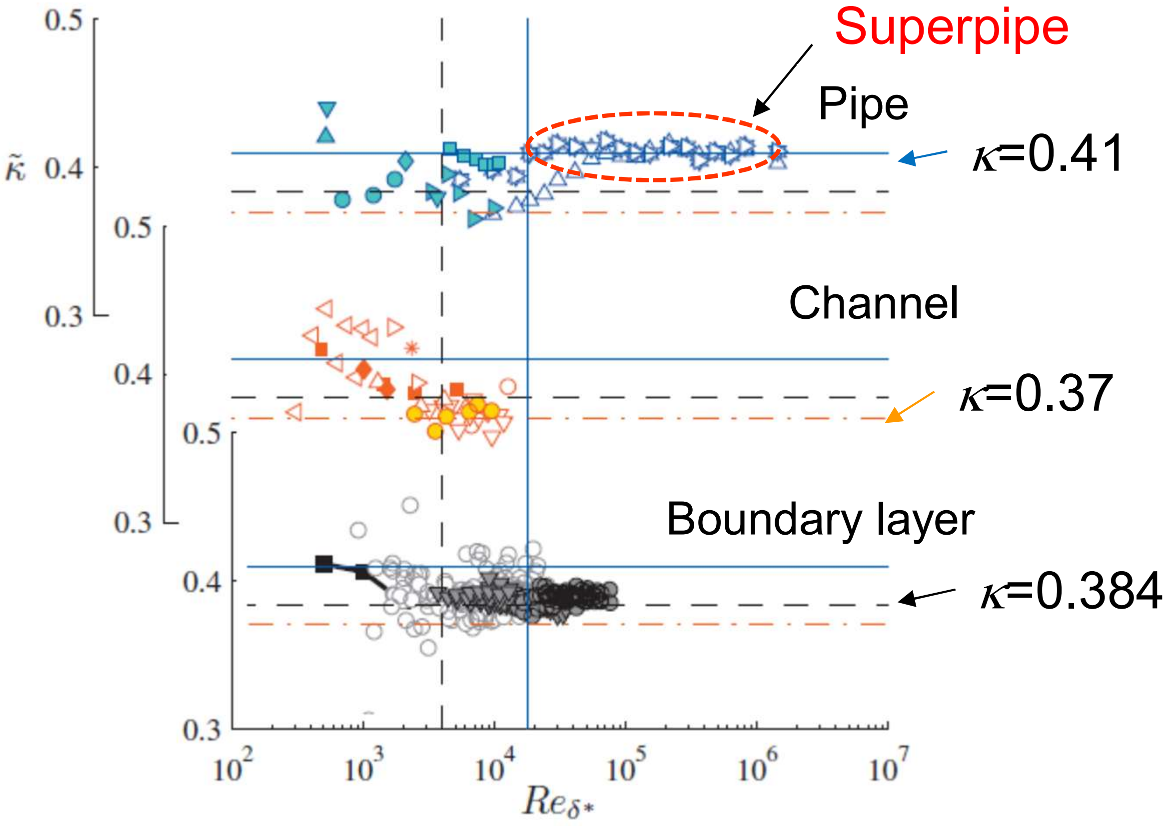
CICLoPE (Bologna Univ.)

- Working fluid：Air
- Pipe diameter : 0.9 m
- Upstream pipe ：124*D*
- Maximum Reynolds number：$<10^6$



