18th International Flow Measurement Conference

The Impact of Geometric Parameters of a S-type Pitot tube on the Flow Velocity Measurement at Smoke-stacks

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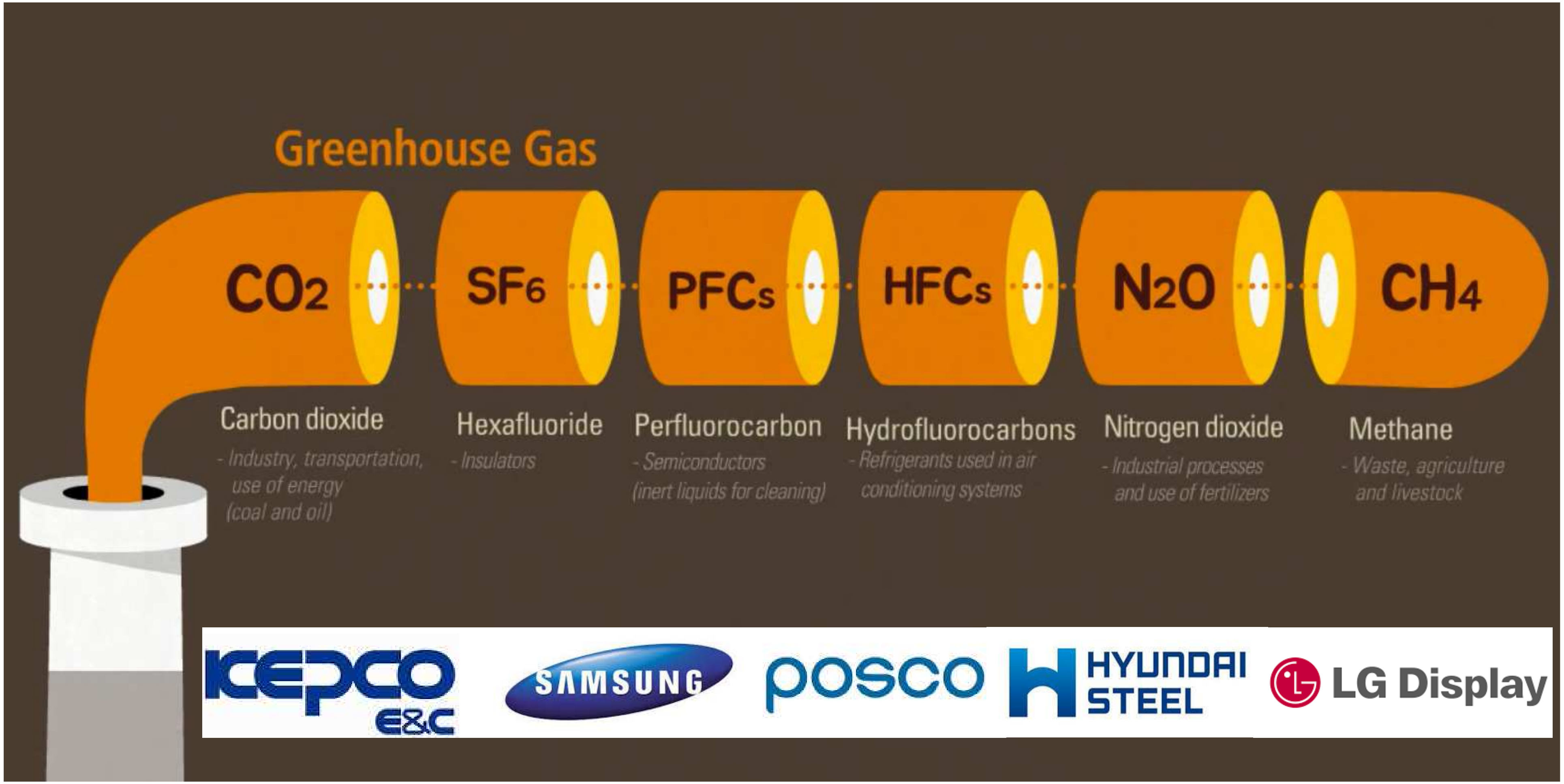
Contents

Korea Greenhouse Gas Emission Inventory

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

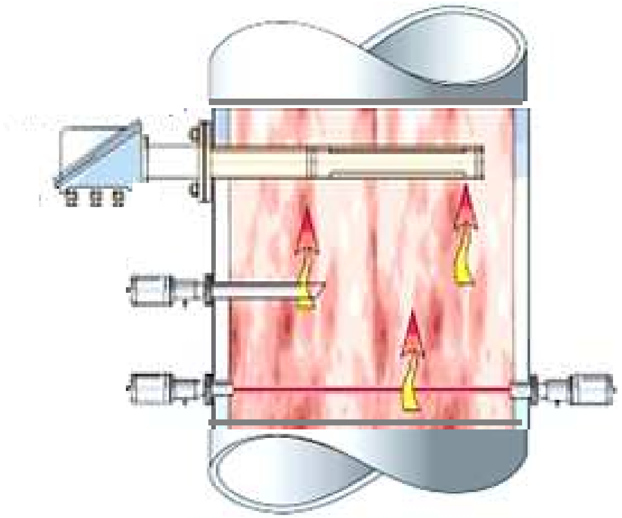


Continuous Emission Monitoring System

- Directly measure GHG emissions(E) by monitoring concentrations(C_i) and volumetric flow rate(Q) of an exhaust gas

$$E_{CEMS} = \sum_{i=1}^{N}(C_{5min,i} \times Q_{5min,i} \times \frac{M_{gas}}{MV})$$

CEMS (Tier 4)
by IPCC guidelines, EPA



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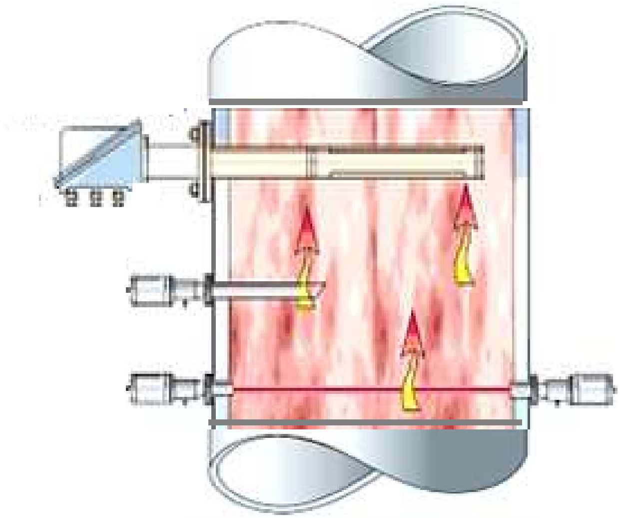
CEMS (Tier 4) by IPCC guidelines, EPA

