Experimental and Numerical Investigations of the Factors Affecting the S-type Pitot Tube Coefficients in GHG Emission Monitoring

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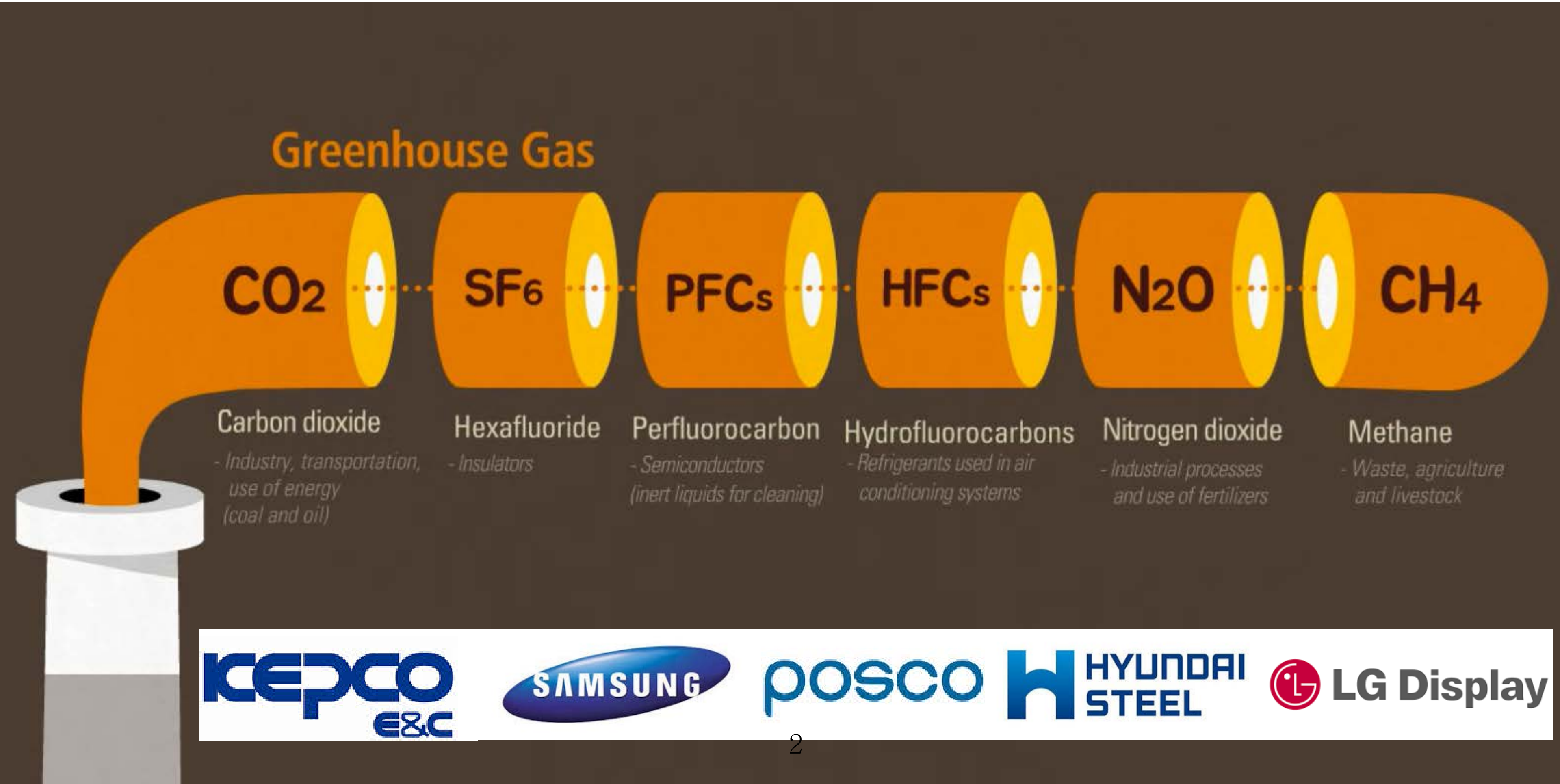
Measurement Challenges and Metrology for Monitoring CO2 Emissions from Smokestacks

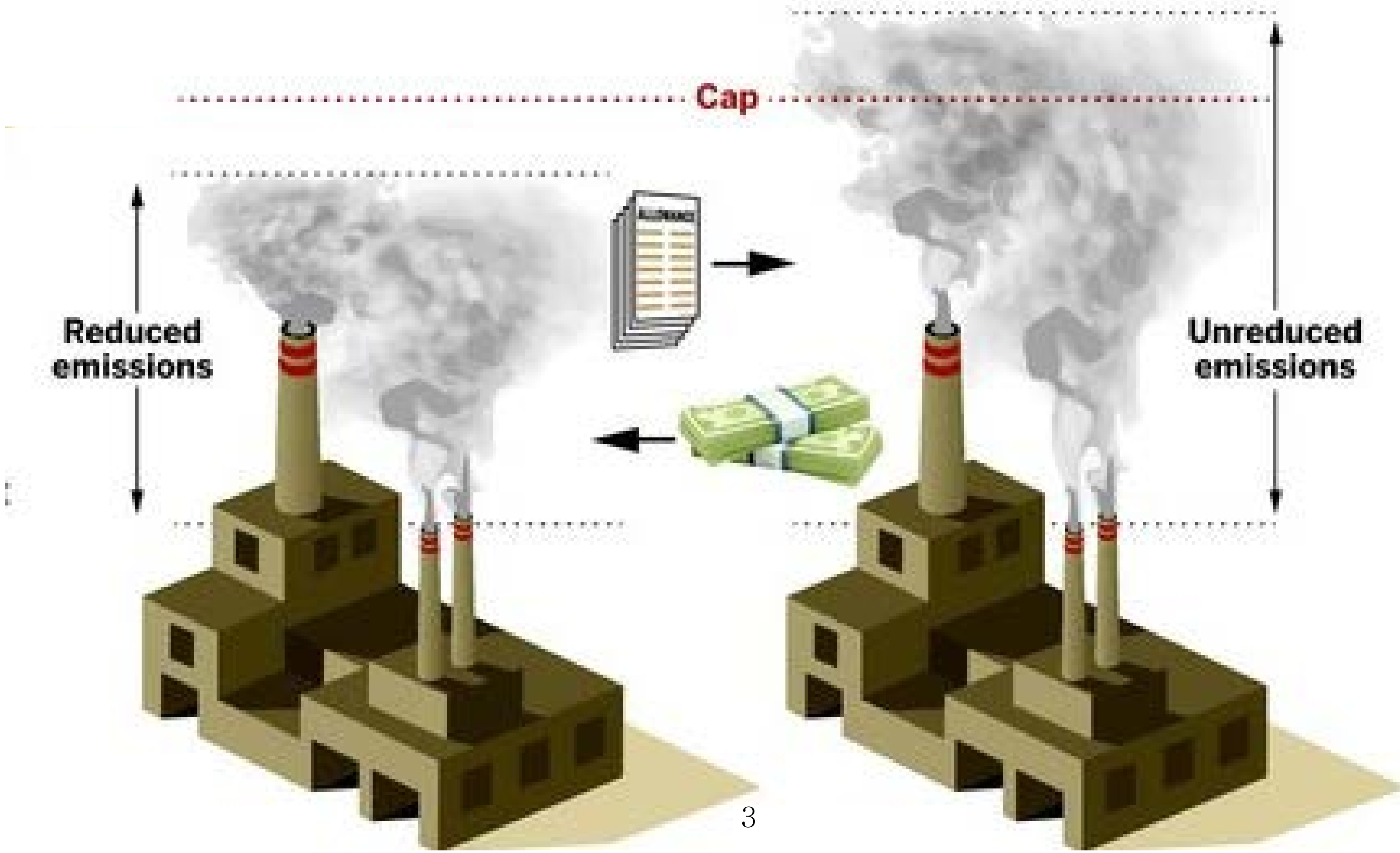
Korea GHG Inventory

- High proportion (90%) of greenhouse gas emissions arising from the energy and industrial fields such as heavy / petrochemical / semiconductor and power plant



Korea Emission Trading Scheme

- Implementation with allocation of emission cap for each company in 2015
- To meet the cap of emissions, company with increasing emissions should buy emission allowance from other emission-reduced company



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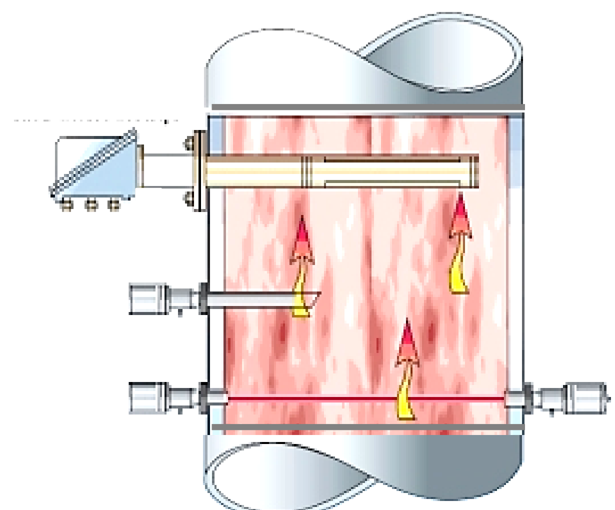
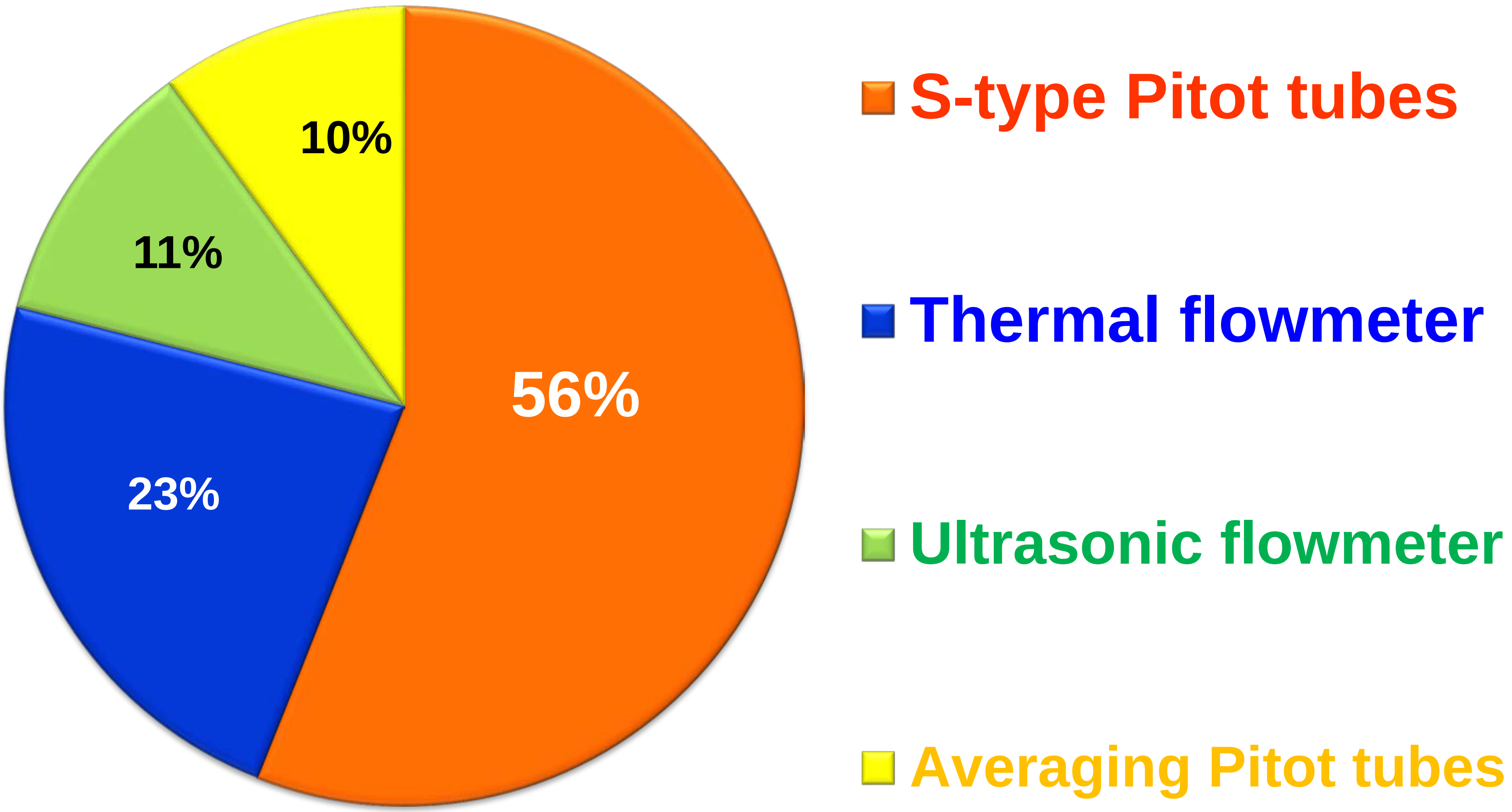
Continuous Emission Measurement

- Directly measure GHG emissions by monitoring concentrations and volumetric flow rate an exhaust gas
- Accurate and actual emissions measurements by U.S. EPA and Korea Ministry of Environment

$$E_{CEM} = \sum_{i=1}^{N} E_{5\min,i} = \sum_{i=1}^{N} \left(\overline{C}_i \times Q_{5\min,i} \times \frac{MW_{gas}}{22.4L}\right)$$



Instruments for Stack Flow Velocity in KOREA



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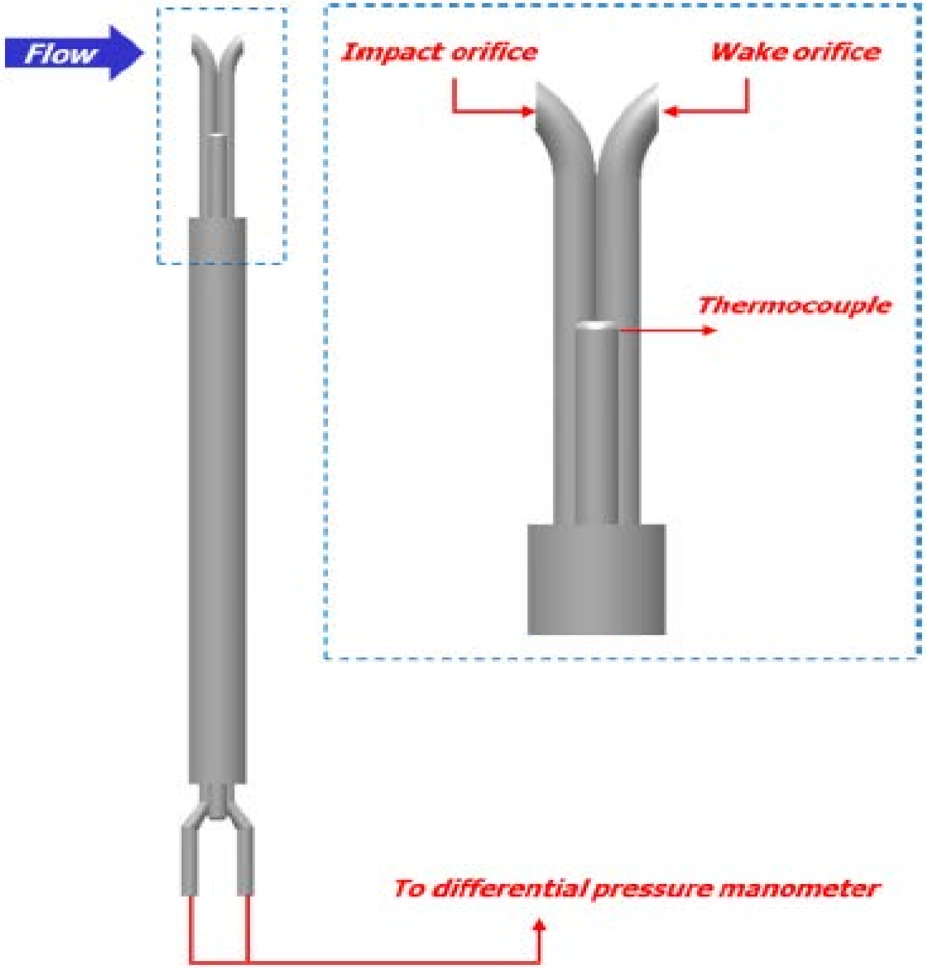
S-Type Pitot tube

- Large pressure orifices(Φ=5~10mm) & Strong tubes for high dust environments like industry stack (ISO 10780, KS M9429, EPA method2)
- Measurement differential pressure between an impact(total pressure) and wake orifice(static pressure) based on Bernoulli equation



$$V = C_{P,S}\sqrt{\frac{2\Delta P}{\rho}}$$

V : flow velocity in the stack gas(m/s)

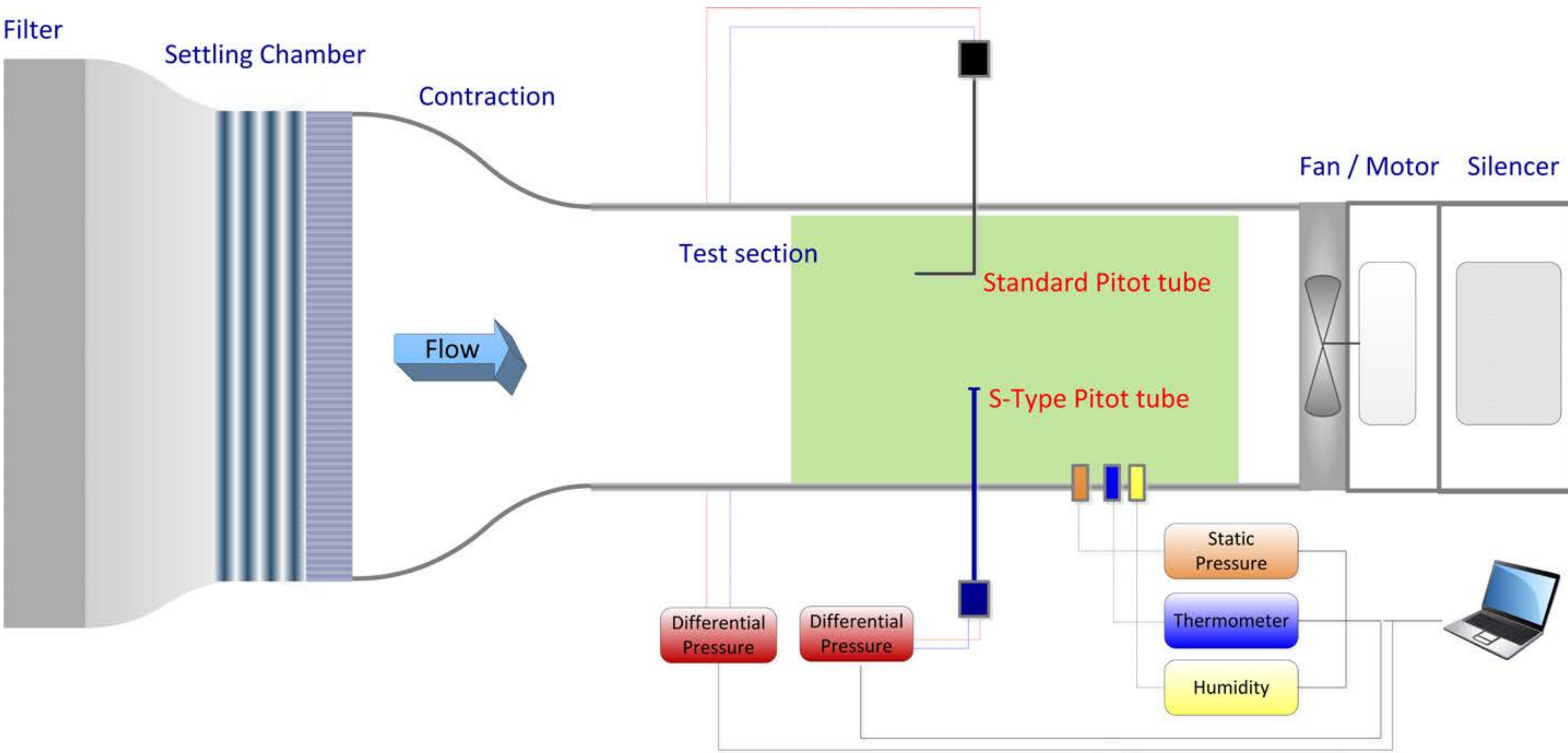
$C_{P,S}$: S type Pitot tube coefficient

ΔP : differential pressure between impact and wake orifice (Pa)

ρ : density of the stack gas (kg/m^3)

Calibration for S Pitot Tube Coefficient (C_p)

- Calibration against L-type Pitot tube in the wind tunnel of the national metrology institute or the accredited calibration laboratories.