Introduction for issues of wall-bounded flow

Kármán constant in wall-bounded turbulence

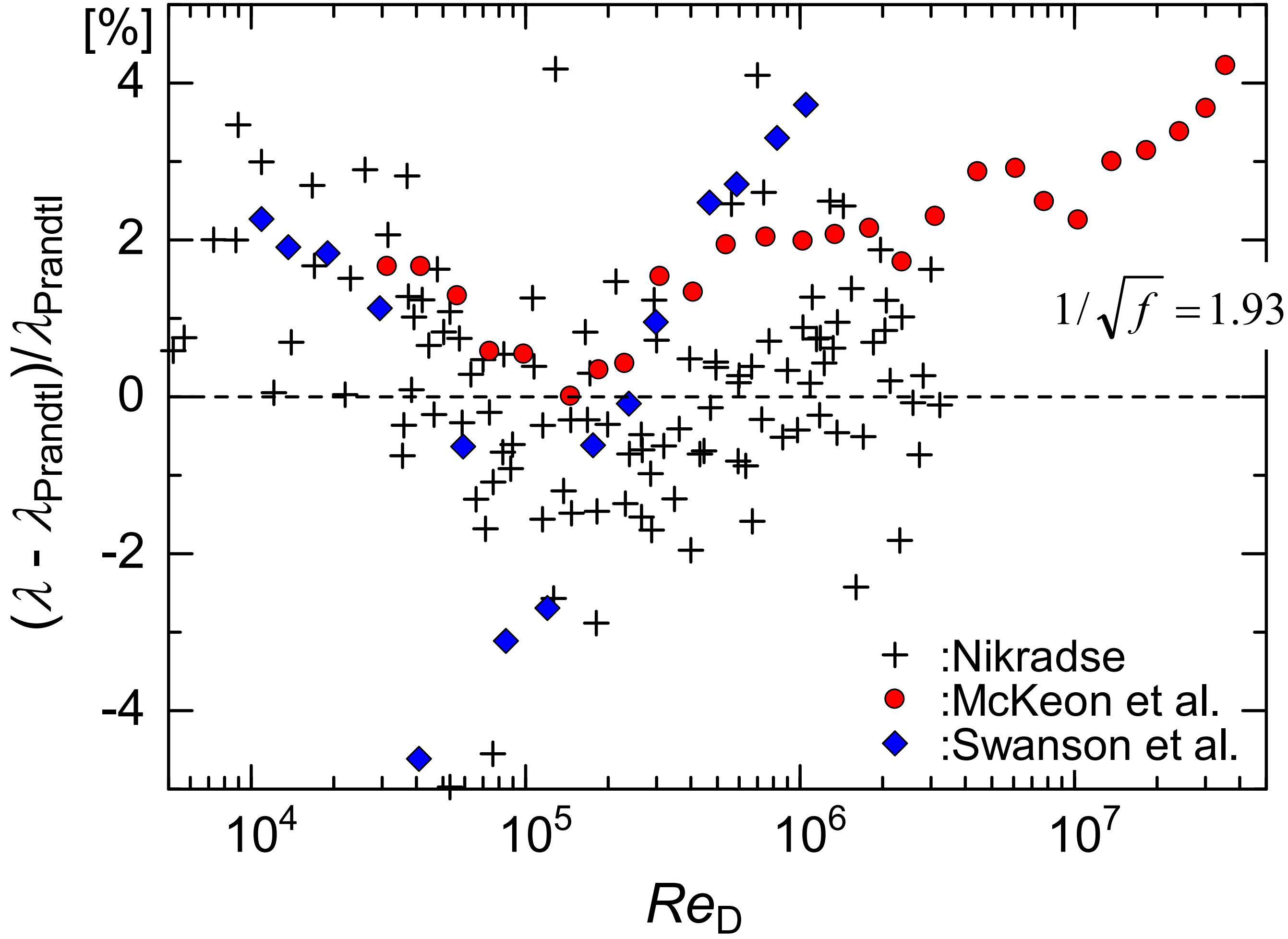


Nagib et al., 2008

- Reynolds number dependency
- Difference with other wall bounded turbulence

■ Introduction for issues of wall-bounded flow

Friction factor relative to Prandtl equation



$$1/\sqrt{f} = 1.930\log\left(Re\sqrt{f}\right) - 0.537$$

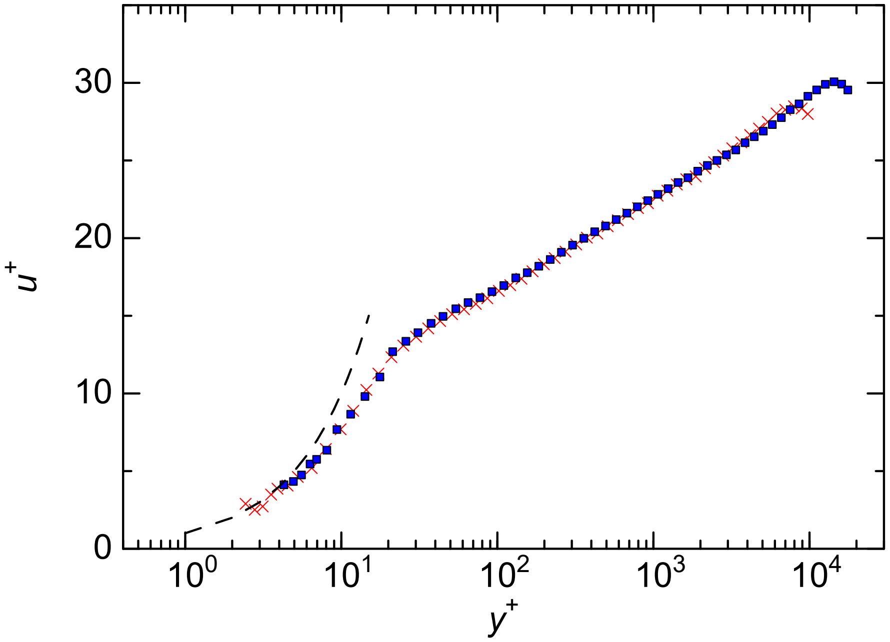
↑

Superpipe

■ Strength of NMIJ experiment

Mean velocity profile

$$u^+ = \frac{1}{\kappa}\ln y^+ + B$$



$$u^+ = \frac{u}{u_\tau} = \frac{u}{\sqrt{\tau_\mathrm{w}/\rho}}$$

u_τ: Friction velocity
τ_w: Wall shear stress
ρ: density

$$\tau_\mathrm{w} = \frac{1}{8}\boxed{\lambda}\rho\boxed{U_\mathrm{b}^2}$$

$$\lambda = \frac{2D\Delta p}{L\boxed{\rho U_\mathrm{b}^2}} = \frac{\pi^2 D^5 \Delta p}{8L\rho Q^2}$$