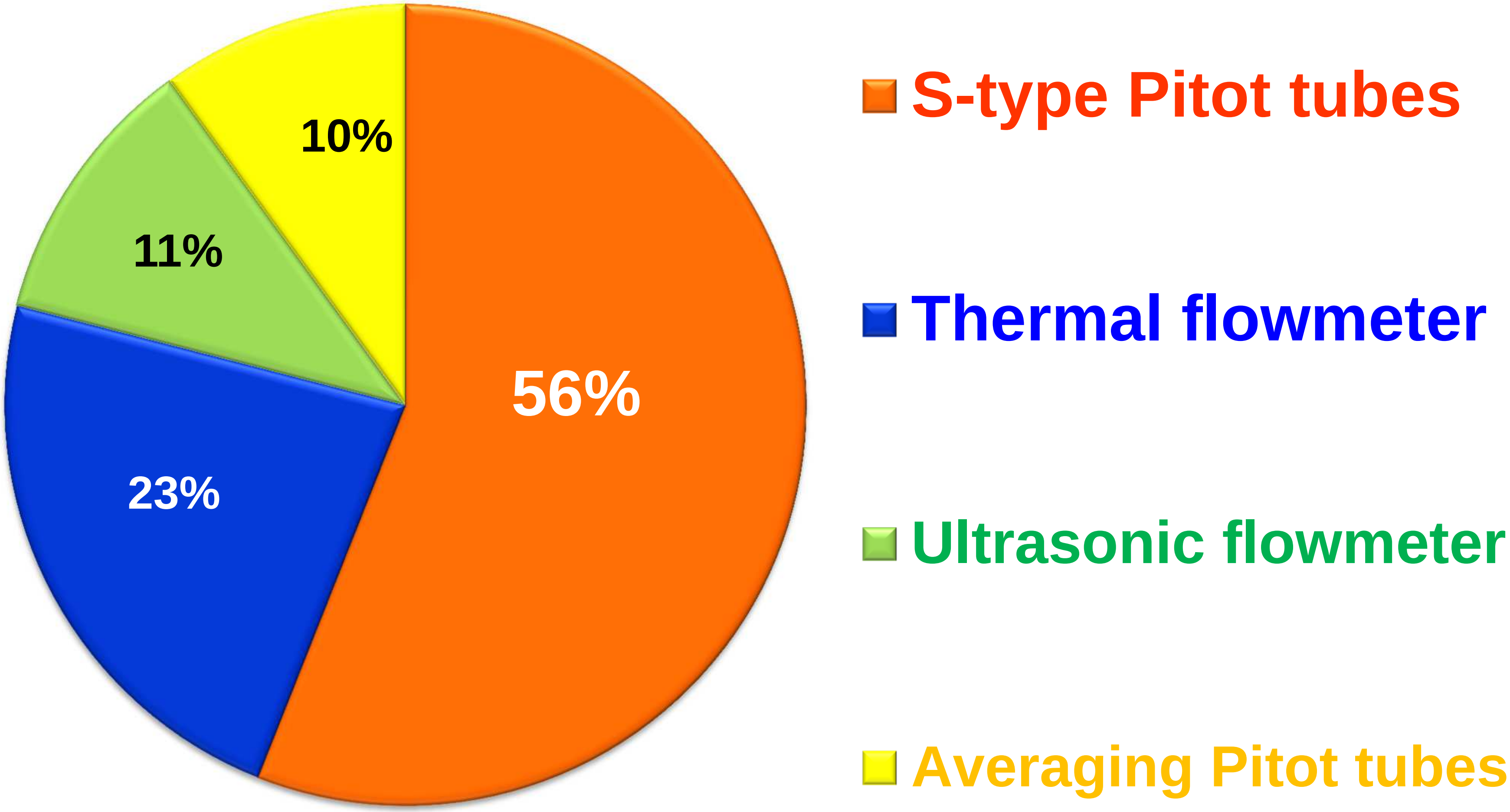
$$Q_{5min} = \bar{V} \times \frac{\pi D^2}{4} \times \frac{P_s}{760} \times \frac{273.15}{T_s} \times (1 - x_w) \times t$$

Volume Flowrate By EPA method 2,4

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

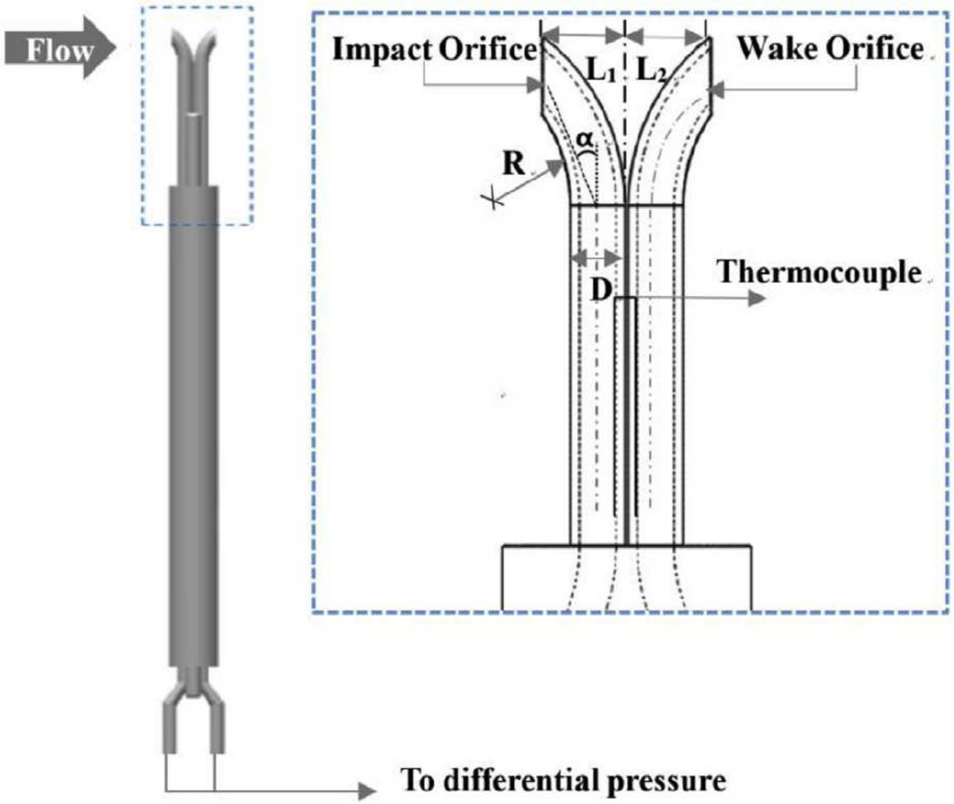


Instruments for Stack Flow Velocity in KOREA



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)