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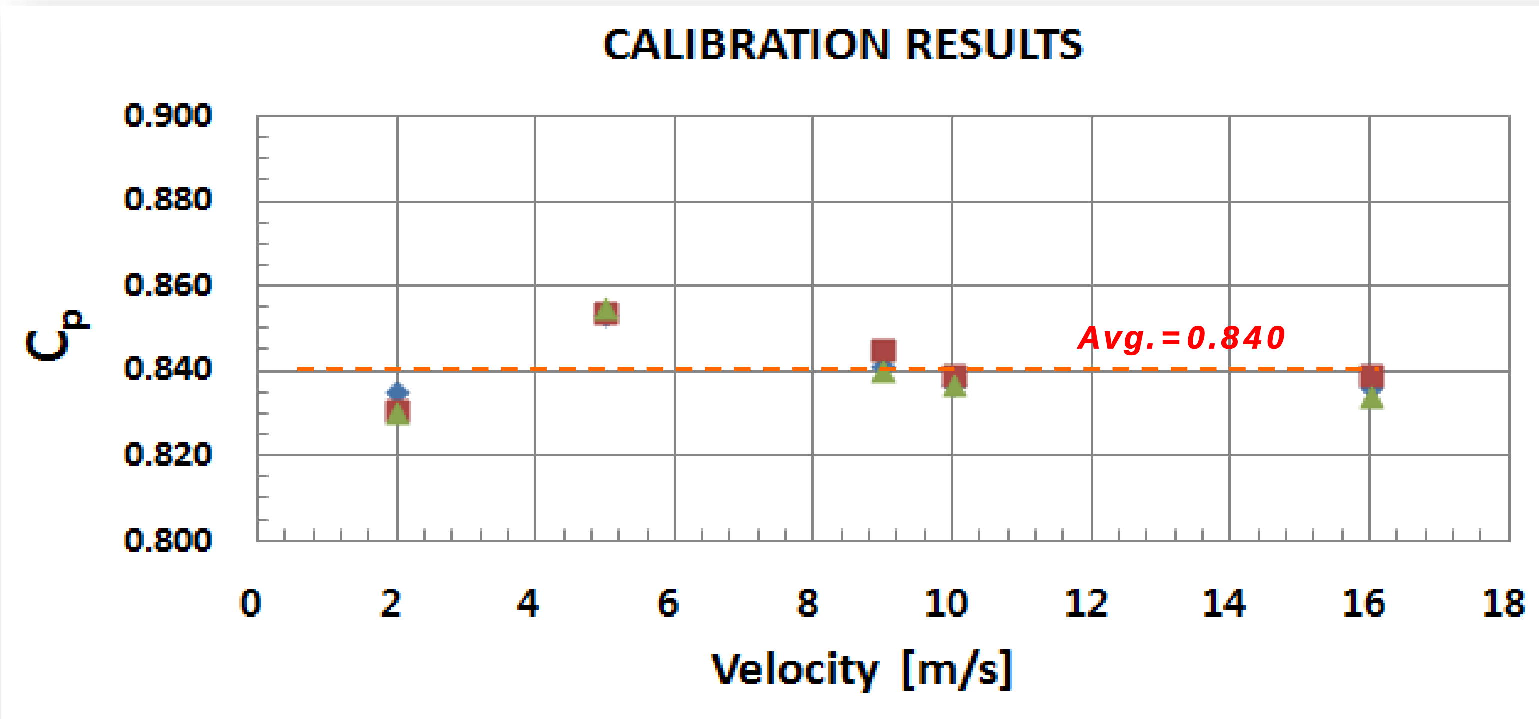
Calibration for S Pitot Tube Coefficient (C_p)

- Determination by comparing the differential pressure of standard pitot tube and S-type Pitot tube

$$C_{P,S\cdot type} = C_{P,Std}\left(\frac{\Delta P_{Std}}{\Delta P_{S\cdot type}}\right)$$

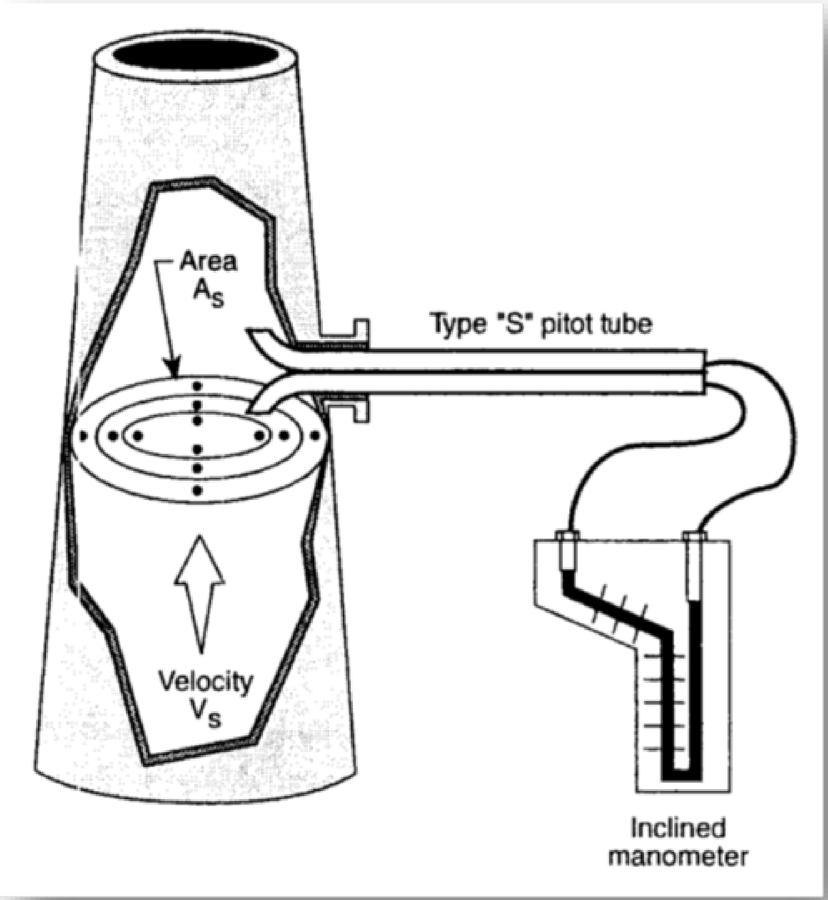
$C_{p,s\text{-}type}$: S Pitot tube coefficient
$C_{p,std}$: Stadard Pitot tube coefficient

$\Delta P_{s\text{-}type}$: differential pressure of S Pitot tube
ΔP_{std}: differential pressure of Standard tube

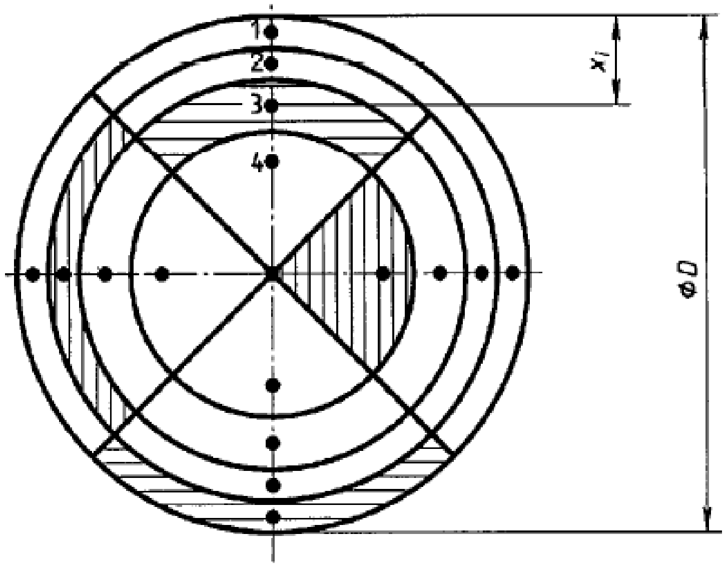


Velocity Measurements in the Stack

- As the diameter of stacks increases, the sampling traverse point for measuring velocity distributions in the stack should increase according to the ISO 10780 and EPA method.



Stack Diameter 2R (m)	raidus	numbers	Distance from center of stack r_1	r_2	r_3	r_4	r_5
< 1	1	4	0.707 R	-	-	-	-
1 ~ 2	2	8	0.500 R	0.866 R	-	-	-
2 ~ 4	3	12	0.408 R	0.707 R	0.913 R	-	-
4 ~ 4.5	4	16	0.354 R	0.612 R	0.791 R	0.935 R	-
> 4.5	5	20	0.316 R	0.548 R	0.707 R	0.837 R	0.949 R



On-site Measurement

On-site Measurement

On-site Measurement

- S-type Pitot tube is usually installed and inserted in harsh environment such as tall stack height and high gas temperature

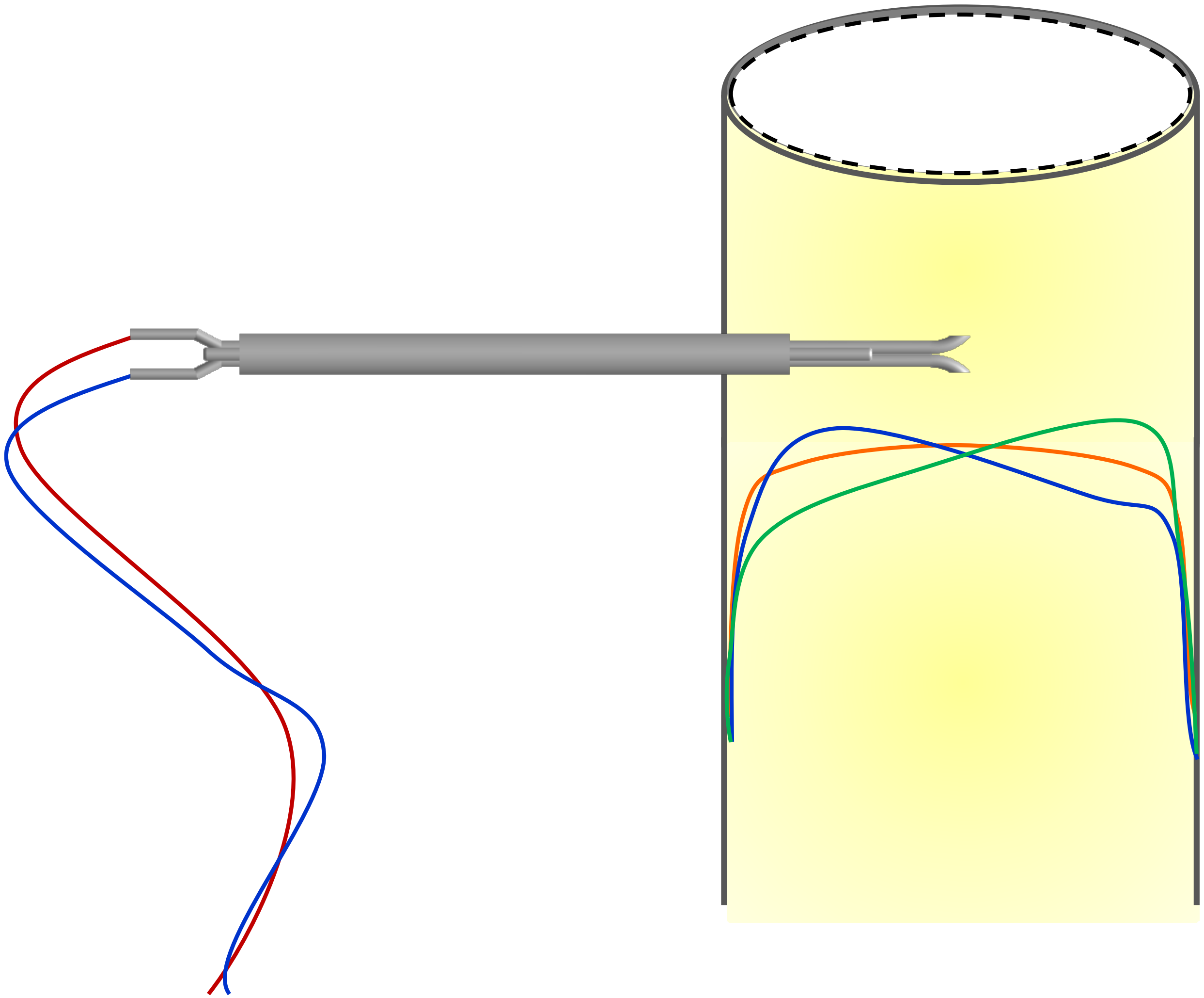
On-site Measurement

- Difficult to observe the inside of the stack and verify the precise installation of the S-type Pitot tube

What Happens Inside the Stack?

What Happens Inside the Stack?

- Flow velocity of emission gas can be altered due to the unstable process in particular industrial condition of plant