λ: Friction factor
U_b: Bulk velocity
Δp: Pressure gradient
D: Pipe diameter

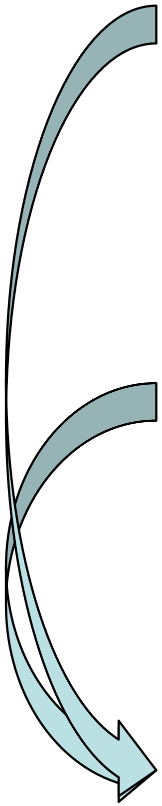
Friction factor

$$\frac{1}{\sqrt{\lambda}} = \frac{1}{2\kappa\sqrt{2}}\ln\left(Re_\mathrm{D}\sqrt{\lambda}\right) + C$$

Strength of NMIJ experiment

Measurement uncertainty for friction factor λ

Uncertainty factor	Standard uncertainty (P1,*D*=100mm)	Standard uncertainty (P2, *D*=387mm)
Diameter of pipe	0.025%	0.032%
Length between taps	0.008%	0.008%
Density	0.005%	0.005%
Differential pressure	0.401%	0.401%
Flowrate	0.110%	0.200%
Repeatability of measurement	0.015%	0.021%
Expanded Uncertainty (*k*=2)	**0.83%**	**0.90%**

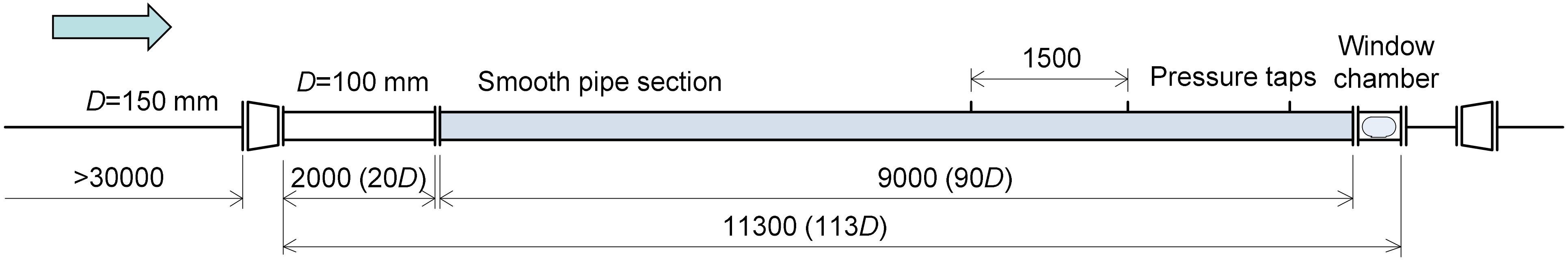


Standard uncertainty of bulk velocity : **0.115%** **0.202%**

■ Experiment in NMIJ

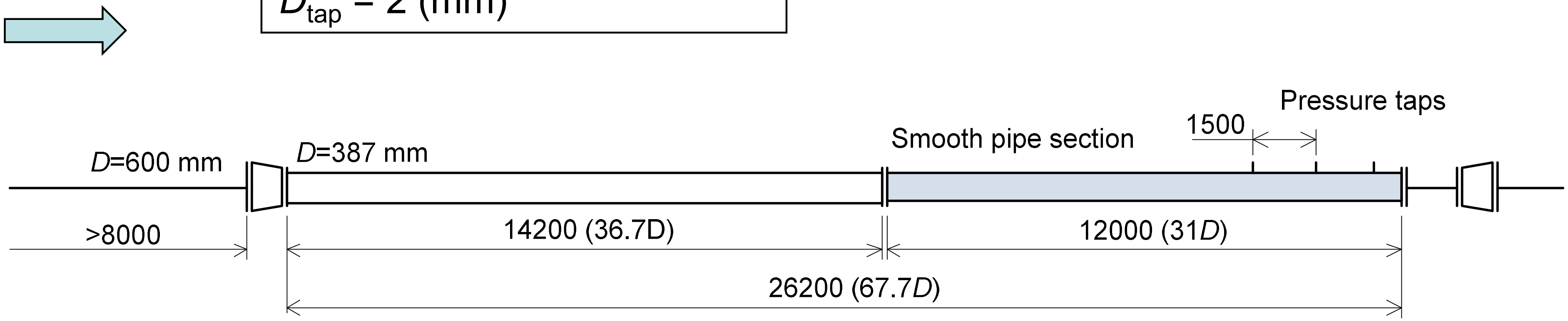
Pipe 1(P1)

D = 100.60 (mm)
L = 1500 (mm) ∼6000 (mm)
Ra = 0.10 (μm)
D_{tap} = 1 (mm) and 2 (mm)



Pipe 2(P2)

D = 387.04 (mm)
L = 1500 (mm) ∼9000 (mm)
Ra = 0.25 (μm)
D_{tap} = 2 (mm)