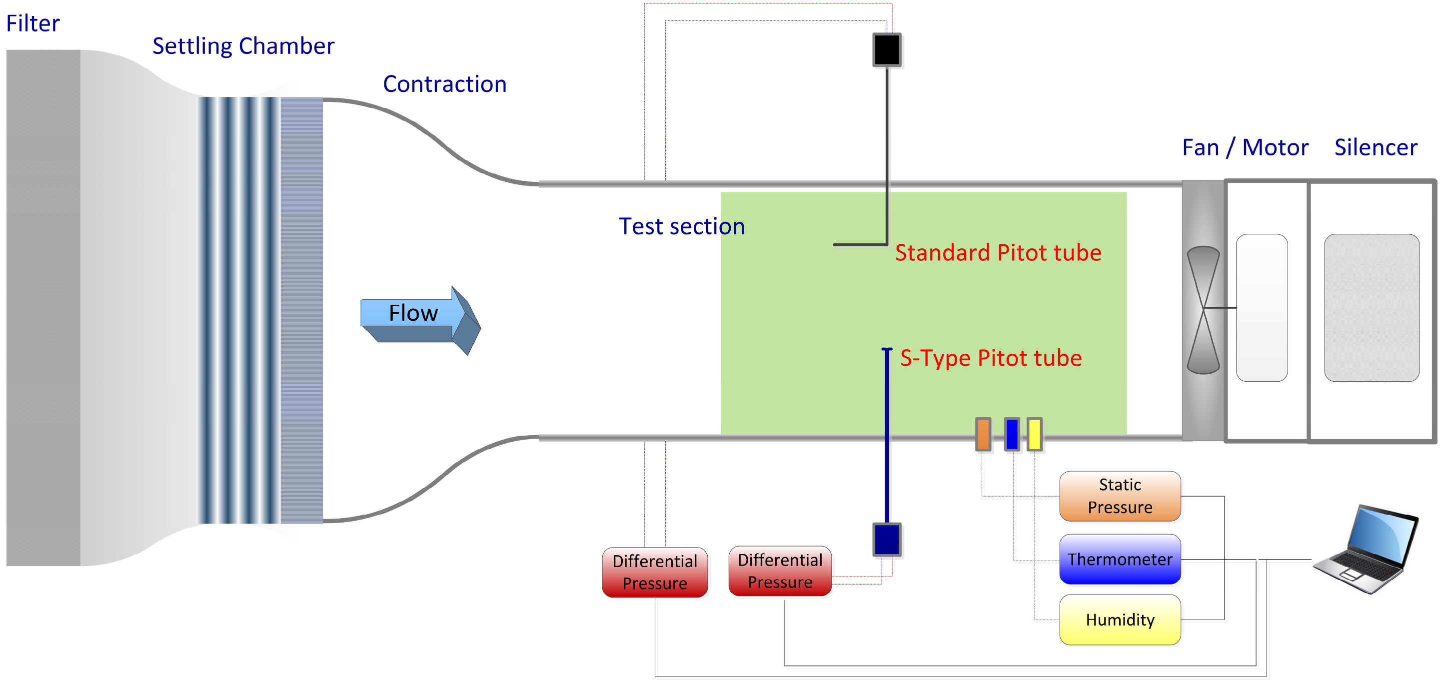
Calibration for S Pitot Tube Coefficient (C_p)

- 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-type Pitot tube coefficient
$C_{p,std}$: Stadard Pitot tube coefficient

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



Calibration for S Pitot Tube Coefficient (C_p)

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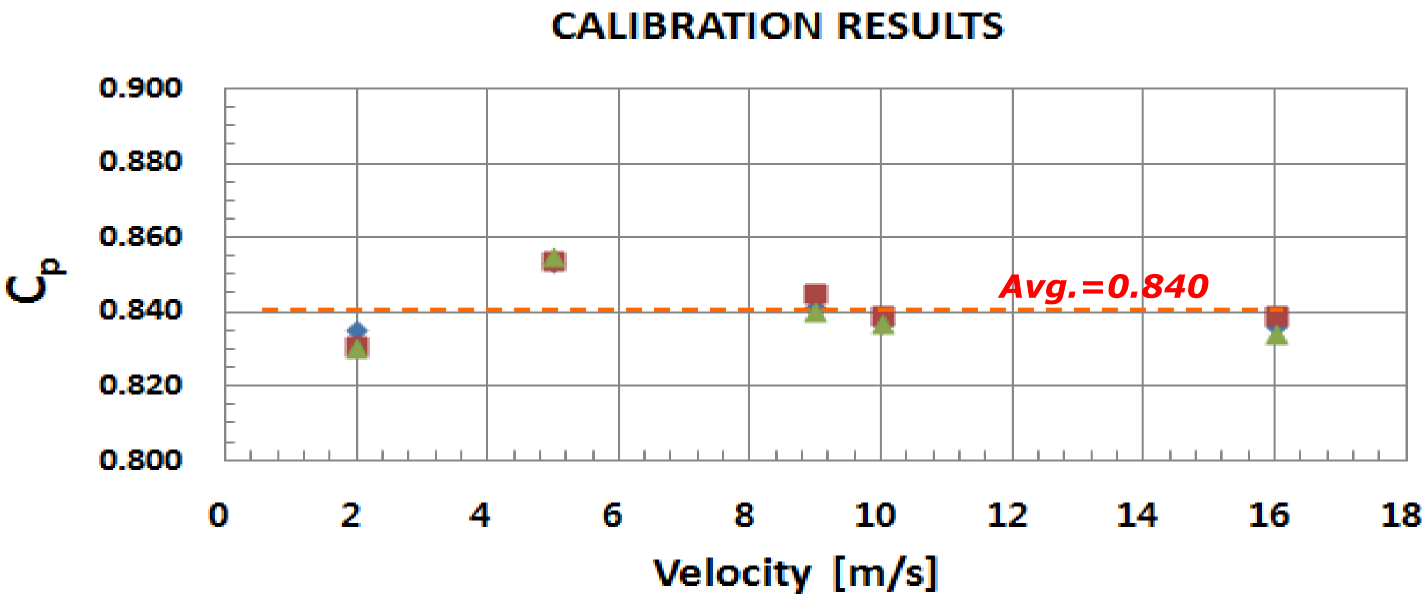
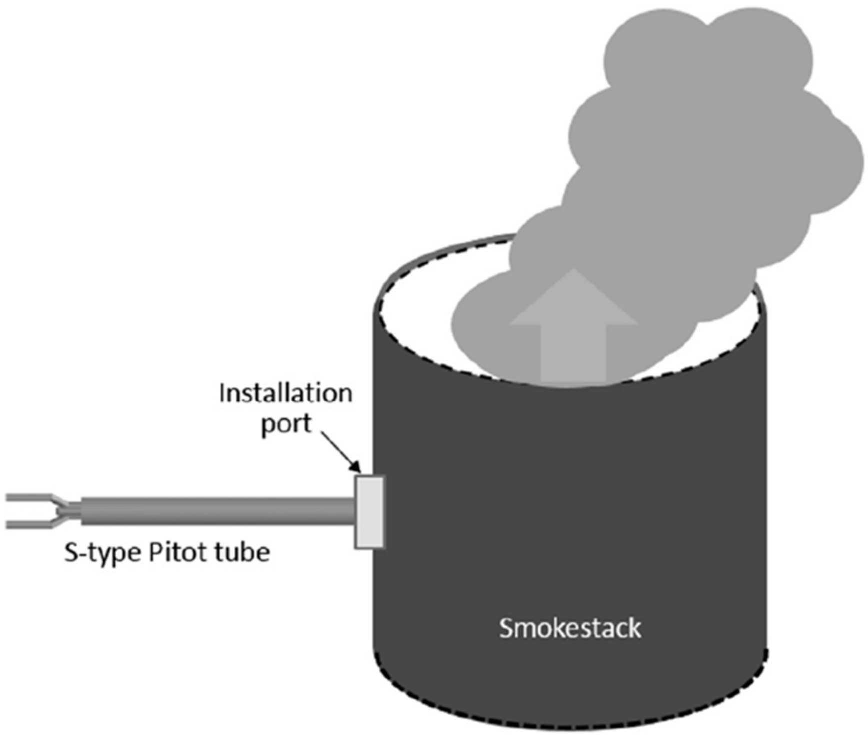