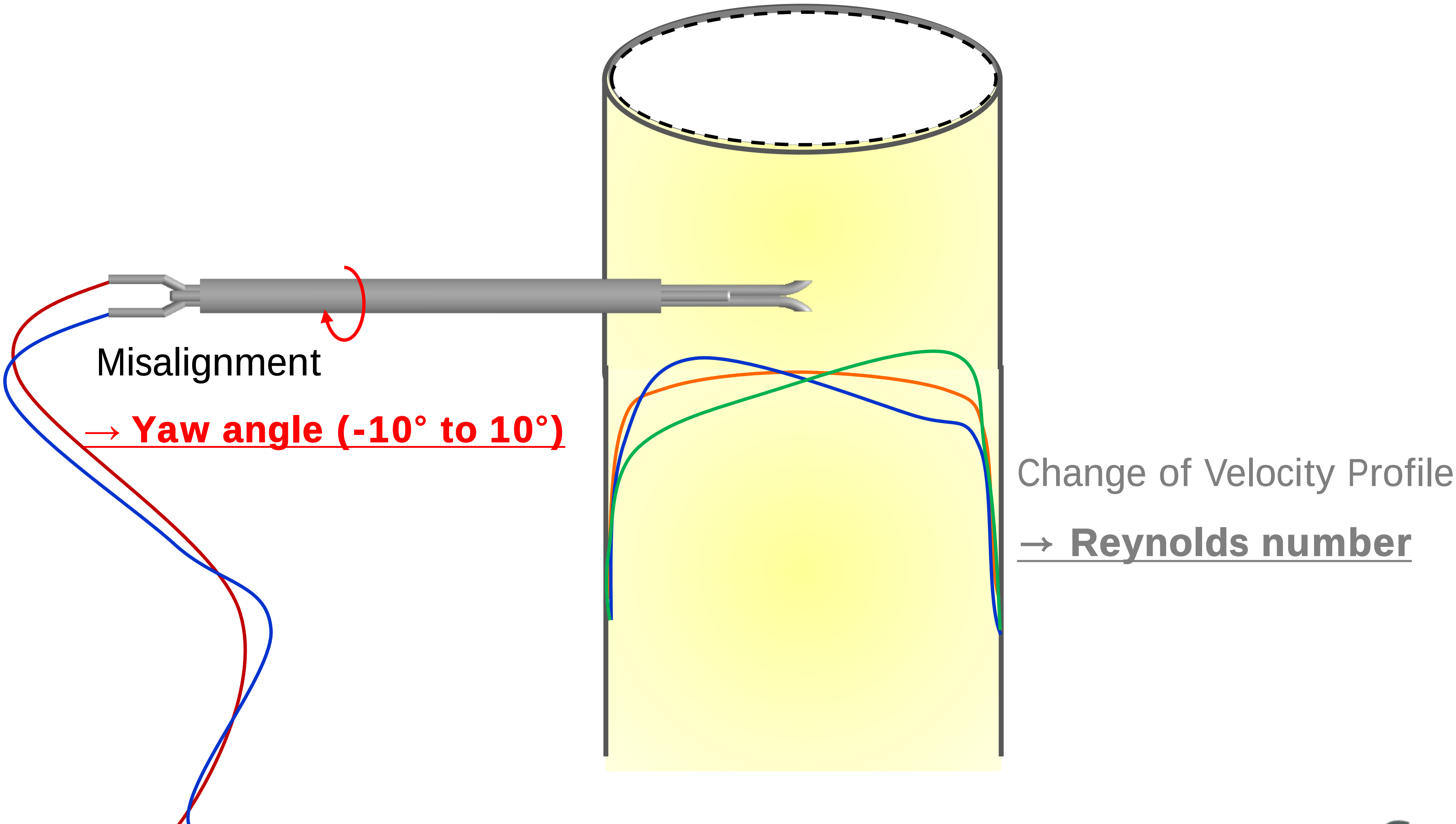


Change of Velocity Profile

<u>→ Reynolds number</u>

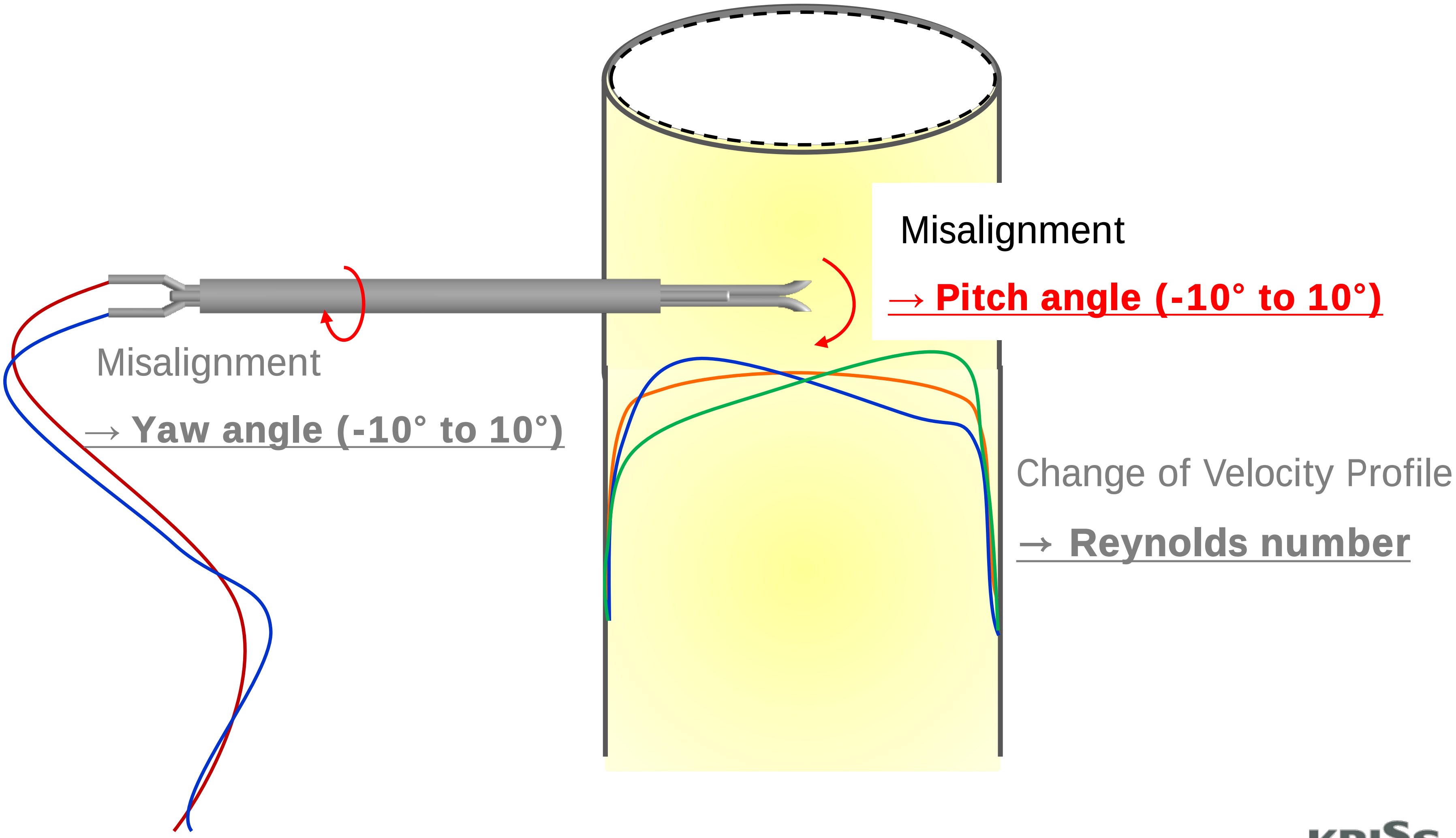
What Happens Inside the Stack?

- Yaw angle misalignment can occur during installation of S-type Pitot tube from outside of the stack due to the difficulty of observation



What Happens Inside the Stack?

- Pitch angle misalignment of S-type Pitot tube can result due to the deflection of the long S-type Pitot tube in large diameter stacks.



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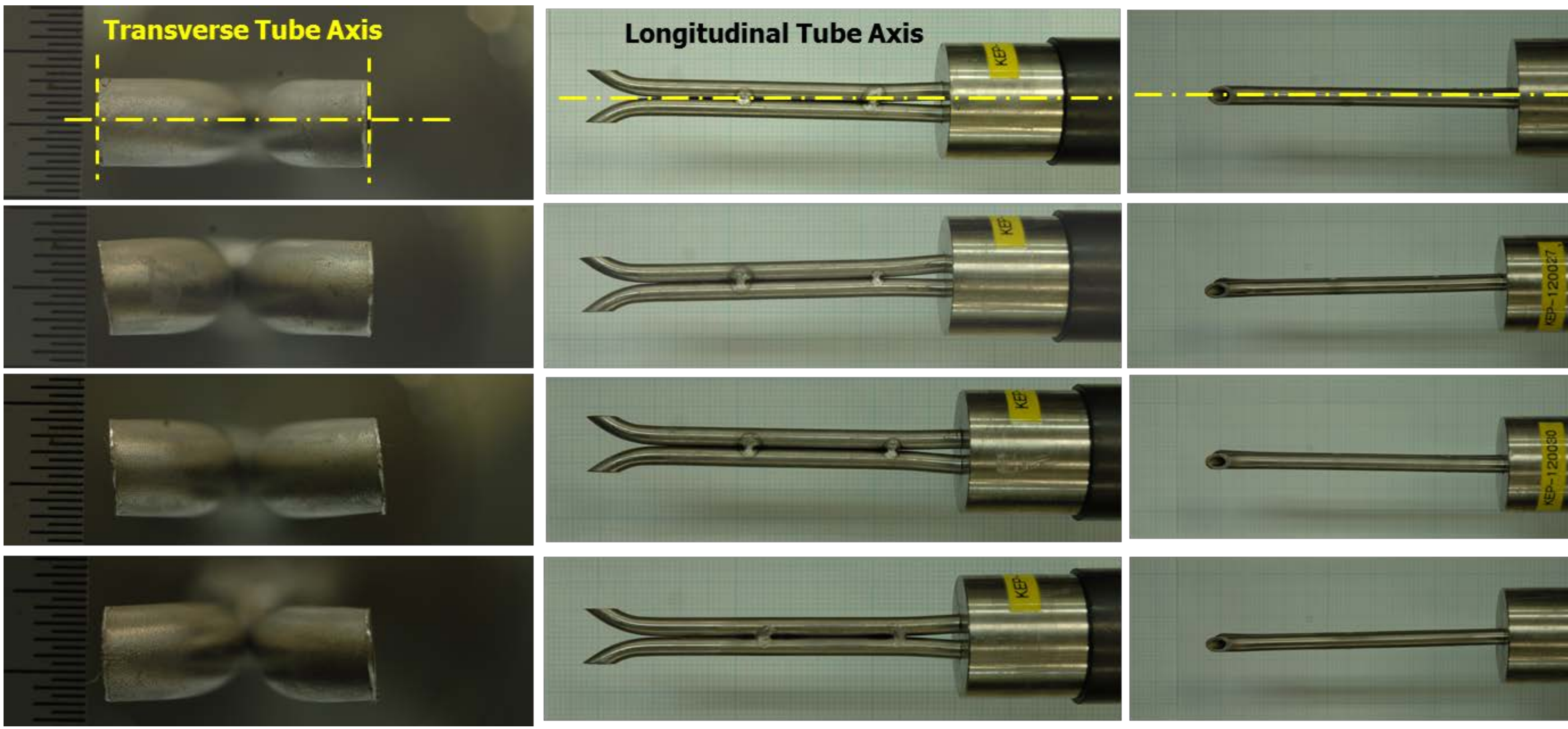
Manufacture Quality

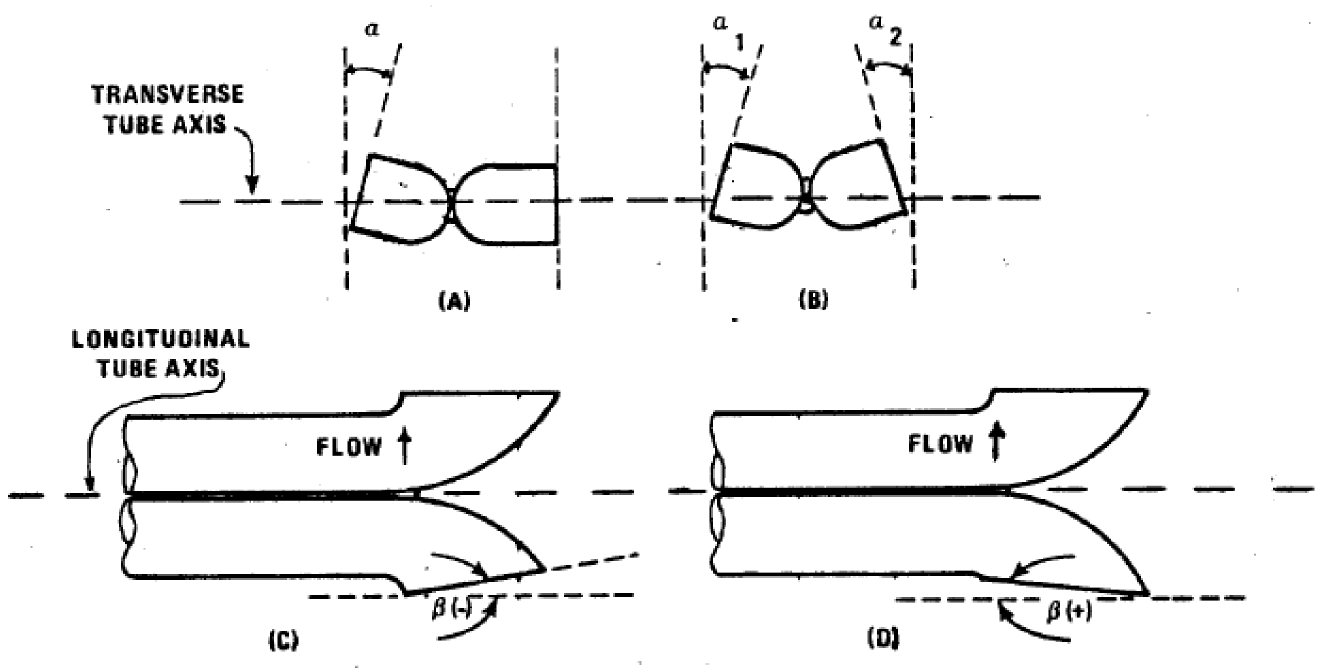
- The geometry of the S-type Pitot tube can be changed by the manufacturing quality of the manufacturer(company) due to not-strong regulation for standard geometry of S-type Pitot tube



Manufacture Quality

- Vollaro et al.(EPA, 1976) investigated the effect of impact opening misalignment on the S-type Pitot tube coefficient

  → 2% Error with impact opening misalignment



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Objective

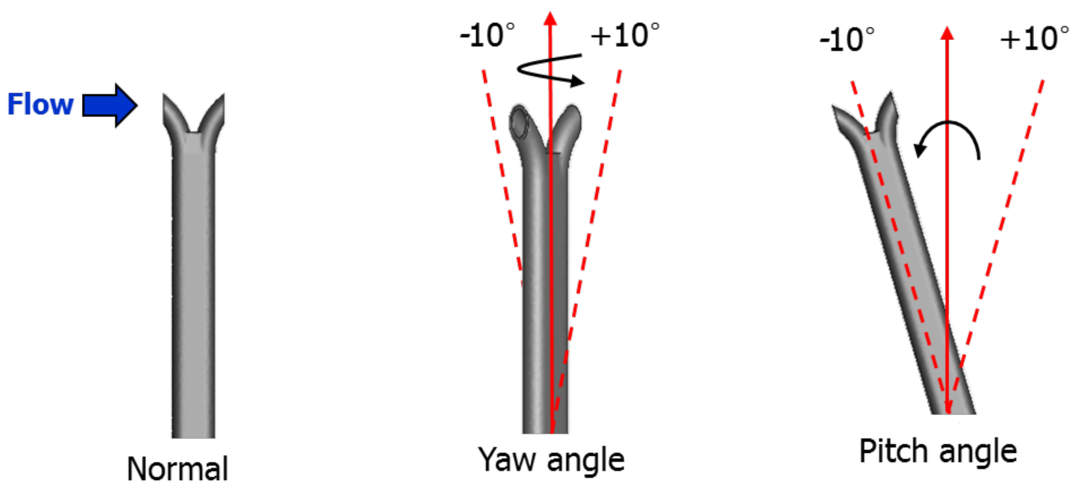
- Evaluate the effect various factors on the S-type Pitot tube coefficients for accurate and reliable measurement GHG emission in industrial stack

1. Reynolds number effect

Velocity = 2 to 15 m/s

Re_D = 3,000 to 22,000 (D: distance between two orifices)