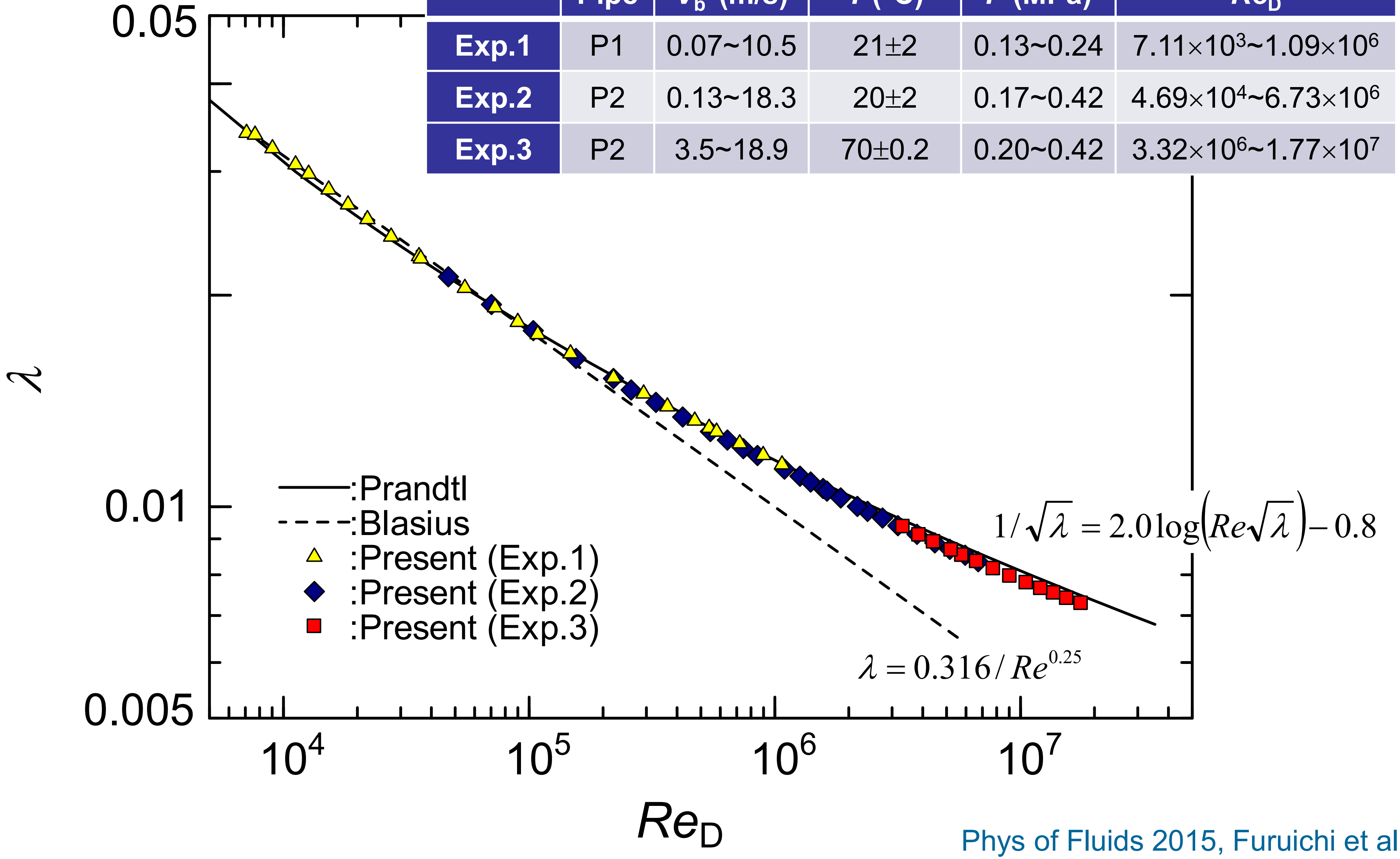
■ Experiment in NMIJ

***D*=100 mm**
Length : 9 m
Mean roughness : 0.1 μm
Roundness : less than ± 10 μm

***D*=387 mm**
Length : 21m (for velocity measurement)
Mean roughness : 0.25 μm
Roundness ; less than ± 25 μm

■ Experimental result in NMIJ

	Pipe	V_b (m/s)	T (°C)	P (MPa)	Re_D
Exp.1	P1	0.07~10.5	21±2	0.13~0.24	7.11×10^3~1.09×10^6
Exp.2	P2	0.13~18.3	20±2	0.17~0.42	4.69×10^4~6.73×10^6
Exp.3	P2	3.5~18.9	70±0.2	0.20~0.42	3.32×10^6~1.77×10^7



Phys of Fluids 2015, Furuichi et al.