On-site Measurement

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

S-type Tube for Smokestack

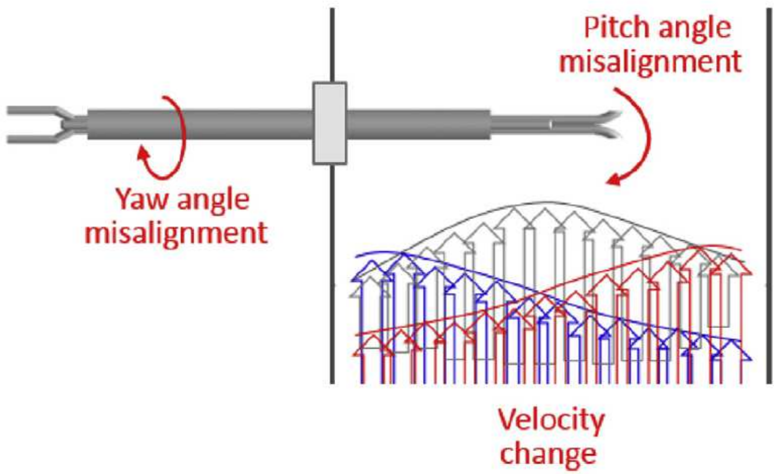
- When S-type Pitot tube install in the stack, there could be yaw, pitch angle misalignment and velocity change.



-Previous research: Flow Meas. & Instr. , Kang et al. 2015

S-type Tube for Smokestack

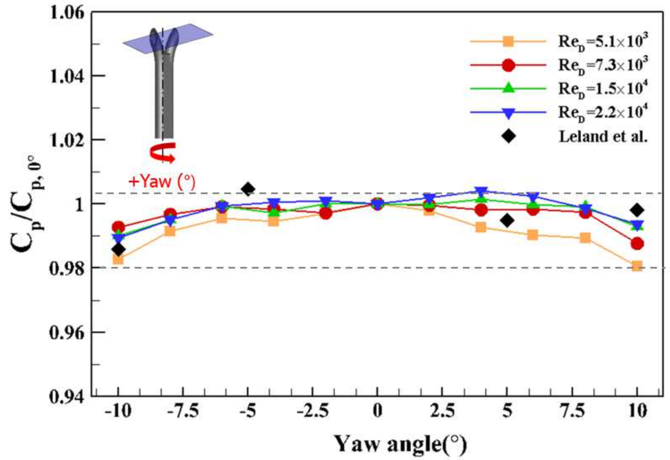
- Flow velocity of emission gas can be altered due to the unstable process in particular industrial condition of plant
- Yaw angle misalignment can occur during installation of S-type Pitot tube from outside of the stack due to the difficulty of observation
- Pitch angle misalignment of S-type Pitot tube can result due to the deflection of the long S-type Pitot tube in large diameter stacks.

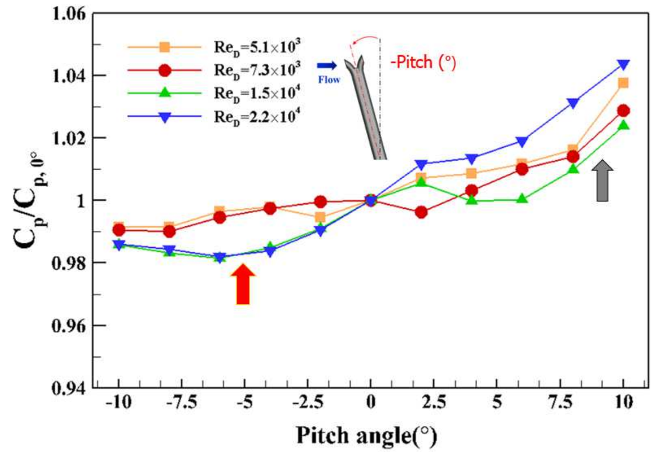


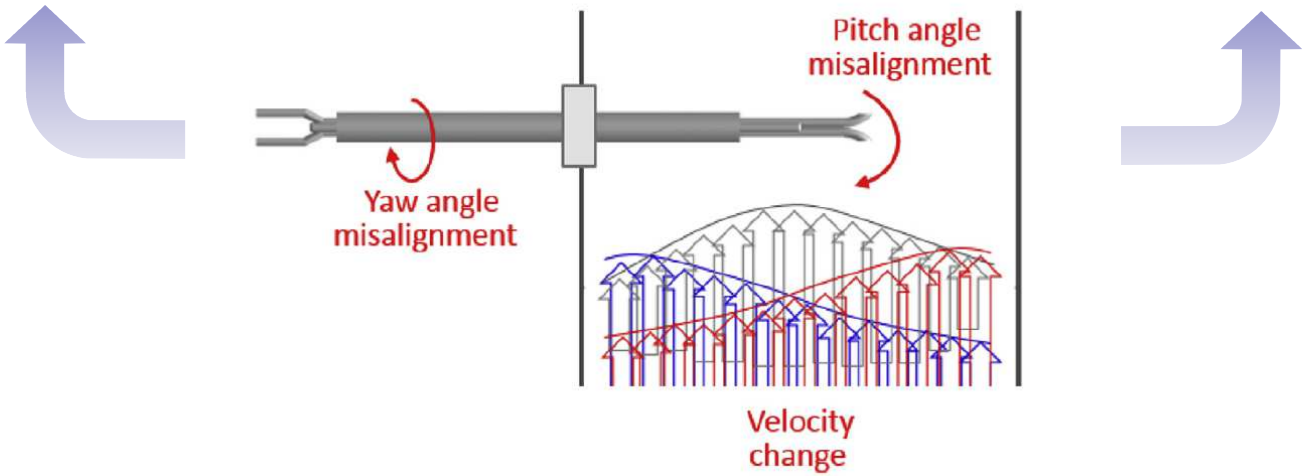
-Previous research: Flow Meas. & Instr. , Kang et al. 2015

S-type Tube for Smokestack

- When S-type Pitot tube install in the stack, there could be yaw, pitch angle misalignment and velocity change.
- But, one average calibration coefficient of S-type Pitot tube was used.