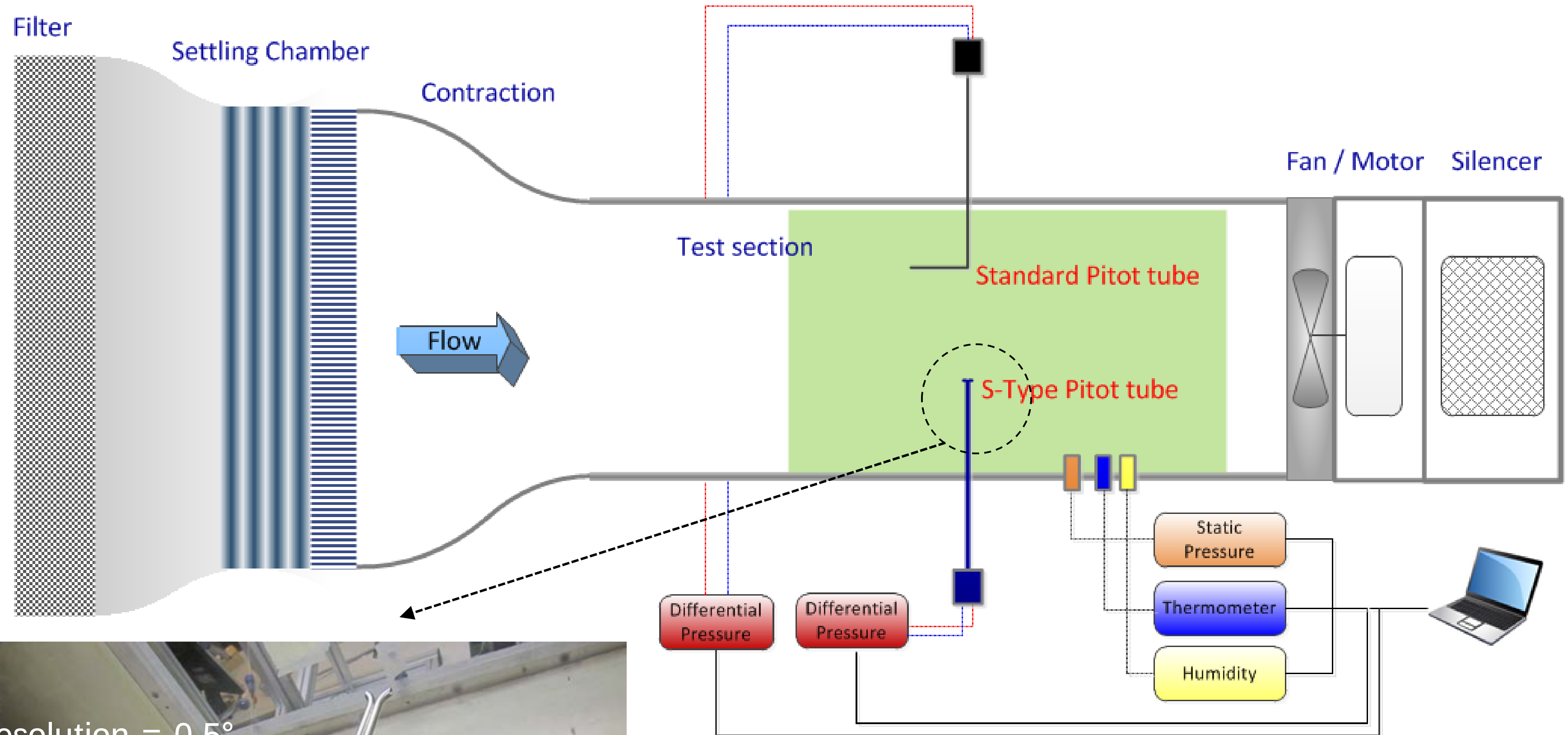
2. Misalignment effect

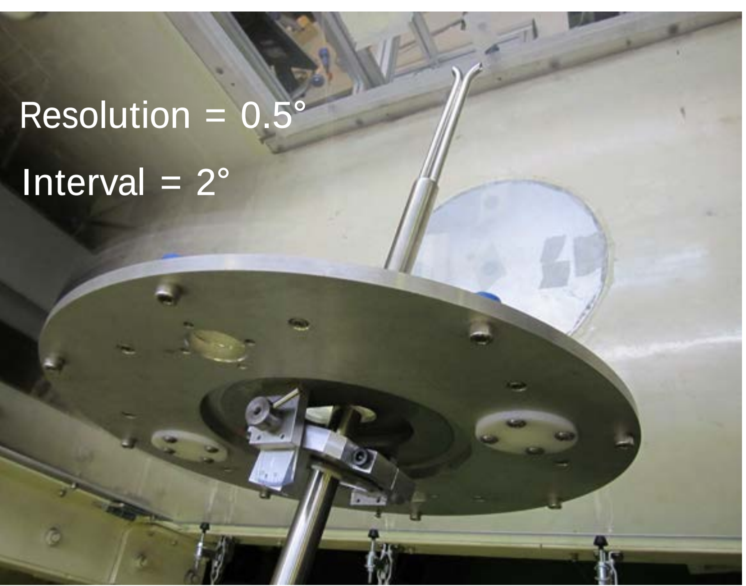


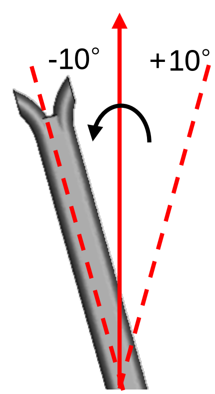
3. Manufacturing Quality

S-type Pitot tube calibration data of 4 major manufacturers in KOREA

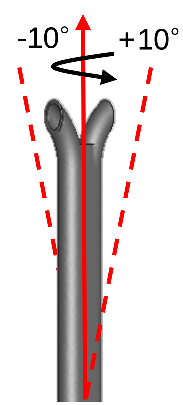
Experiment apparatus







Pitch angle

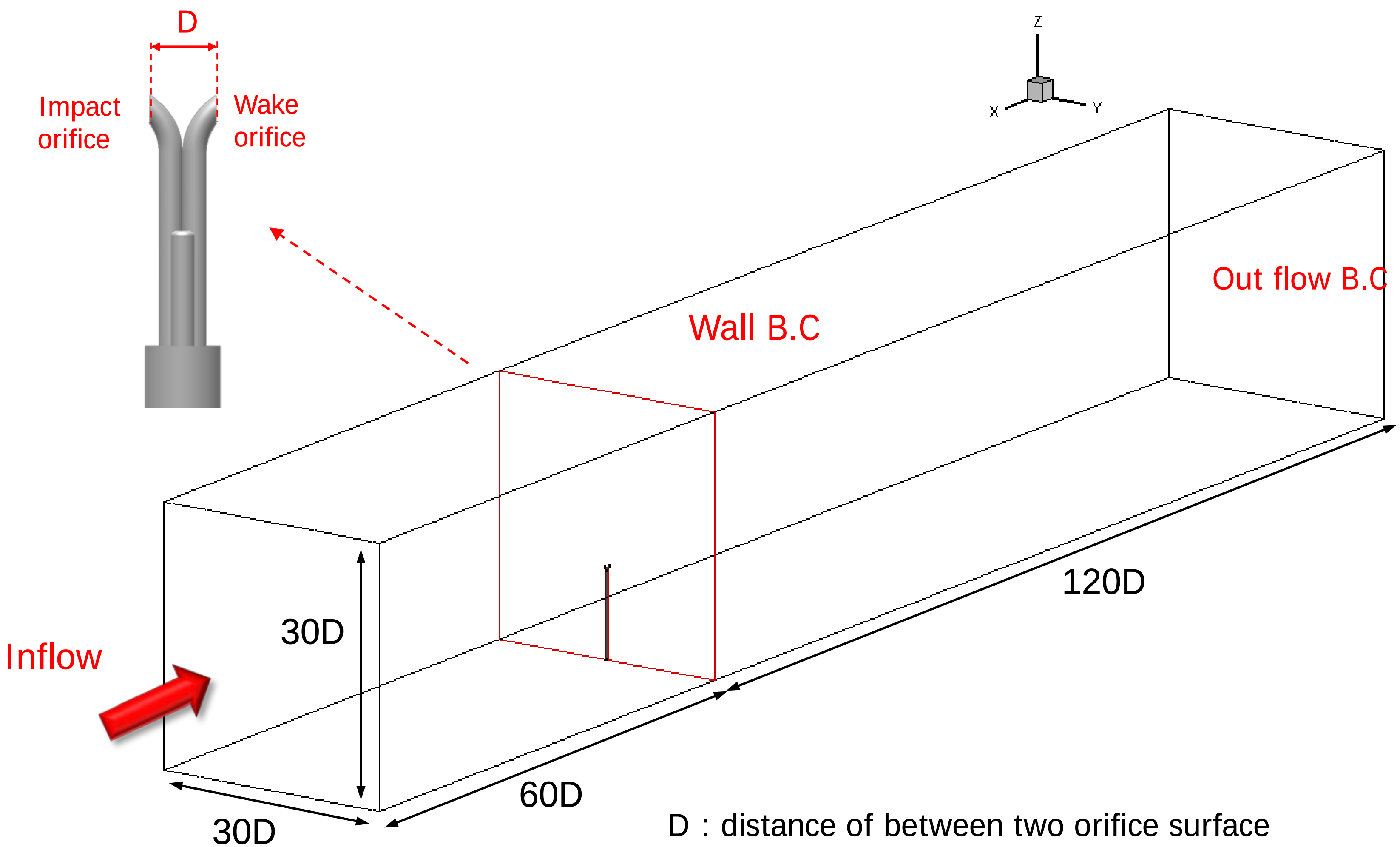


Yaw angle

KRISS Subsonic Wind Tunnel	
Wind tunnel Type	Open-Suction type
Velocity range	2 m/s to 15 m/s
Test section area	0.9 m X 0.9 m
Uncertainty (%)	0.60 % to 1.1%

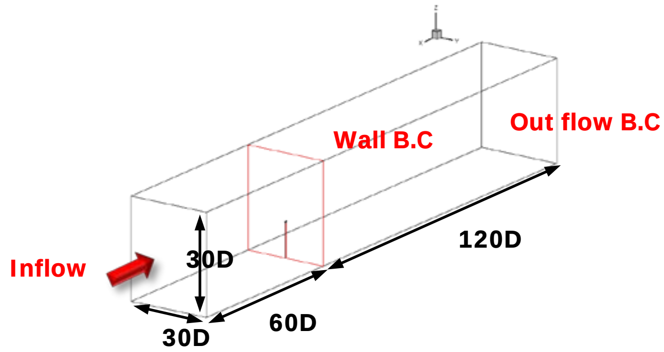
Numerical Simulation

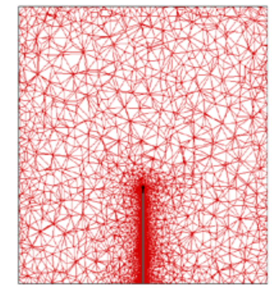
- To understand flow phenomena around S-type Pitot tube when misalignment and distortion of geometries were present



D : distance of between two orifice surface

Numerical Simulation



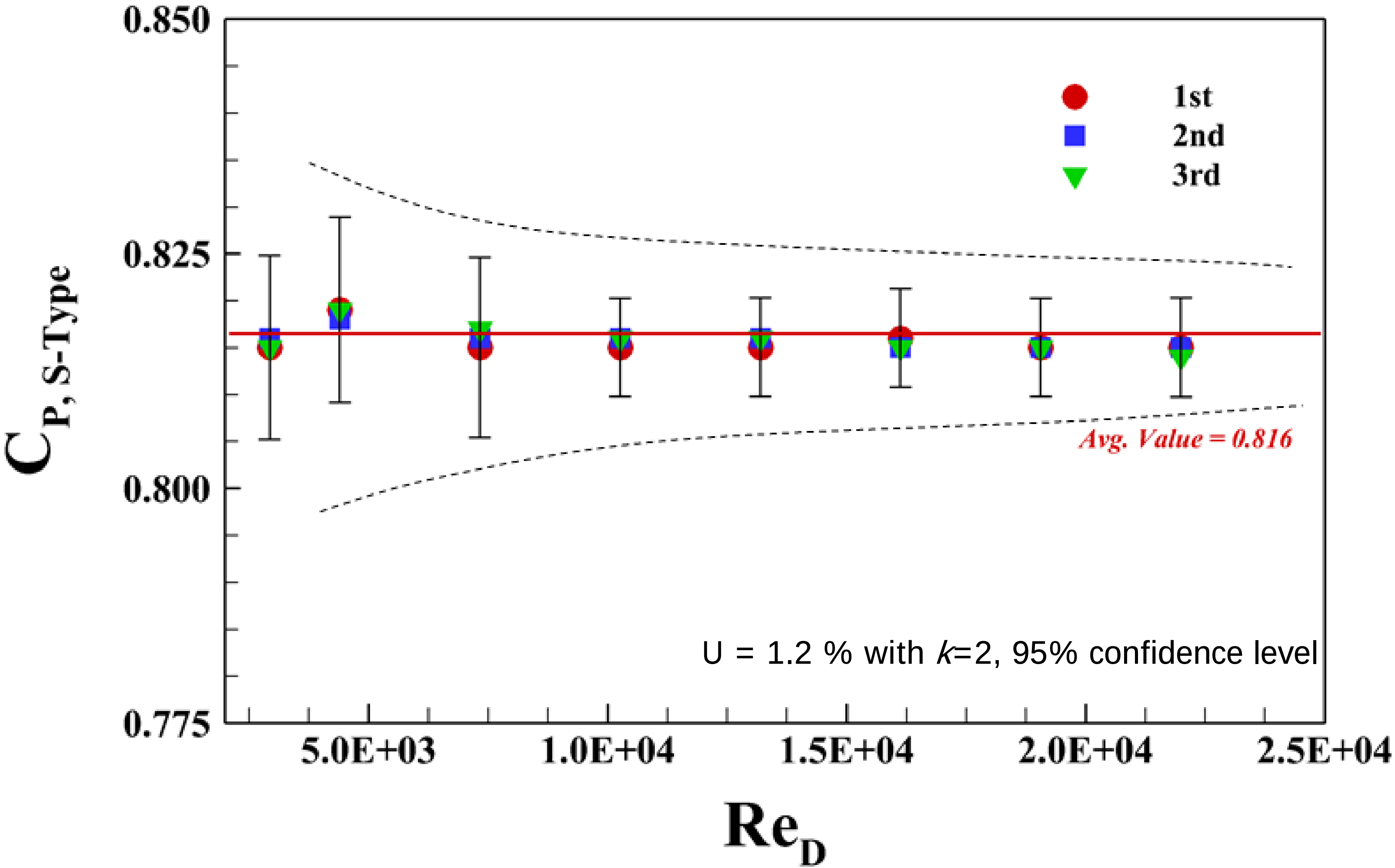


Numerical Method	
Equation	3-D Incompressible Navier-Stokes Eq. (ADINA 8.7.1)
Meshes	Unstructured mesh (Tetrahedral type) 875,000 meshes, Δ = 3.5 X 10^{-2}D
Boundary Conditions	Inflow B.C : Turbulent flow (turbulence intensity = 2%) Wall B.C : no-slip Outflow : Pressure out
Turbulence Model	Detached Eddy Simulation model - Spalart – Allmaras model ($\mu_t=\rho\upsilon f_{\upsilon l}$)

The effects of Reynolds number

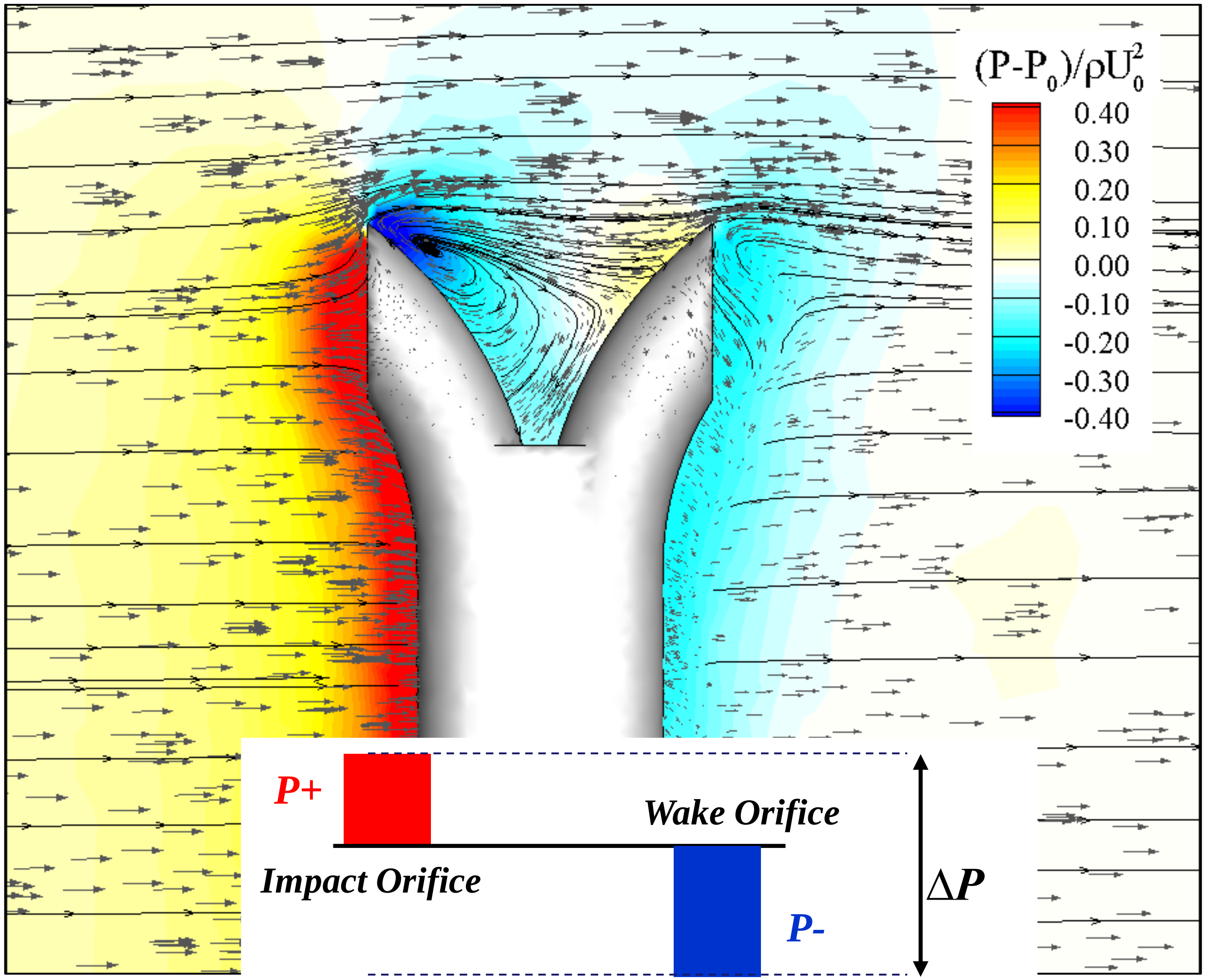
The effects of Reynolds number

- The deviation of each value from the average value of S-type Pitot tube coefficients was less than 0.3% within entire range of Reynolds numbers
- The effect of Reynolds number on S-type Pitot tube coefficients is negligible compared to the total uncertainty of measurements



The effects of Reynolds number

- Due to complicated geometry between the impact and wake orifices, the separated flows are developed to a vortical structure behind impact orifice
- The flow phenomena around S-type Pitot tube appear identically regardless of the change of Reynolds number

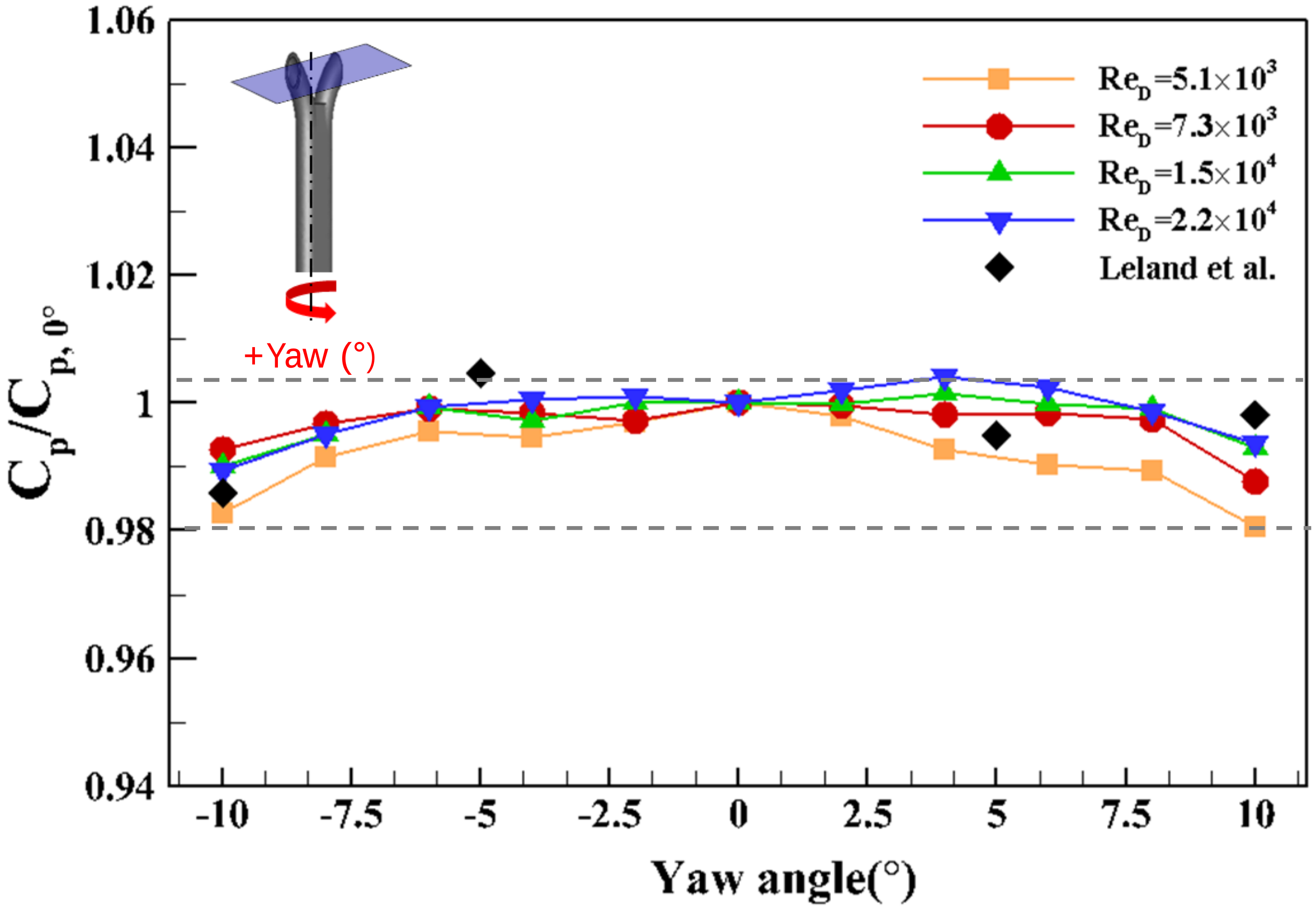


Re_D = 10,000

The effects of Yaw angle misalignment

The effects of Yaw angle misalignment

- S-type Pitot tube coefficients(C_P) at each yaw angle are normalized by S-type Pitot tube coefficients($C_{P,0°}$) at a yaw angle of 0°
- The normalized S-type Pitot tube coefficients decreased by up to – 2% as the yaw angle increases to ±10 ° with symmetric tendency