■ Experimental result in NMIJ

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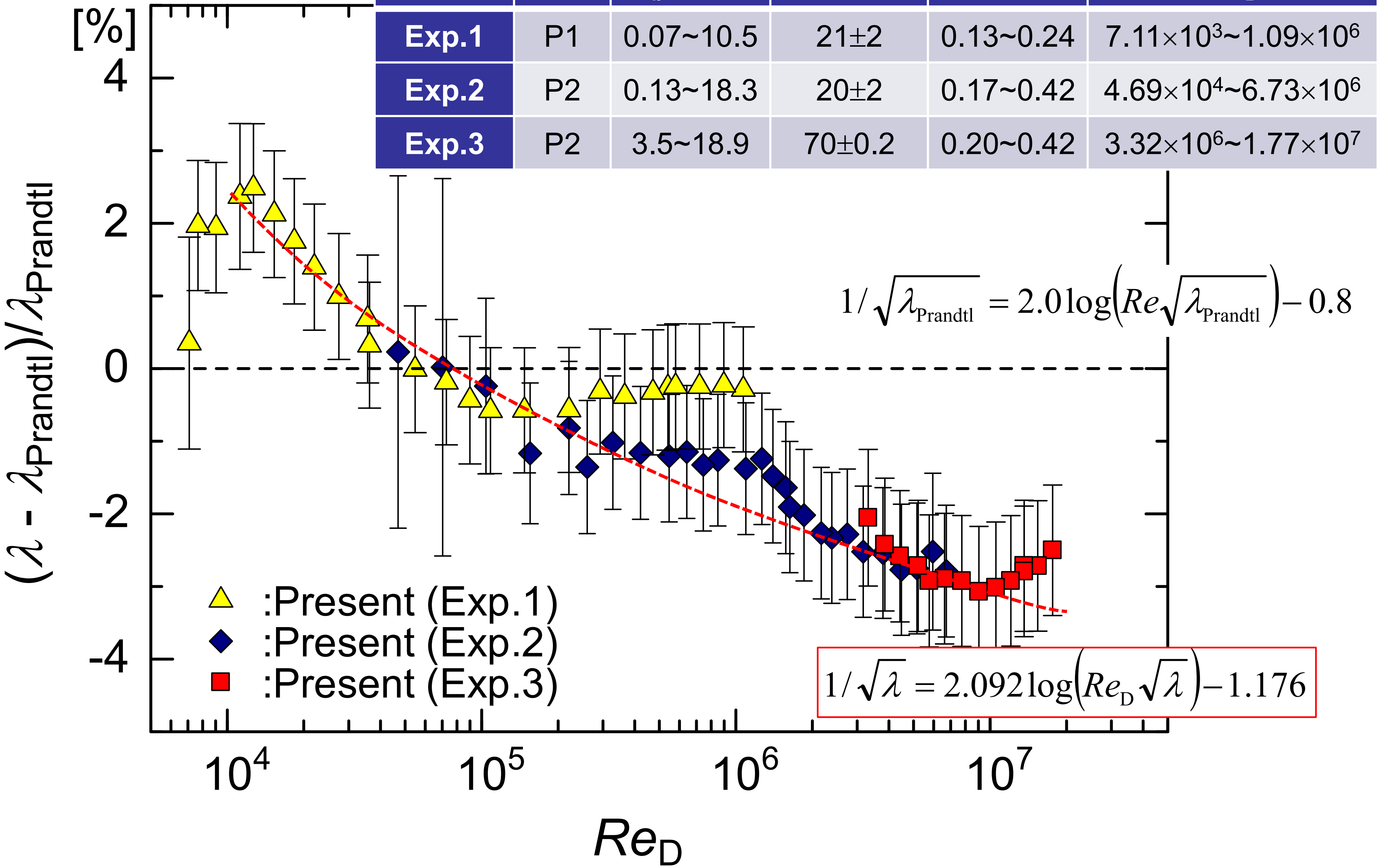
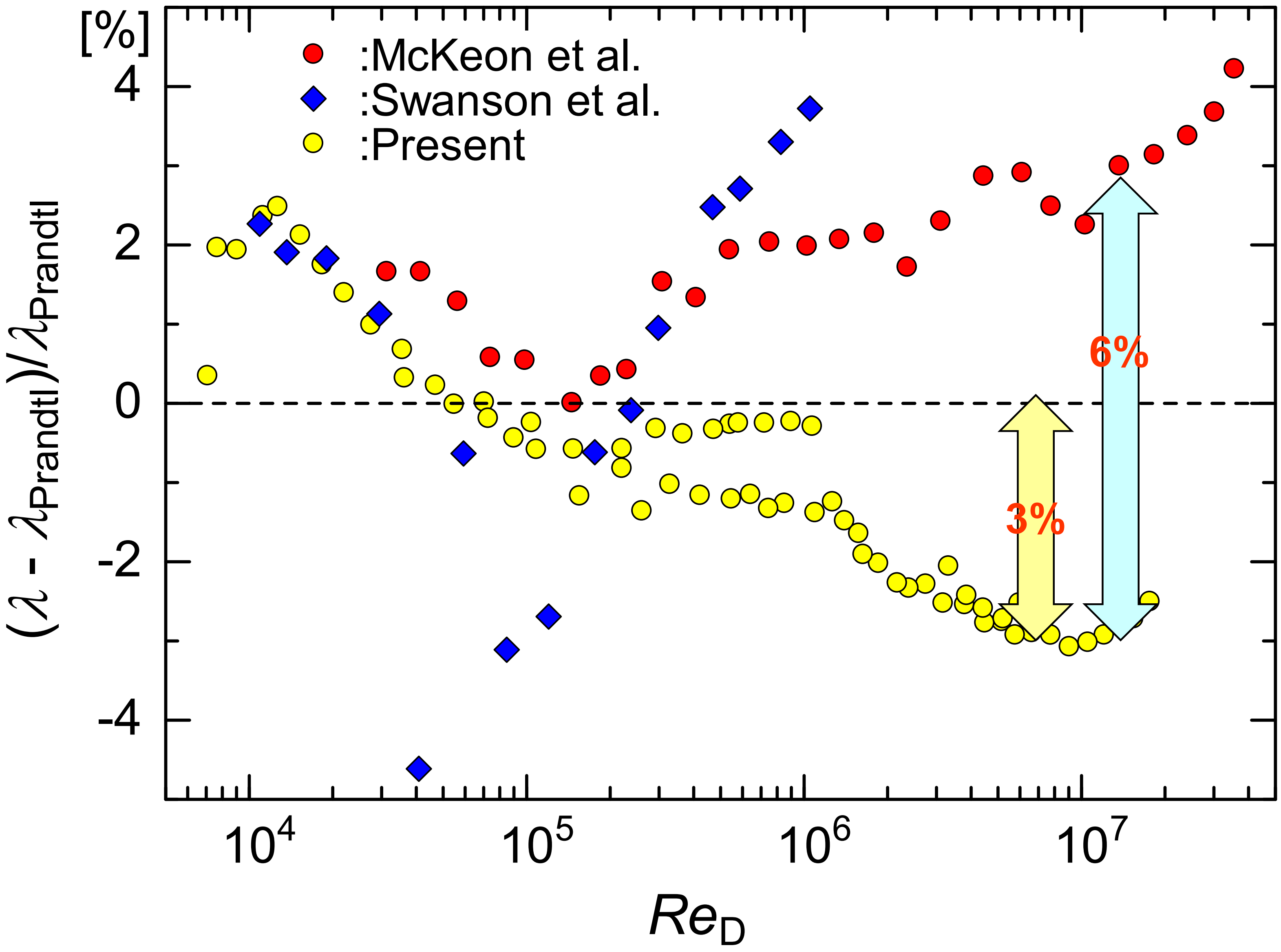