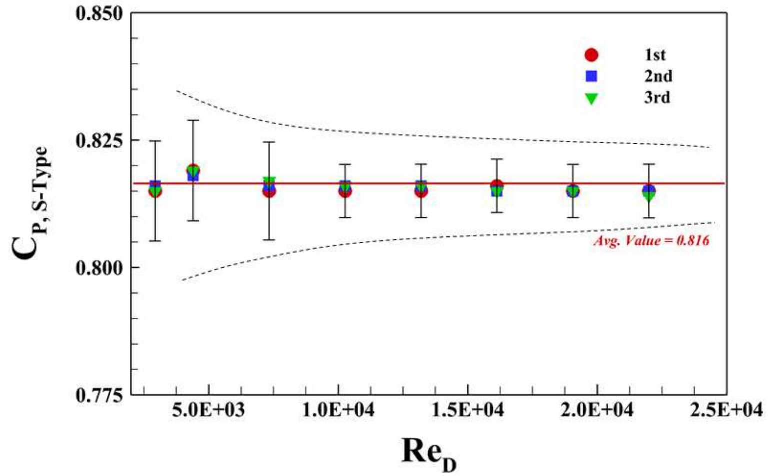




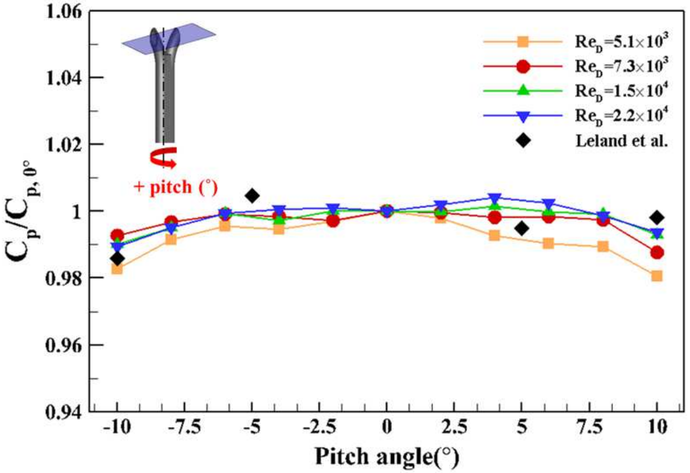
-Previous research: Flow Meas. & Instr. , Kang et al. 2015

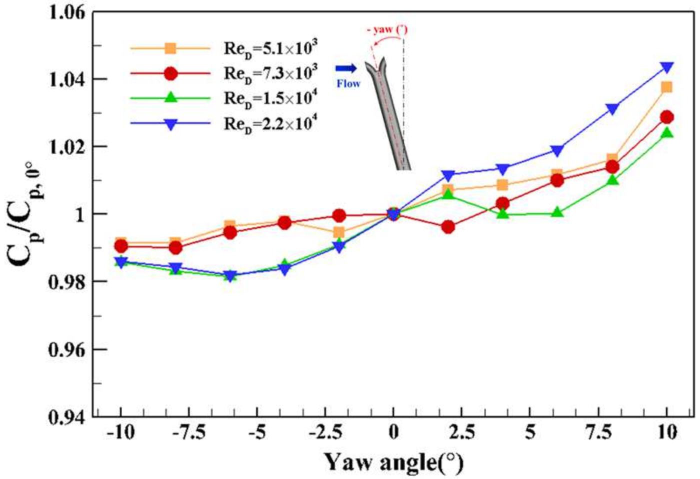
What is Ideal S-Type Pitot tube ?

- Linearity, Repeatability of S-type Pitot tube coefficient in the used range of Reynolds number



- Less sensitivity to the effect of yaw and pitch angle misalignment





Standardization of S-Type Pitot tube

INTERNATIONAL STANDARD

ISO 10780

First edition
1994-11-15

Stationary source emissions — Measurement of velocity and volume flowrate of gas streams in ducts

Émissions de sources fixes — Mesurage de la vitesse et du débit-volume des courants gazeux dans des conduites

ASTM INTERNATIONAL

Designation: D3796 – 09

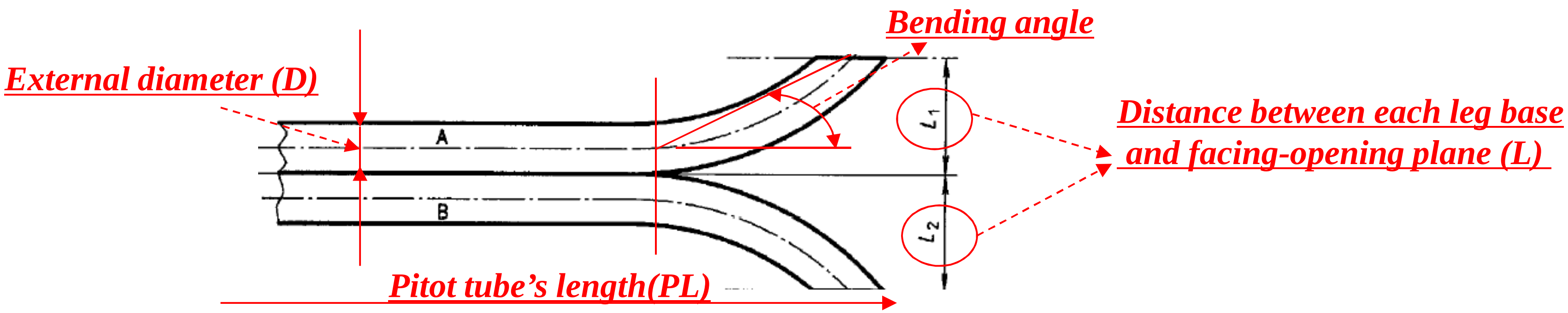
Standard Practice for
Calibration of Type S Pitot Tubes[1]

EPA
United States
Environmental Protection
Agency

Method 2—Determination of Stack Gas Velocity and Volumetric Flow Rate (Type S Pitot Tube)

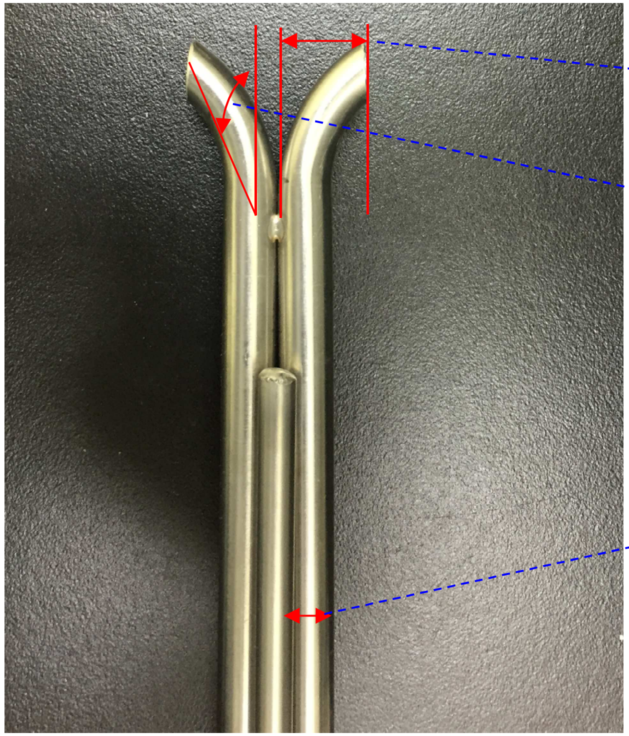
Recommended Configuration of S Pitot tube

ISO 10780	ASTM D3796(Ref. 1)	EPA
External diameter of leg (D) : 4 mm to 10 mm Distance between the base of each leg of the Pitot tube and its face-opening plane : 1.05D ≤ L ≤ 10D This distance shall be equal for each leg	Bending a 45° angle on the end of 0.95 cm stainless steel tube The Pitot tube's length : 0.6 m ≤ PL ≤ 3.0 m Cutting is parallel to the main body of the tube	External diameter of leg (D) : 4.8 mm to 9.5 mm Distance between the base of each leg of the Pitot tube and its face-opening plane : 1.05D ≤ L ≤ 1.50D This distance shall be equal for each leg