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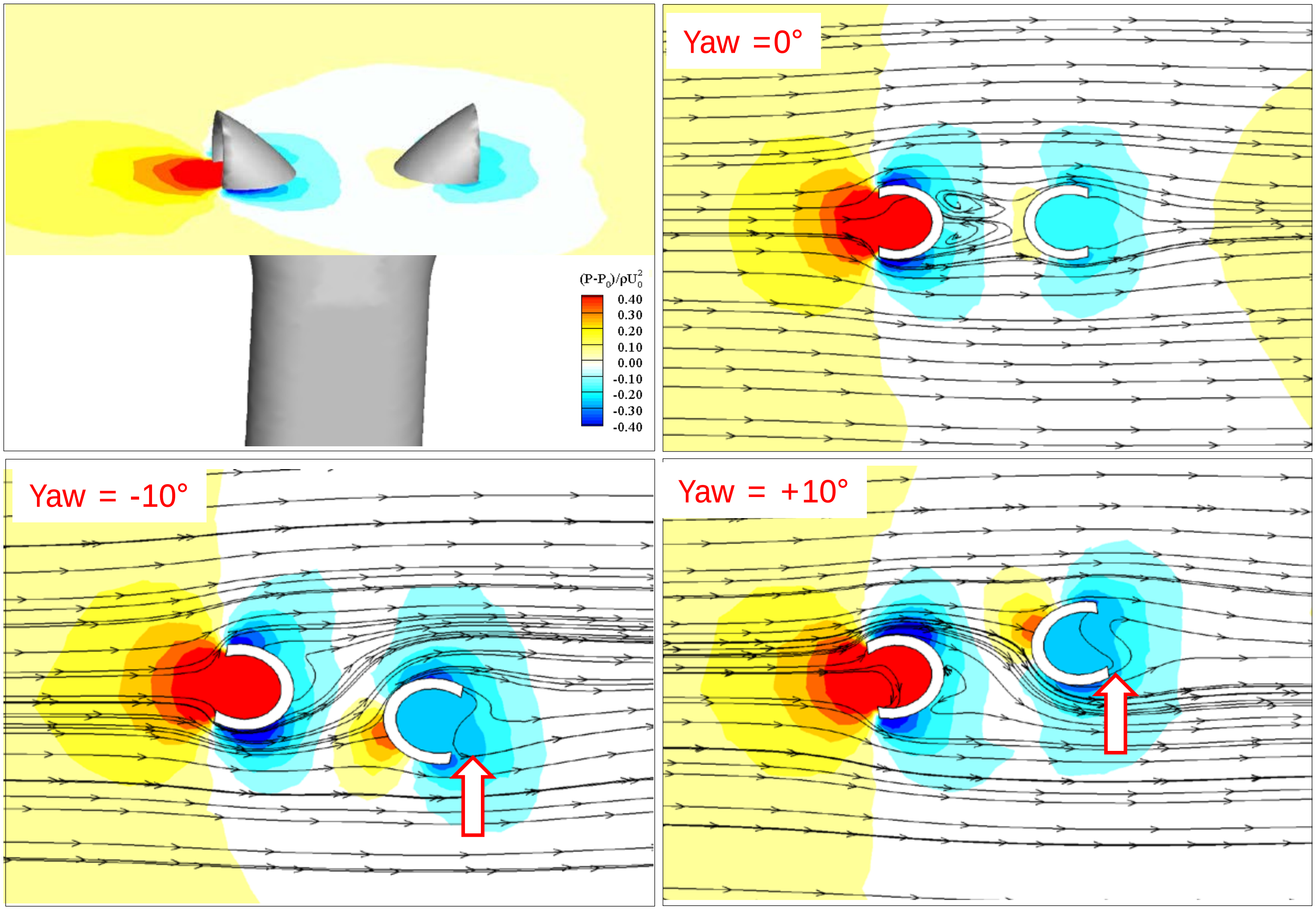
The effects of Yaw angle misalignment

- Pressure values near wake orifice decrease due to the enhancement of separated flow from orifice surface, which shows symmetry ± yaw angle



Re_D = 10,000

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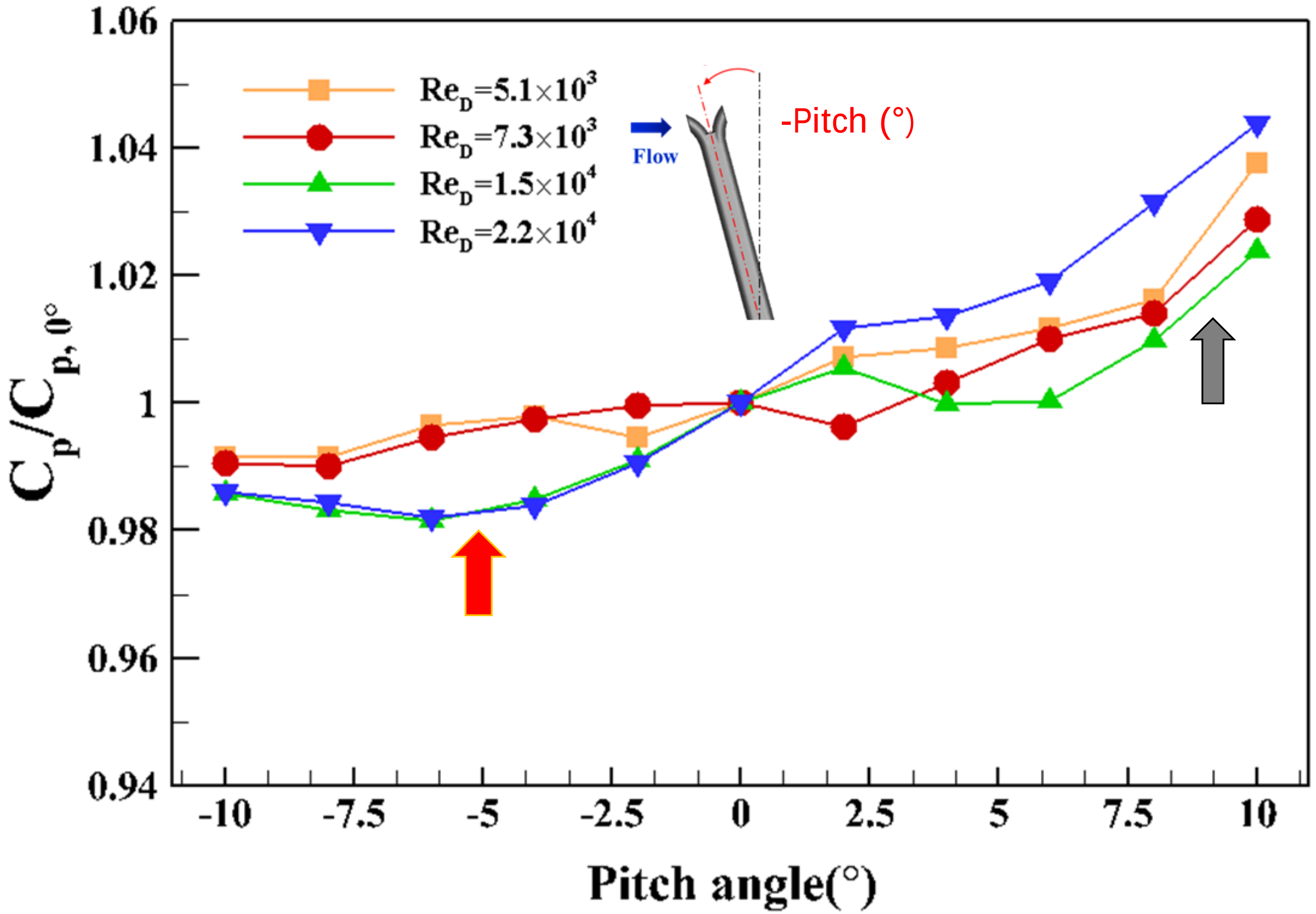
The effects of Pitch angle misalignment

The effects of Pitch angle misalignment

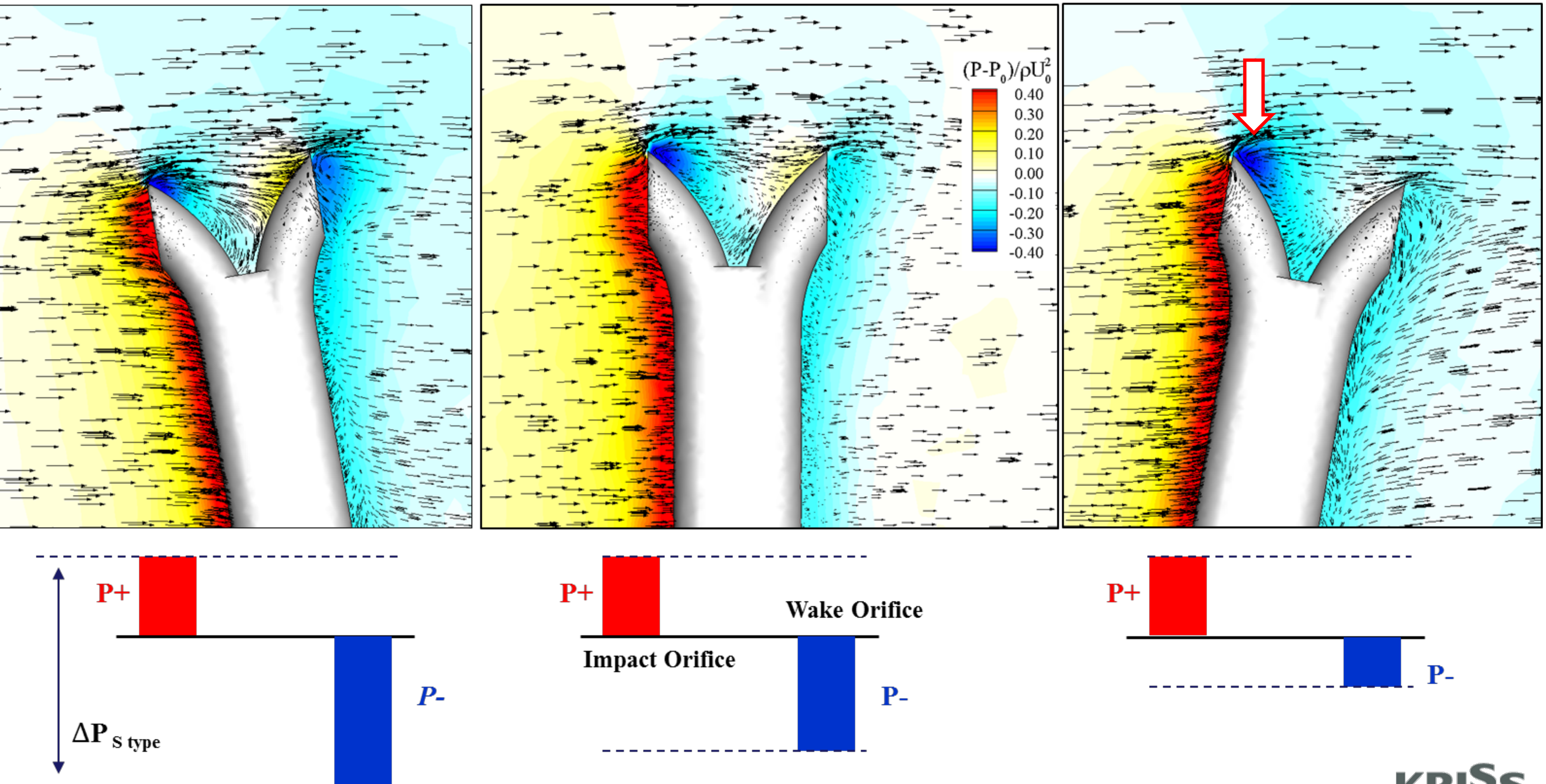
- The normalized S-type Pitot tube coefficients increase up to 4 % as the pitch angle increases to +10°
- In negative Pitch angles, S-type Pitot coefficients decrease to –2%, which can occur in industry stacks due to defection of long S type Pitot tube



The effects of Pitch angle misalignment

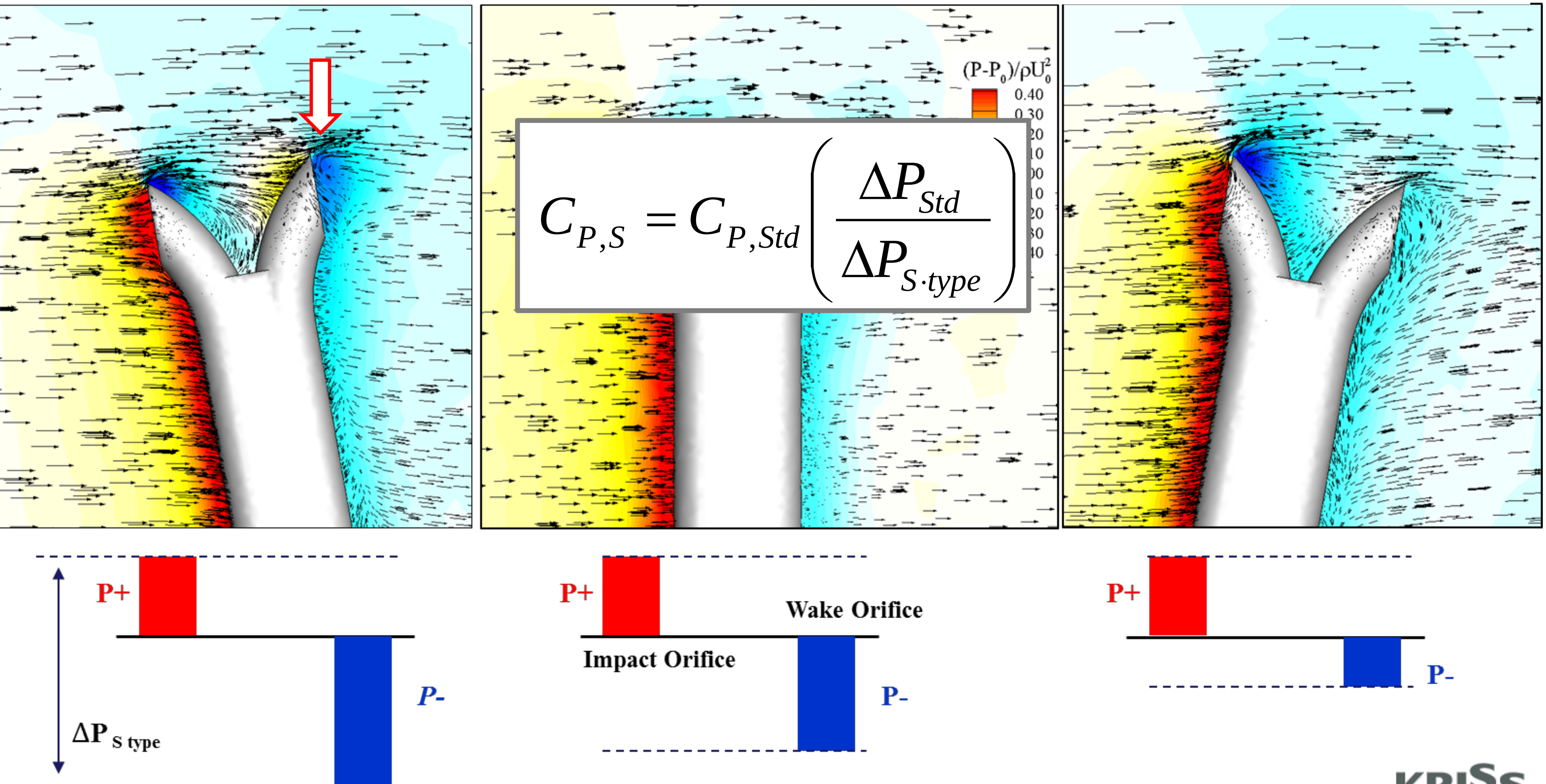
- In the positive pitch angle, the incoming flow separate strongly at the upper edge of the impact orifice due to tilted geometry
- Recovery of the pressure distribution near wake orifice