$$1/\sqrt{\lambda_{\text{Prandtl}}} = 2.0\log\left(Re\sqrt{\lambda_{\text{Prandtl}}}\right) - 0.8$$

$$1/\sqrt{\lambda} = 2.092\log\left(Re_D\sqrt{\lambda}\right) - 1.176$$

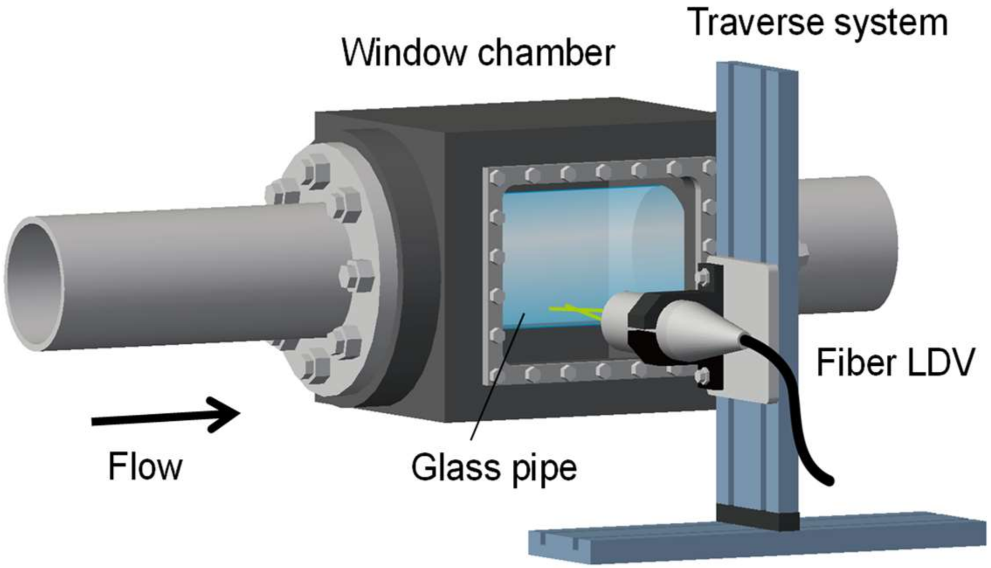
■ Experimental result in NMIJ

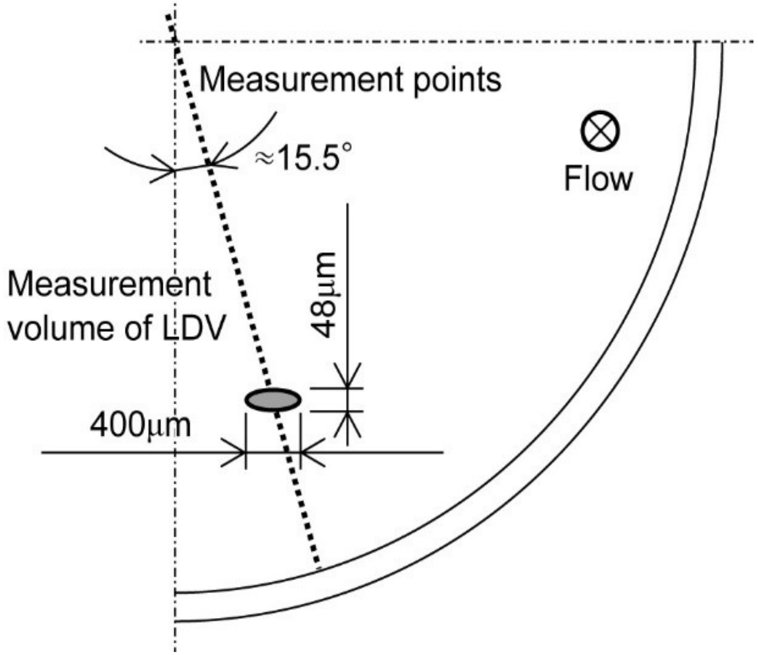