Configuration of S-type Pitot tube

- S-type Pitot tube KRISS used



Distance between each leg base and facing-opening plane (L)

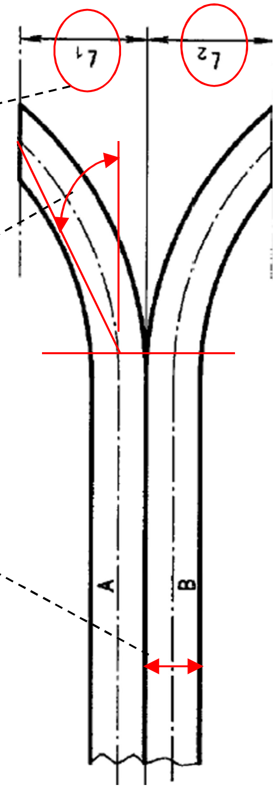
→L=1.6D

Bending angle

→α= 30 °

External diameter (D)

→D=9.5 mm



Contents

Research objective

- Evaluate the effect of various geometries of S-type Pitot tube on the S-type Pitot tube coefficients including the sensitivity to velocity change, pitch and yaw angle misalignments

→ Determine the optimal geometry of the S-type Pitot tube
to improve the accuracy of the velocity measurement in the real stack

Parameter #1: Distance between leg base and facing-opening plane (L)

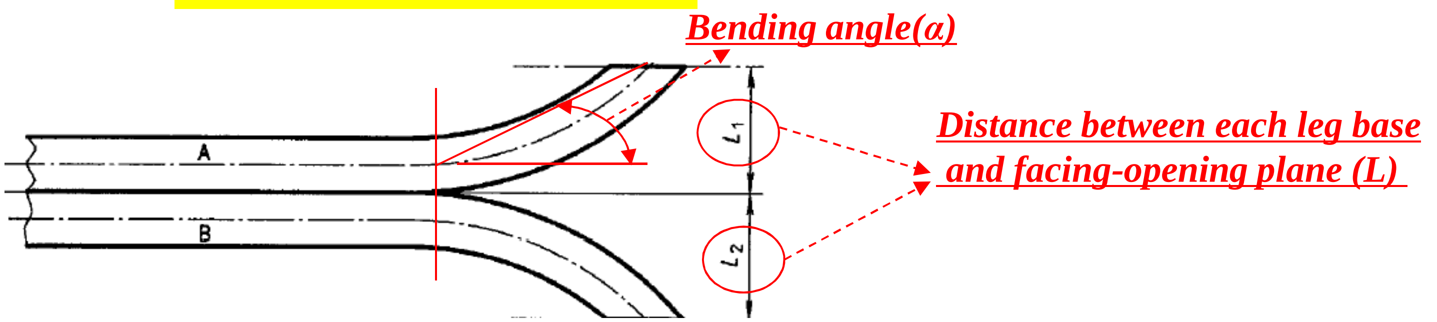
- ISO: 1.05D ≤ L ≤ 10D, EPA: 1.05D ≤ L ≤ 1.5D

→ **L = 1.05D, 1.6D, 3D**

Parameter #2: Bending Angle of opening parts

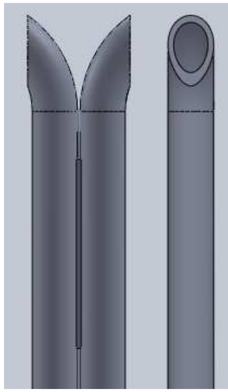
- ASTM: 45° (KRISS S Pitot = 30 °)

→ **α = 15°, 30°, 45°**

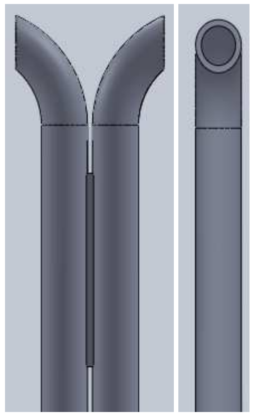


Configuration of S-type Pitot tube

- S-type Pitot tube KRISS used



L =1.05D, α = 30°

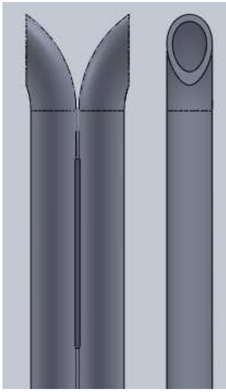


L = 1.6D, α = 30°

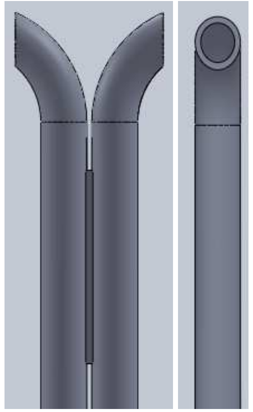
L = 3D, α = 30°

S-type Pitot tube Manufacturing

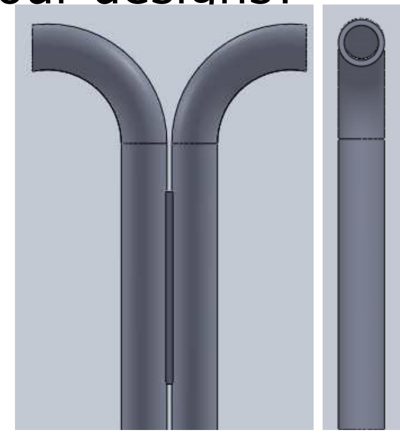
- How to manufacture S-type Pitot tube model for our designs?