Pitch angle =-10° Pitch angle =0° Pitch angle =+10°



The effects of Pitch angle misalignment

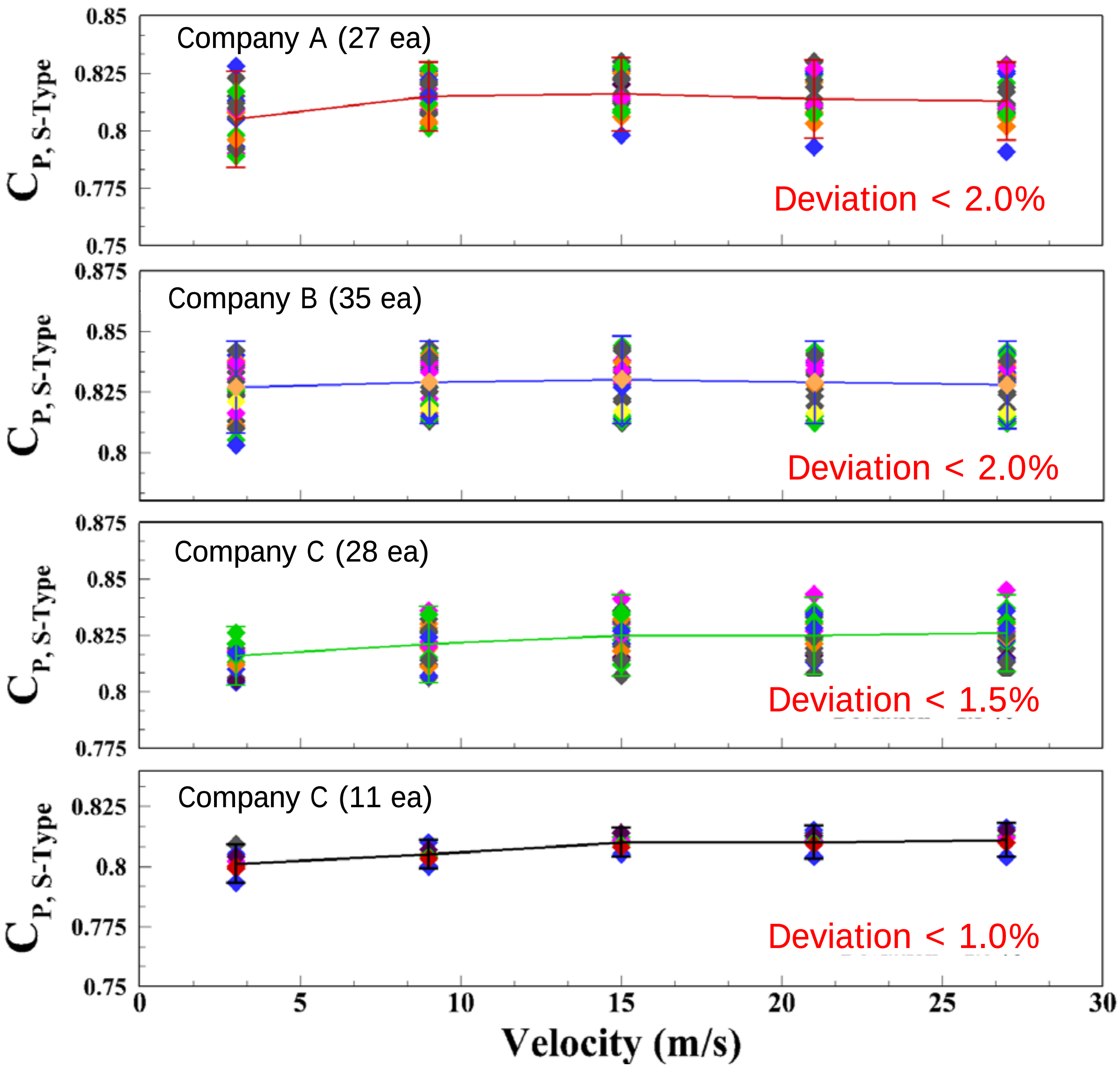
- In the negative pitch angle, low pressure distributions are observed near wake orifice because a vortical structure grows behind the wake orifice
- S-type Pitot tube coefficients decrease for negative yaw angle by the definition of S-type Pitot tube coefficient



$$C_{P,S} = C_{P,Std}\left(\frac{\Delta P_{Std}}{\Delta P_{S\cdot type}}\right)$$

Manufacturing Quality

- 101 ea of S-type Pitot tubes of 4 major manufacturers in KOREA were calibrated in accredited calibration laboratory (Korea Environment Corporation) in 2011



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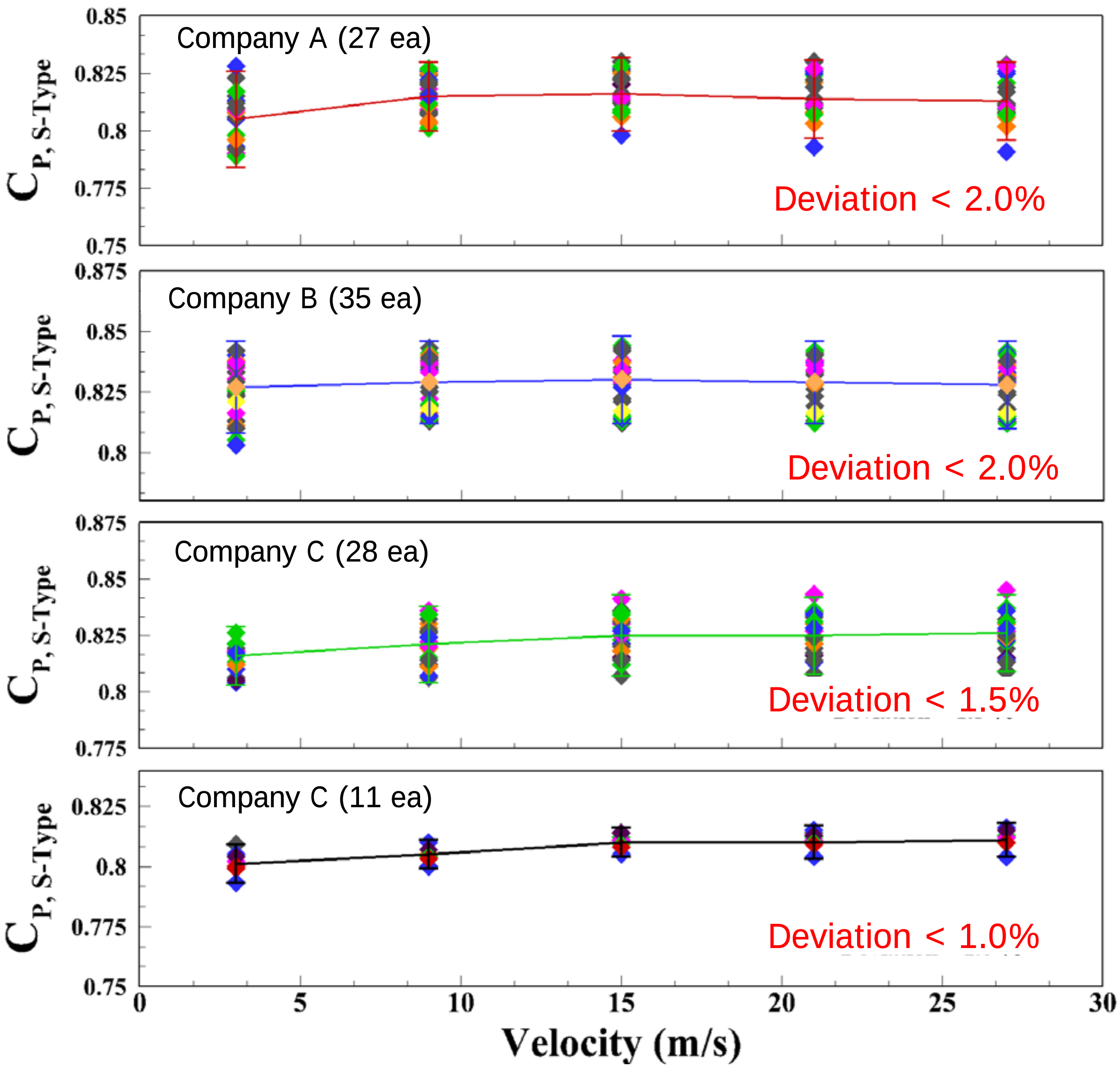
Manufacturing Quality

- The deviations of the S-type Pitot tube coefficients for the same product of one company vary from 1% to 2%



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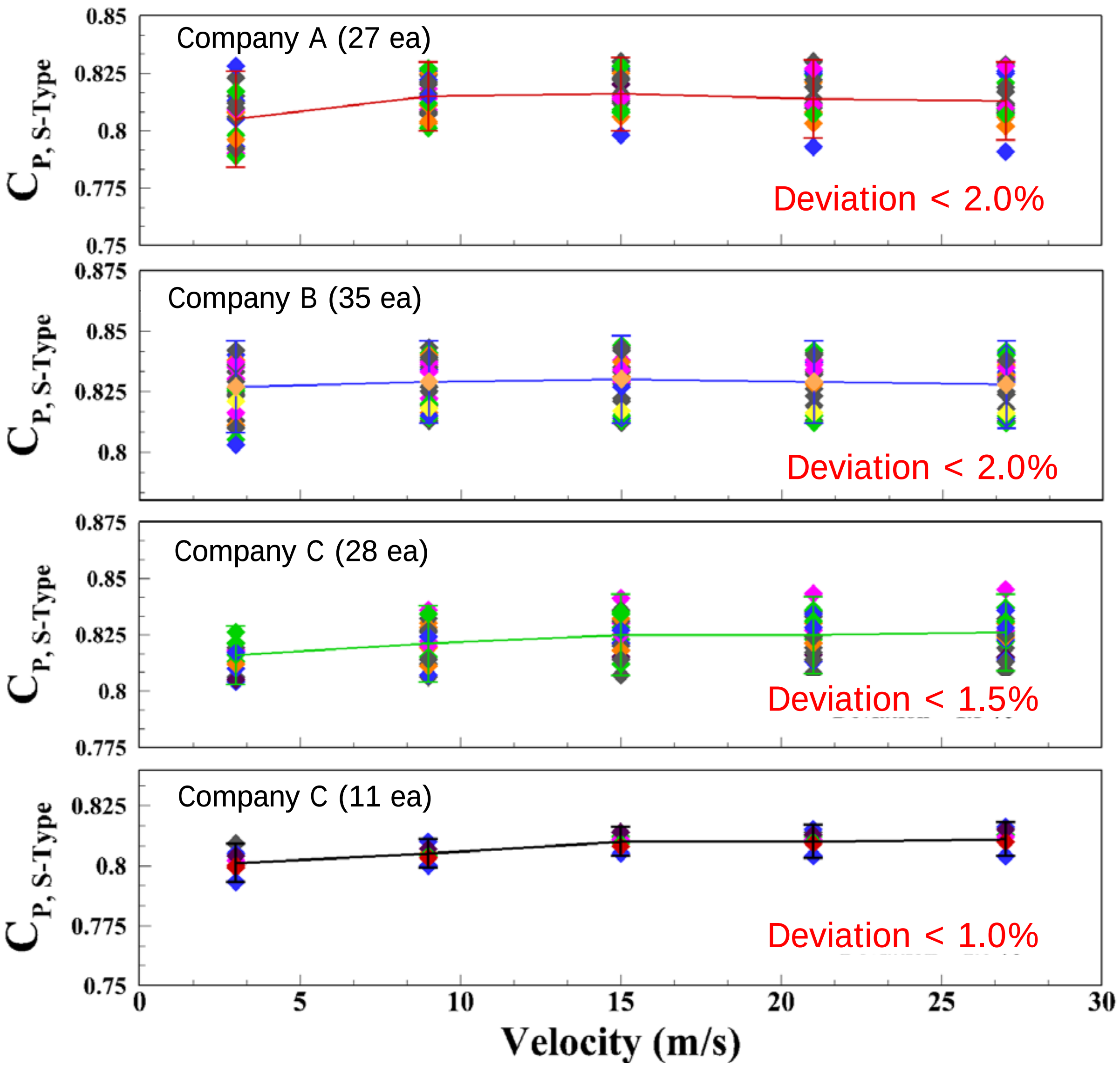
Manufacturing Quality

- Difference in the level of manufacturing quality of company due to not-strong regulation for standard geometry of S-type Pitot tube



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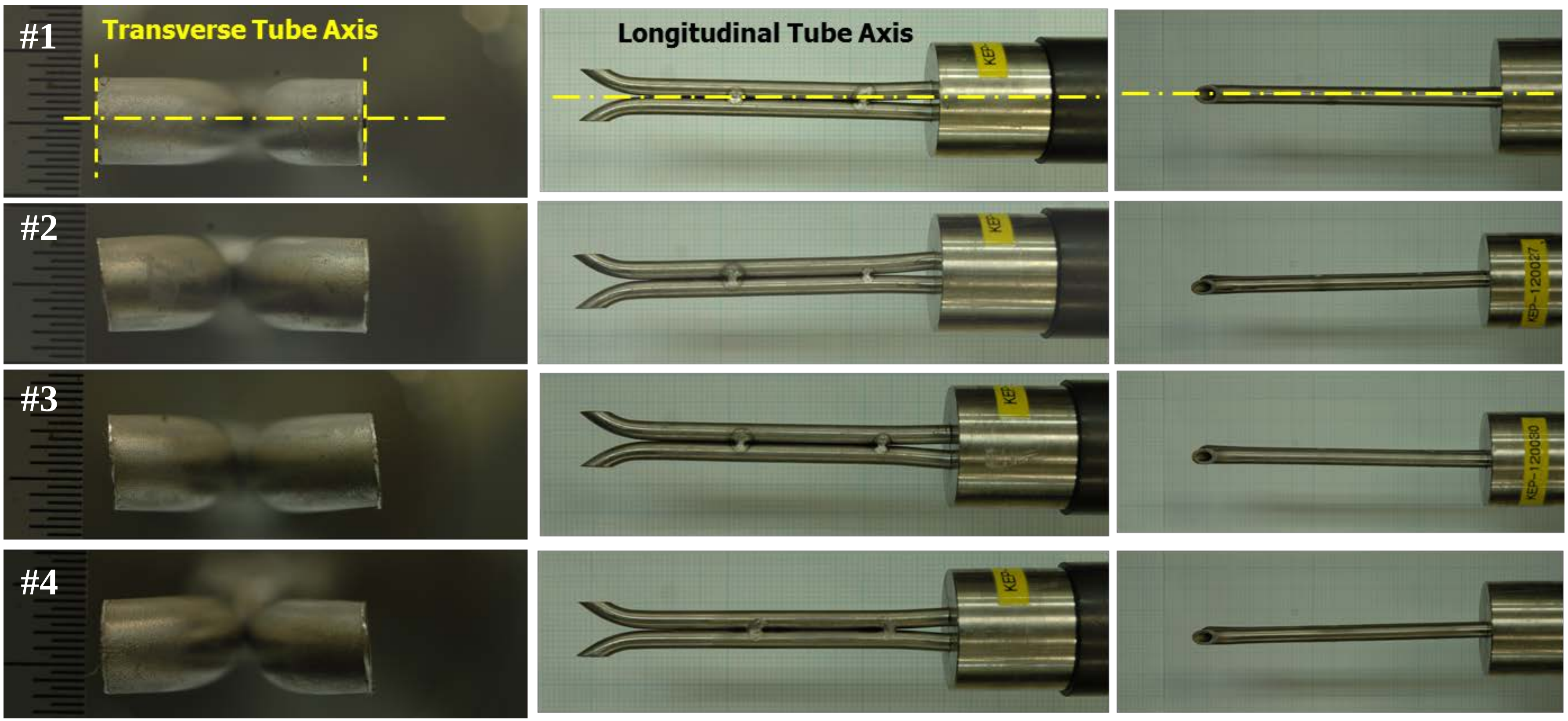
Manufacturing Quality

- 4 S-type Pitot tubes manufactured as same model by one company
- S-type Pitot tube calibration for comparison of 4 S-type Pitot tube coefficients



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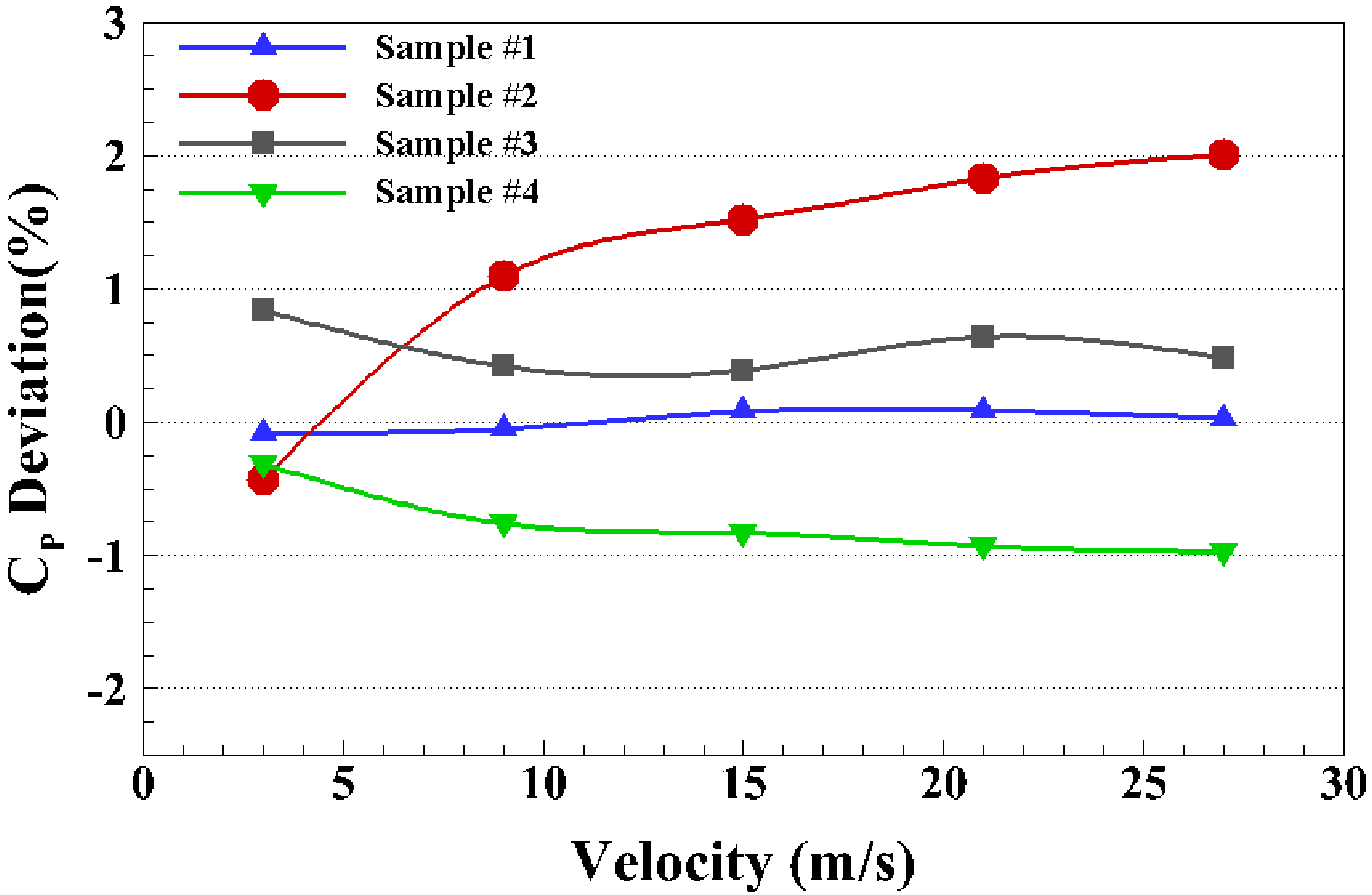
Manufacturing Quality