■ Experiment for velocity profile

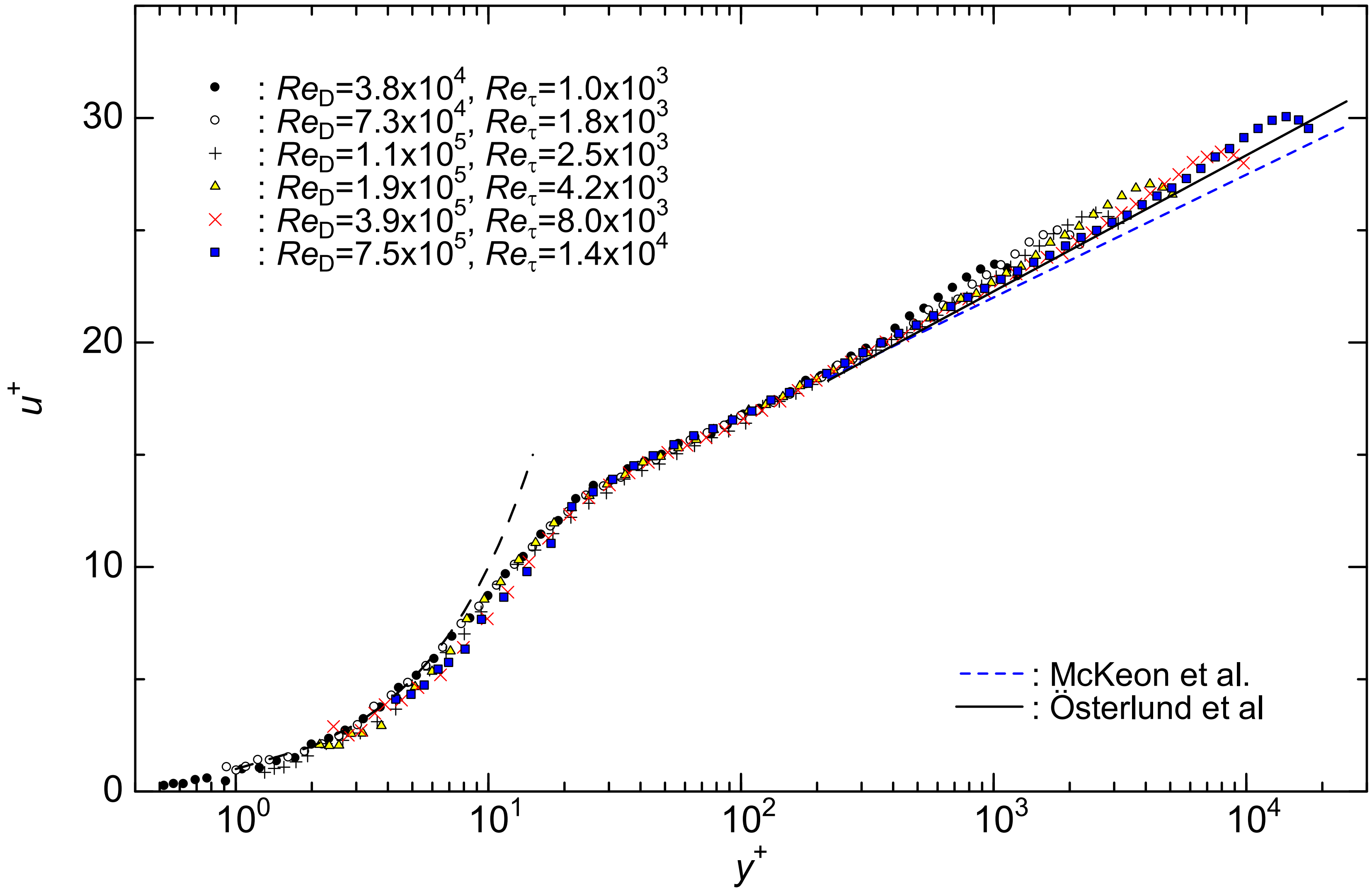
Specifications of LDV measurement

Laser : 2W Argon-Ion Laser
Wave length : 514.5 nm
Focal length : 160 mm
Spatial resolution : 0.048 mm x 0.107 mm x 0.40 mm
Measurement uncertainty of velocity : 0.20% (k=2)