L =1.05D, α = 30°

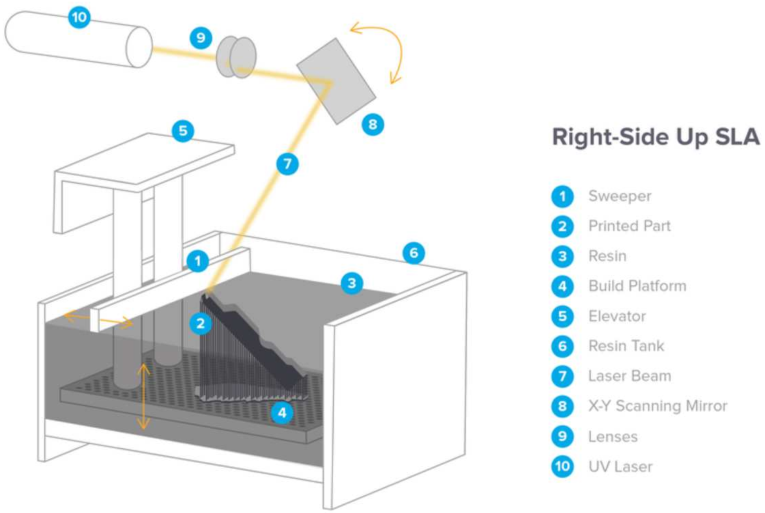


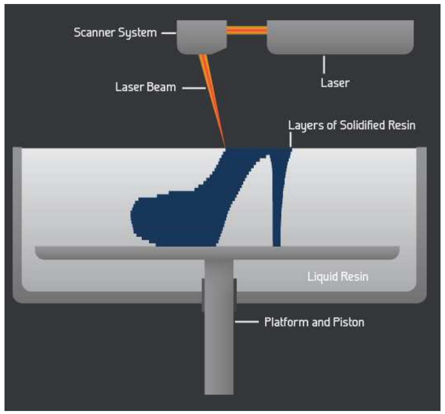
L = 1.6D, α = 30°

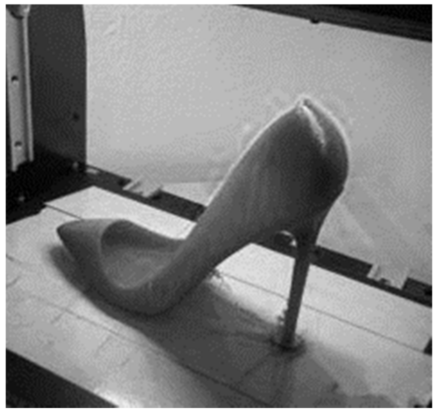


L = 3D, α = 30°

- 3D Printing (SLA, Streolithograhpy)
  - focusing an ultraviolet (UV) laser on to a vat of photopolymer resin with elevator



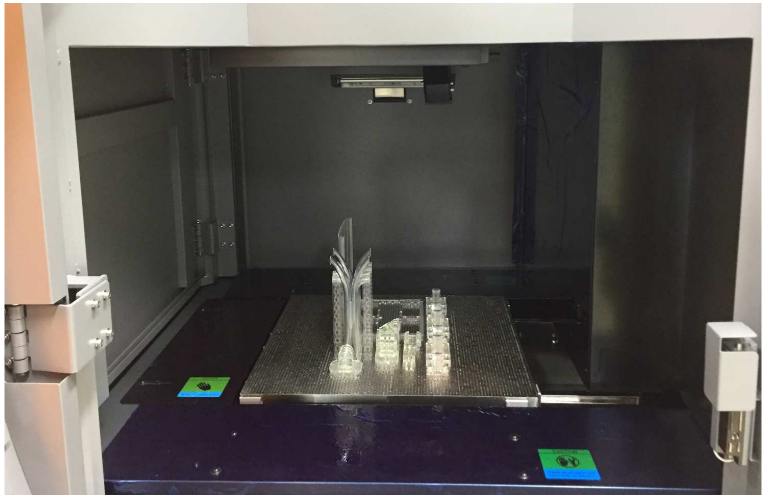




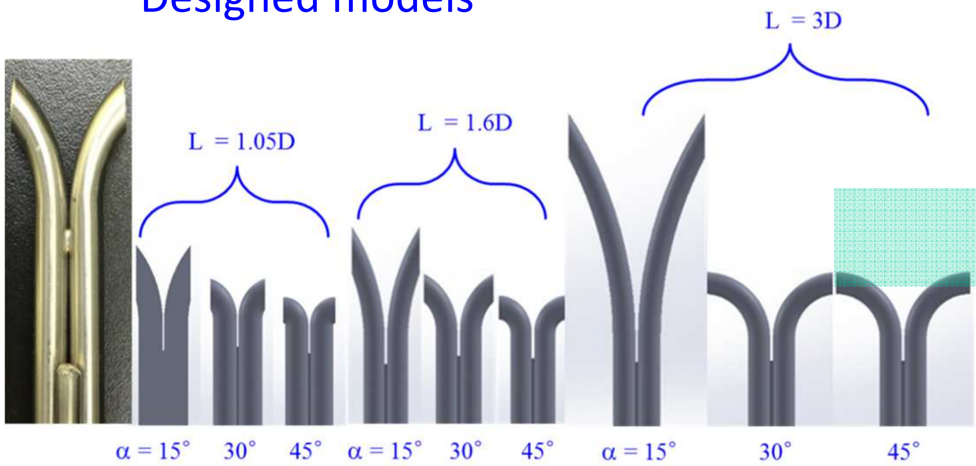
3D Printing for S-type Pitot tube

- 3D Printing S-type Pitot tube for our design(Daejeon Techno-park)

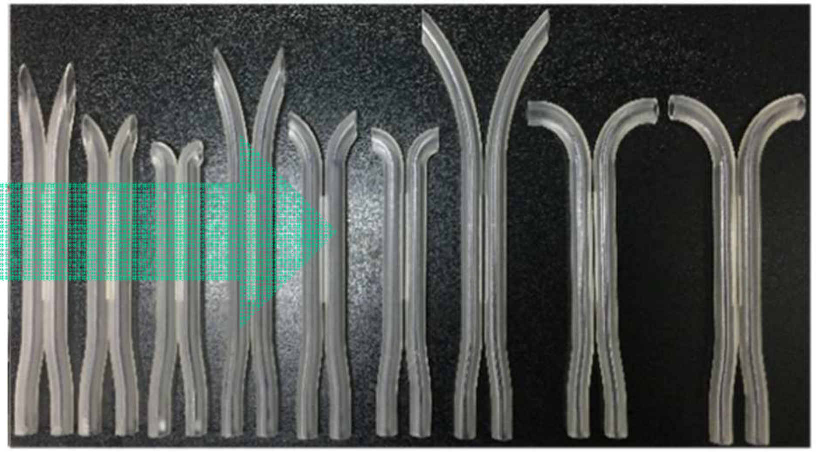
Model	ATOMm-4000
Equipped Laser	Solid state laser 400mW 40KHz
Scanning Method	Digital (TSS4)
Laser Warranty Period	1 year
Maximum Scanning Speed	30,000mm/sec
Laser Diameter	0.10 - 0.60mm (automatically changeable)
Maximum Model Size	400×400×300mm
Z Table	Minimum layer pitch 25μm *depends on the resin used
Recoater	Blade recoater
Resin Surface Control	Balloon
Power Supply	AC100V×1 Single phase 15A
Equipment Dimension	Approx.W1565×D1050×H1860mm
Equipment Weight	Approx.550kg (not including resin)
Software	C-Sirius
PC OS	Windows 7
Operation	English/ Japanese