- Different deviations of each S-type Pitot tube coefficients within velocity range



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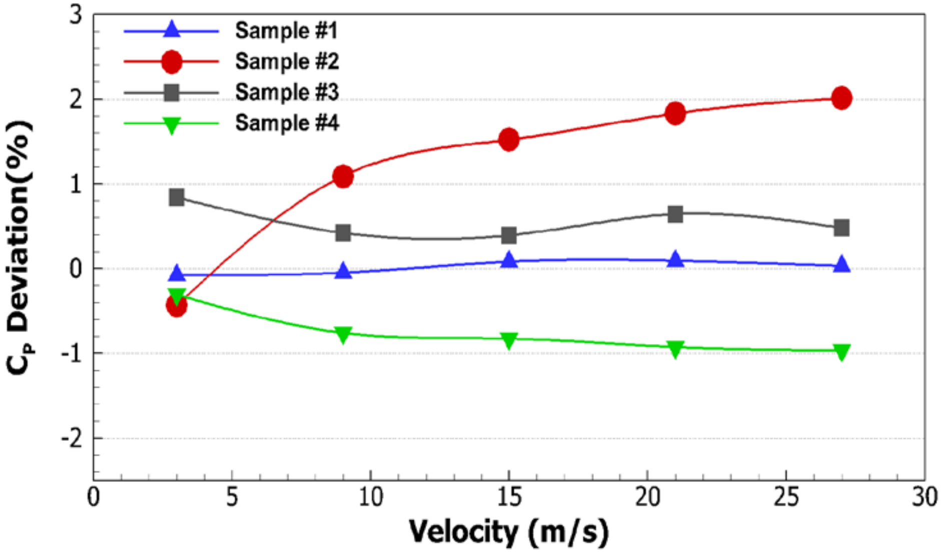
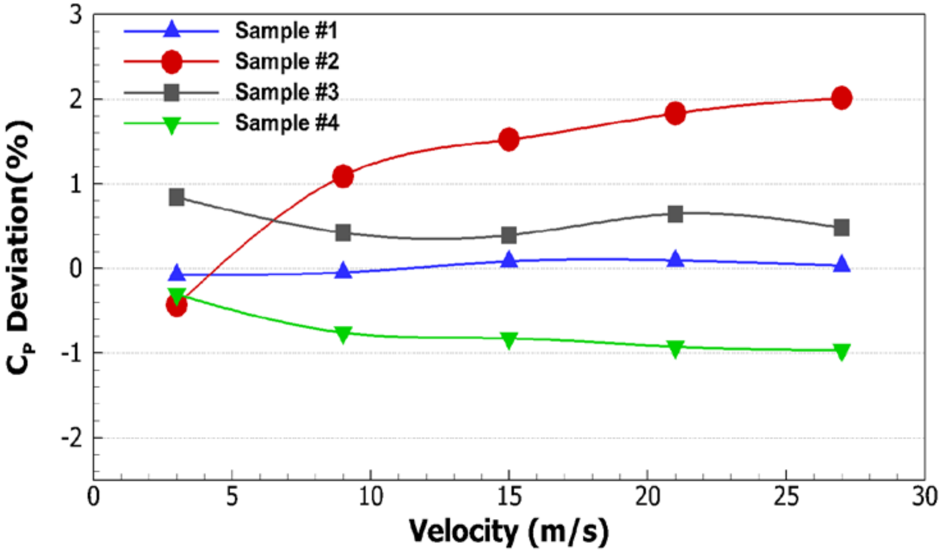
Manufacturing Quality

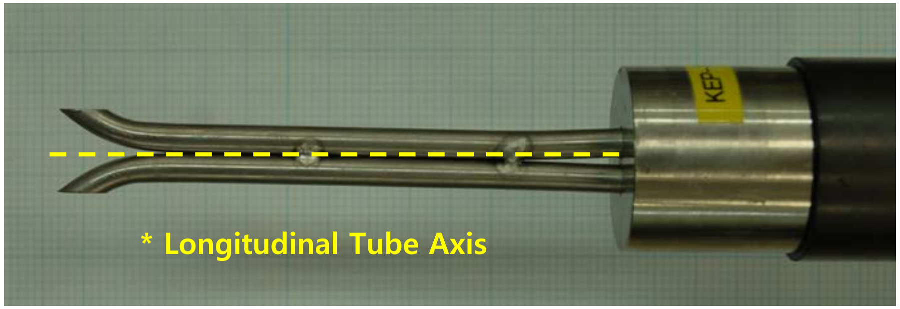
- To examine the cause for various deviation distributions of the same S-type Pitot tube model, detailed geometry of 4 S-type Pitot tube are compared

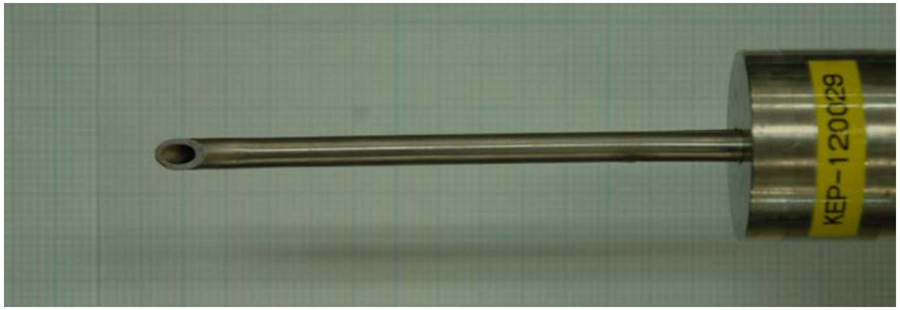


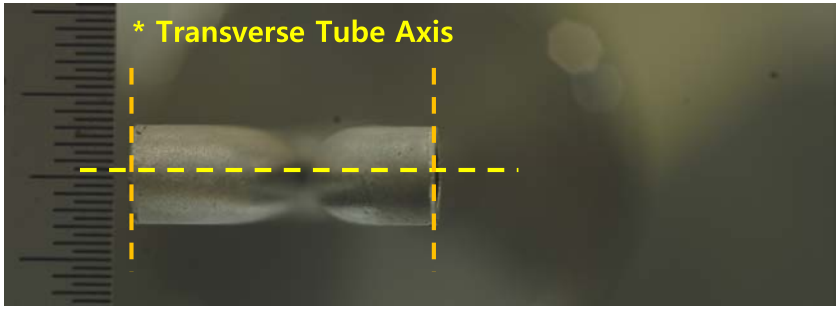
Manufacturing Quality : Sample #1

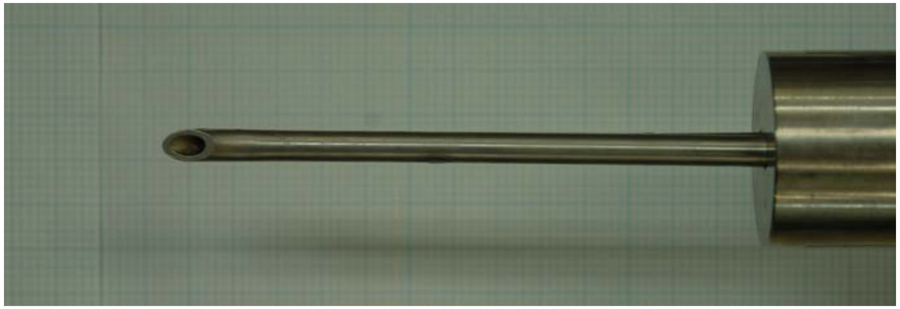
- Transverse tube axis is perpendicular to the surface of two orifices, longitudinal tube axis is parallel to S-type pitot tube





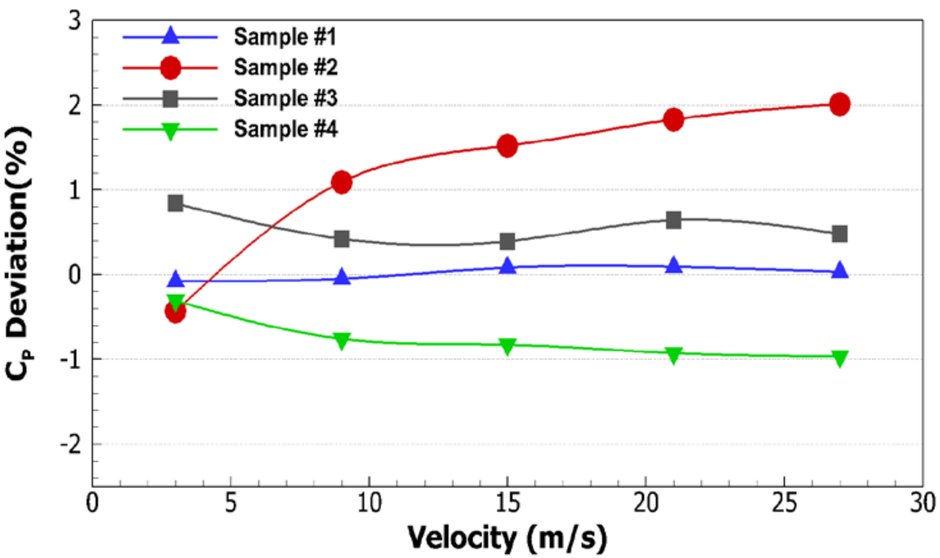


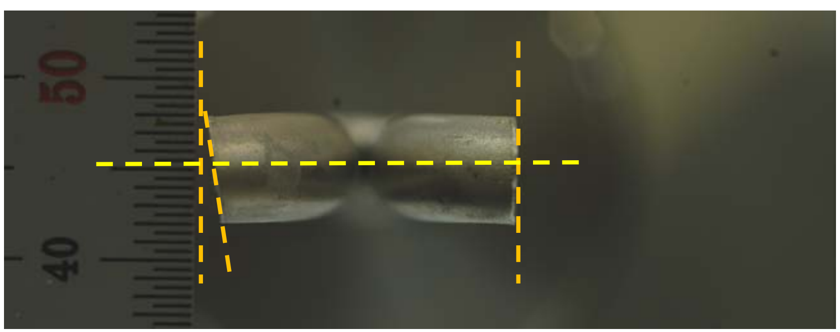


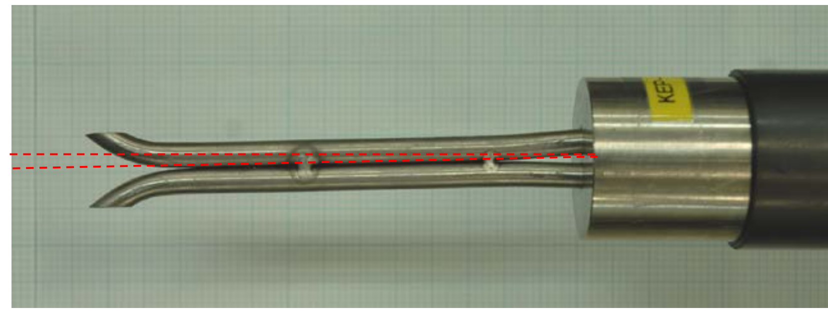


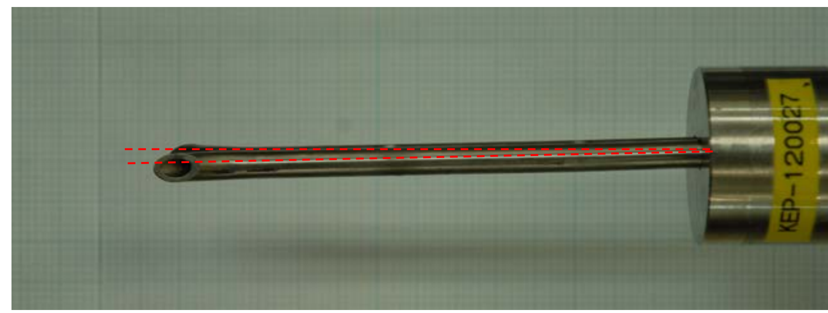
Manufacturing Quality : Sample #2

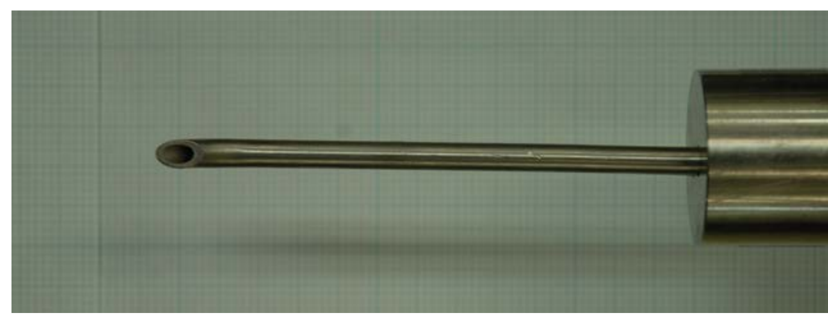
- Deviation of S-type Pitot tube coefficient increases up to 2% as the velocity increase





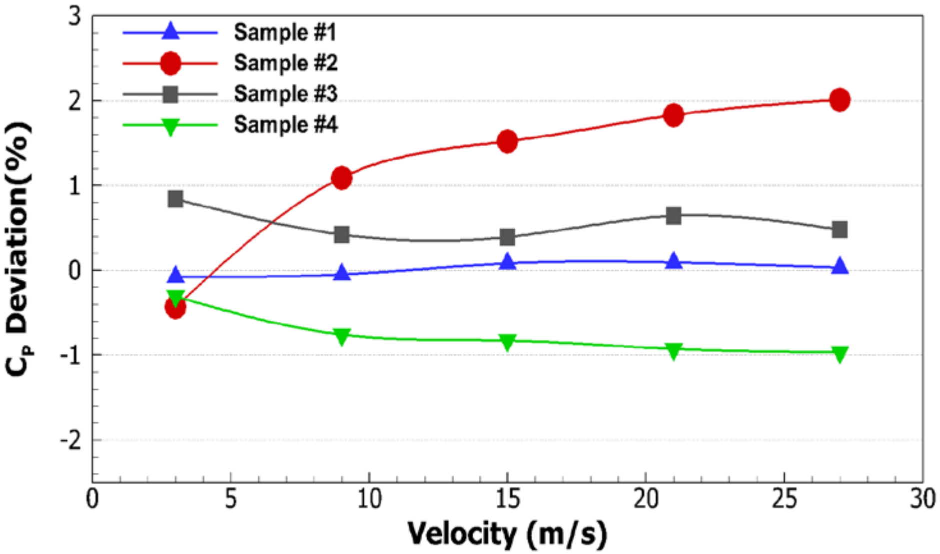


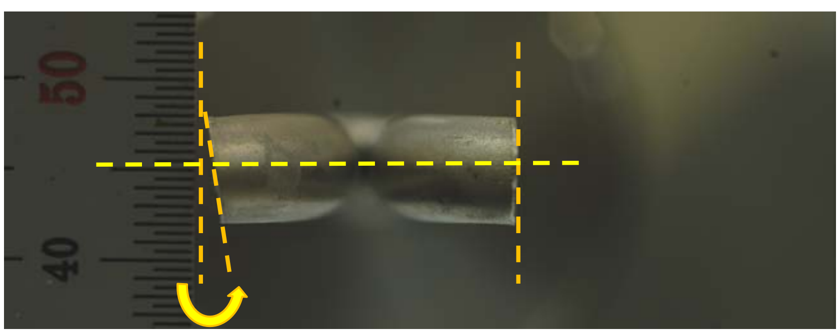


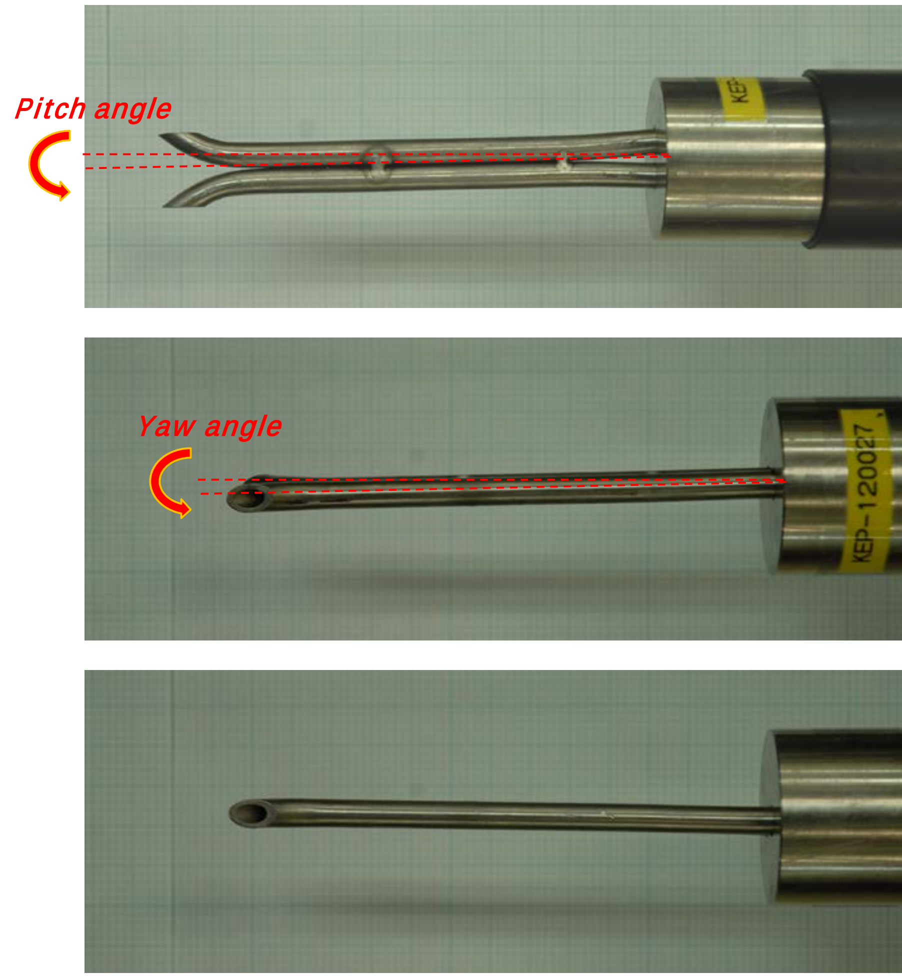


Manufacturing Quality : Sample #2

- Tilted longitudinal tube axes can induce pitch and yaw angle misalignment
- Asymmetric twisted surfaces of the impact and wake orifices