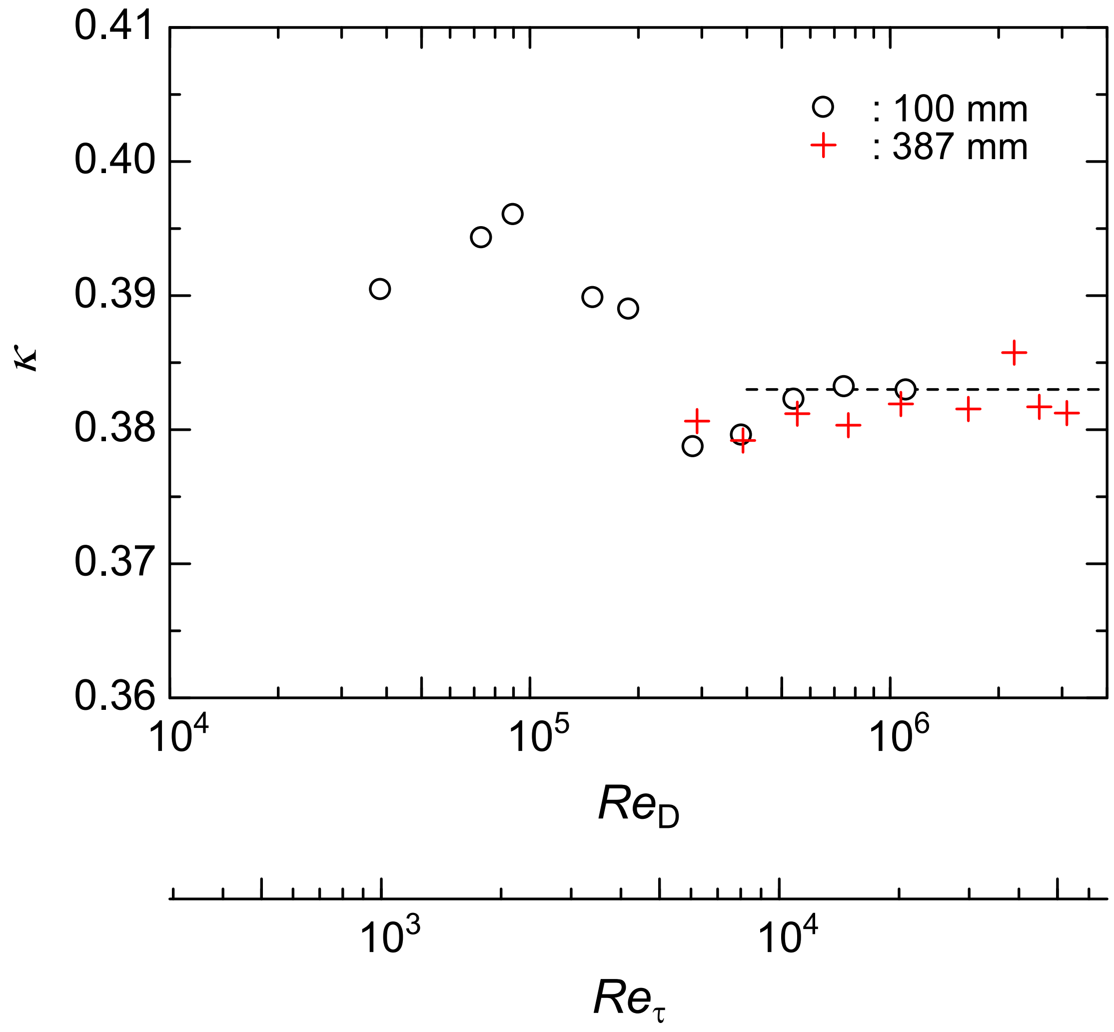




■ Experimental result in NMIJ



Karman constant



$$\psi = U^+ - \frac{1}{\kappa}\ln y^+$$

for $3(Re_\tau)^{0.5} \sim 0.2Re_\tau$

κ = **0.384**

- ✓ Karman constant approaches to asymptotic value for $Re_\tau > 10{,}000$.
- ✓ The value is 0.384, which is similar with other canonical flows.

Phys of Fluids 2018, Furuichi et al.

Summary

- New relation between friction factor and Reynolds number is given as following, instead of Prandtl equation

$$1/\sqrt{\lambda} = 2.092\log\left(Re_{\mathrm{D}}\sqrt{\lambda}\right) - 1.176$$

- The value of κ (generally called as Karman constant) in the log-law profile is not constant for $Re_\tau<10{,}000$.

$$u^+ = \frac{1}{\kappa}\ln y^+ + B$$

- The value of κ approaches to asymptotic value, which is 0.384, for $Re_\tau>10{,}000$.

Thank you for your attention.

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