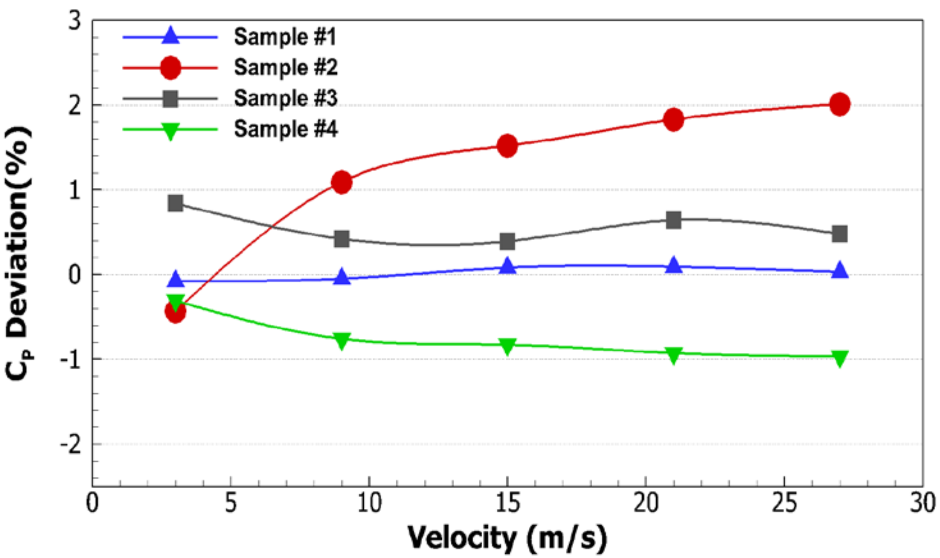


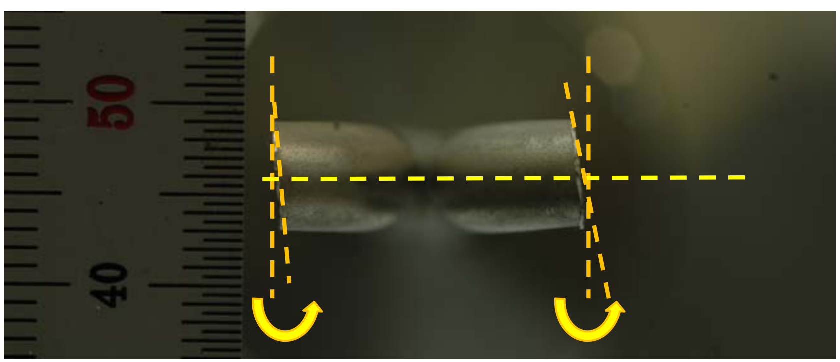


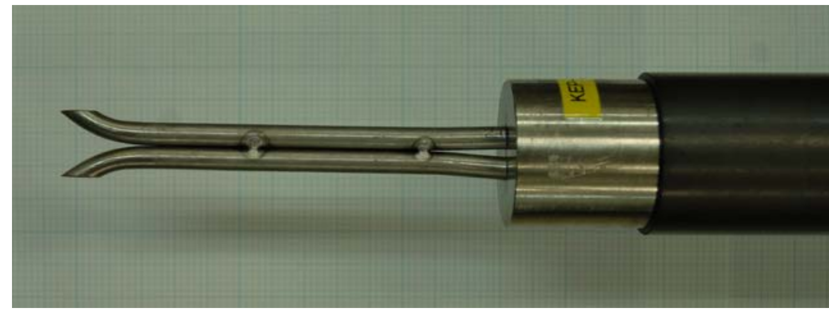


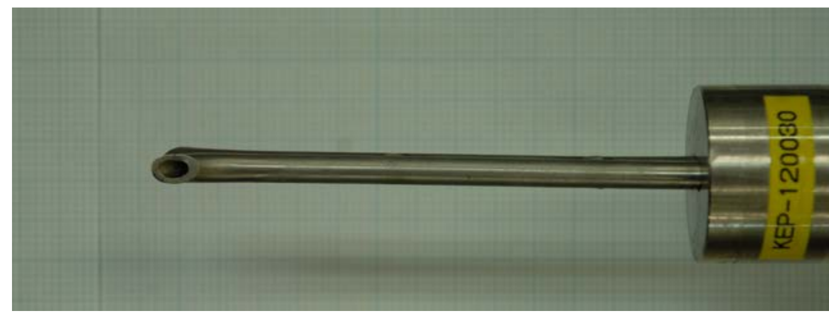
Manufacturing Quality : Sample #3

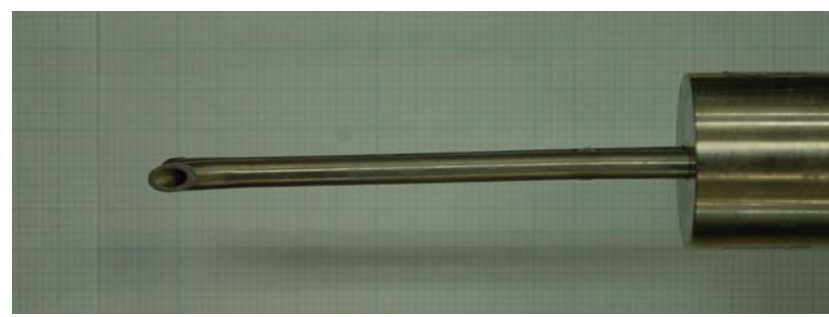
- Asymmetric twisted surfaces of the impact and wake orifices











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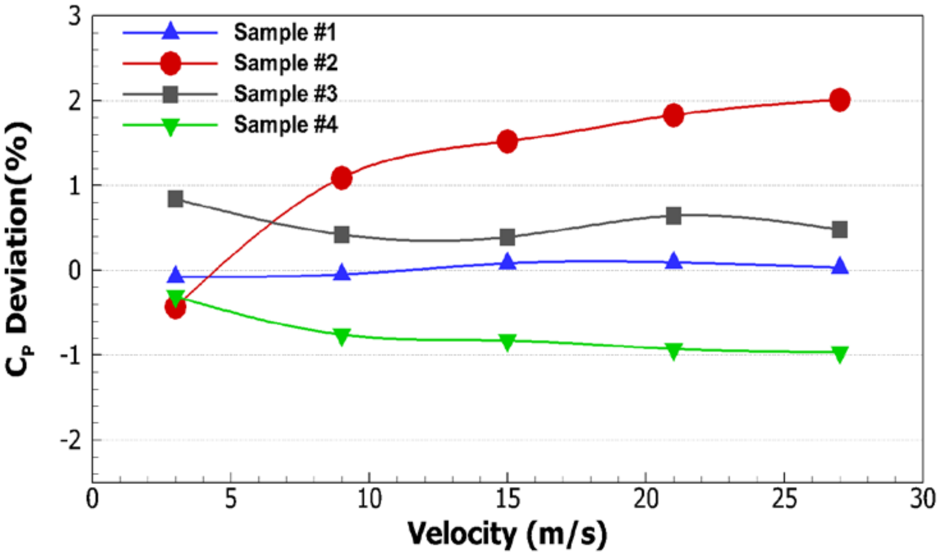
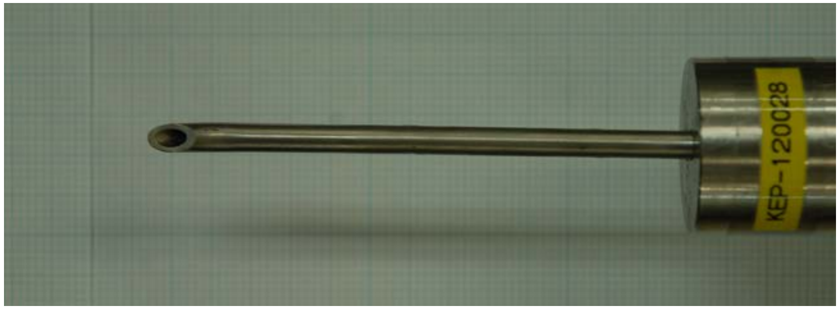
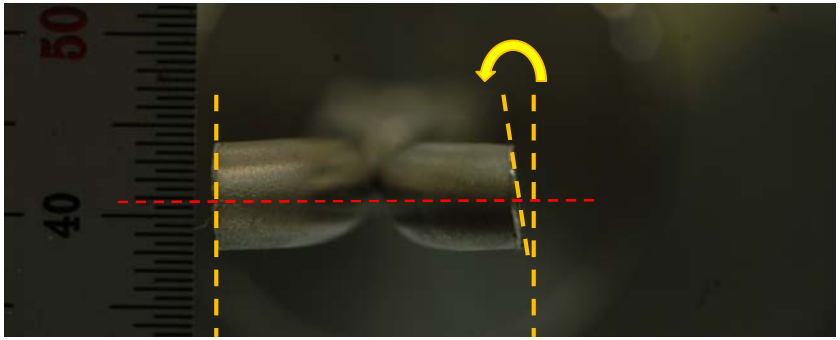
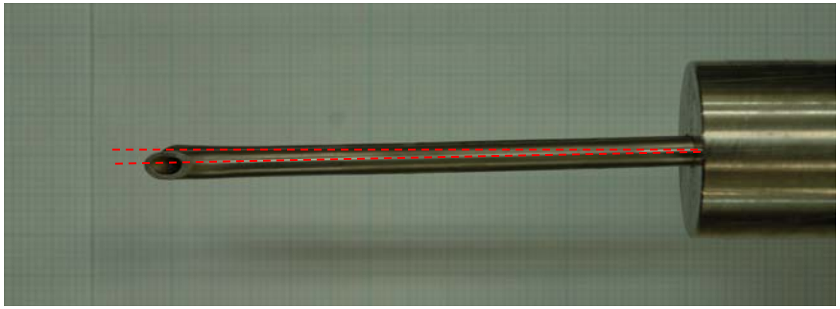
Manufacturing Quality : Sample #4

- Asymmetric twisted surfaces of the impact and wake orifices with tilted longitudinal tube axes









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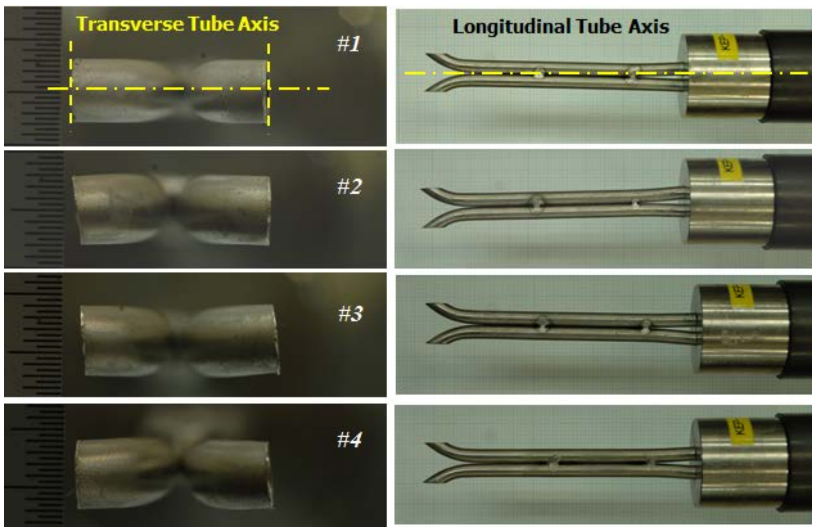
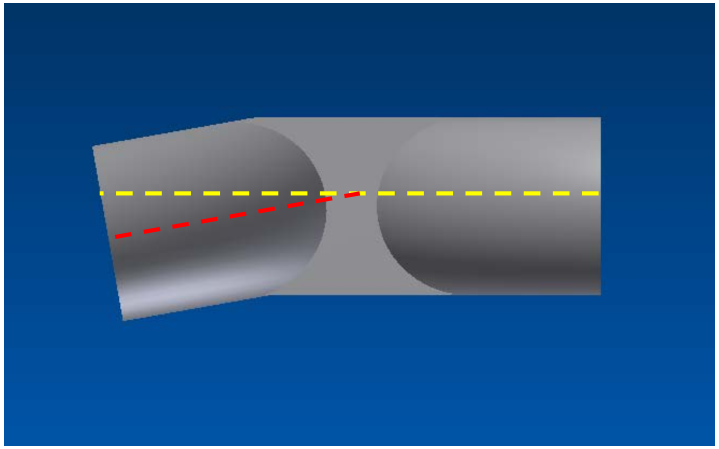
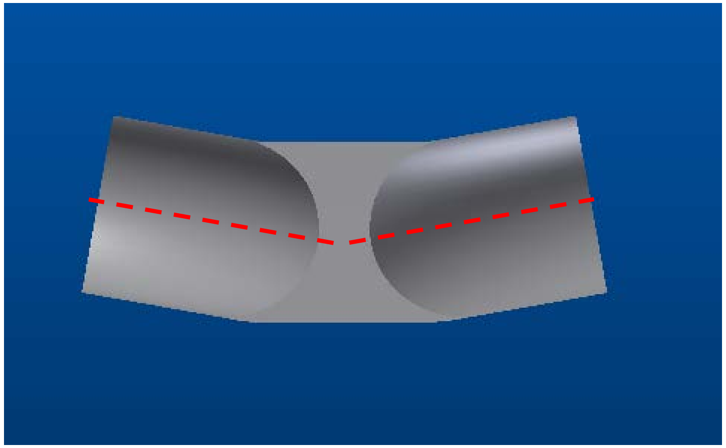
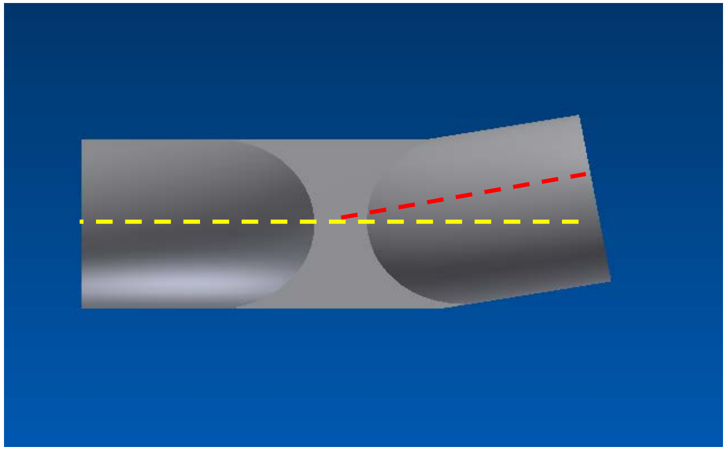
Future work : Numerical simulation

- Combined and complicated effect of deformed geometry of S-type Pitot tube









Uncertainty Evaluation

- 9th ISFFM, Kang et al. "Uncertainty Analysis of Stack Gas Flow Measurement with S-Type Pitot Tube for Estimating GHG Emissions"

$$Q = V \times A \times \frac{T_{std}}{T_s} \times \frac{P_s}{P_{std}} \times (1 - X_w) \times 300$$

Uncertainty Evaluation

- Largest uncertainty component is the velocity distribution inside the stack in uncertainty budget

Symbol	Value	unit	Uncertainty component		Sensitivity coefficient	Combined uncertainty contribution
			Type A %	Type B %		
C_p	0.826	-	-	0.55	1	0.55 %
ΔP	136.4	Pa	0.80	1.09	0.5	0.68 %
ρ	1.33	kg/m^3	0.0054	1.05	0.5	0.53 %
D	2500	mm	-	0.23	2	0.46 %
P_s	756	mmHg	0.0019	0.13	1	0.13 %
T_s	409	K	0.0046	0.24	1	0.25 %
$1-X_w$	91.5	%	0.0016	0.30	1	0.30 %
ΔV_D	14.8	m/s	1.54	-	1	1.54 %
Q	12972.5	m^3/min (5min)				
Combined uncertainty of the flow rate measurement						1.94 %
95 % confidence level, k=						2
Expanded Uncertainty, U =						3.88 %

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Conclusion

- S-type Pitot tube is mainly applied to measurement stack velocity for CEM in KOREA
- The effect of Reynolds numbers, misaligned installations and manufacturing quality on S-type Pitot tube coefficients were investigated by wind tunnel experiments and numerical simulation
- As long as S-type Pitot was manufactured properly, the change of Reynolds number has no effect on S-type Pitot tube coefficients
- S-type Pitot tube coefficients decreased by up to -2% as yaw angle misalignments occurred between -10° and + -10°
- The maximum deviation of S-type Pitot tube coefficient is approximately -2% for negative pitch angle (deflection of Pitot tube), 4% for positive pitch angle
- The deviation of S-type Pitot tube coefficients for the same manufactured products varied from 1% to 2% due to insufficient manufacturing quality control. It can cause additional errors with misalignment effect

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