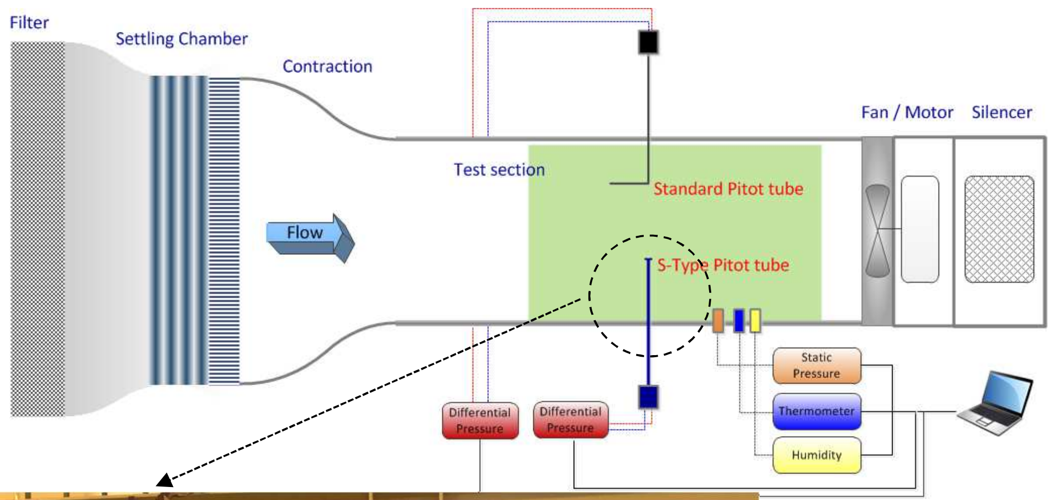
Designed models



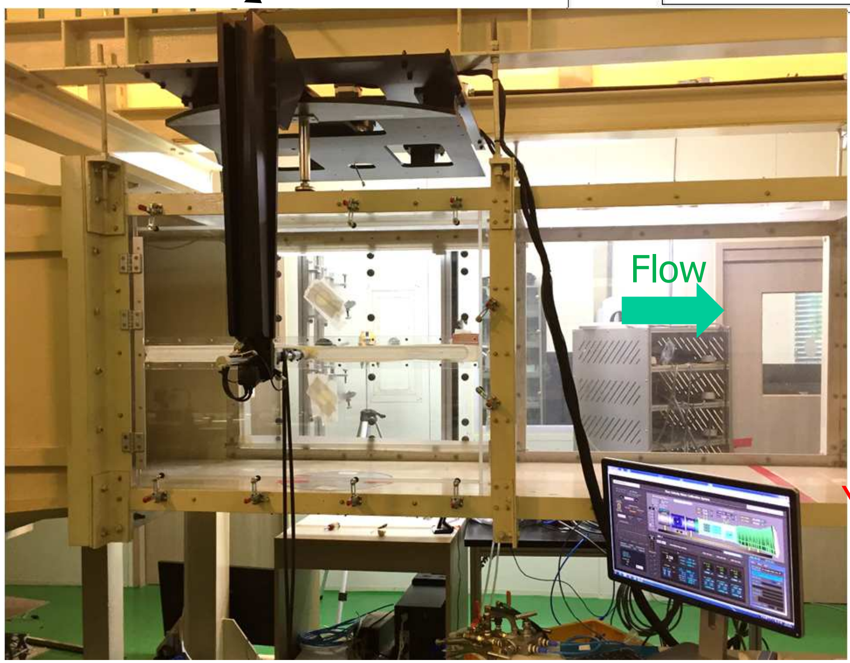
3D printer models

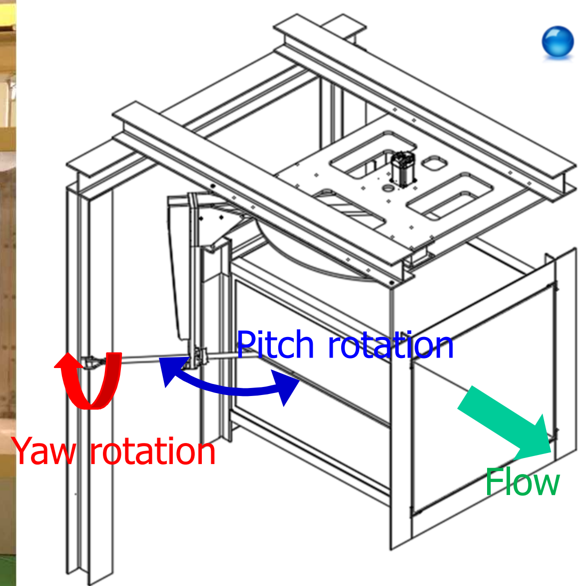


Windtunel experiments



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%



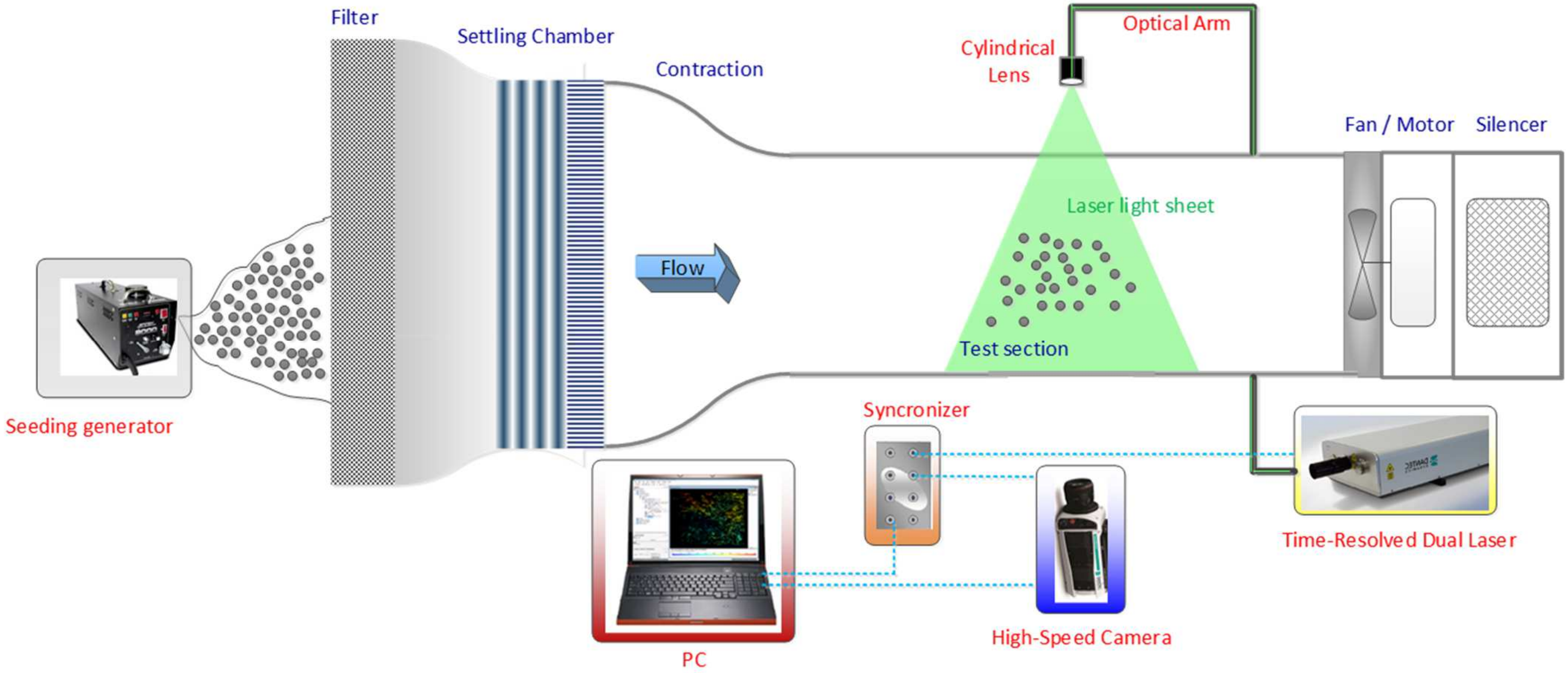


New rotating device

- Pitch angle: ±45°
- Yaw angle: ±180°
- Interval: 1°

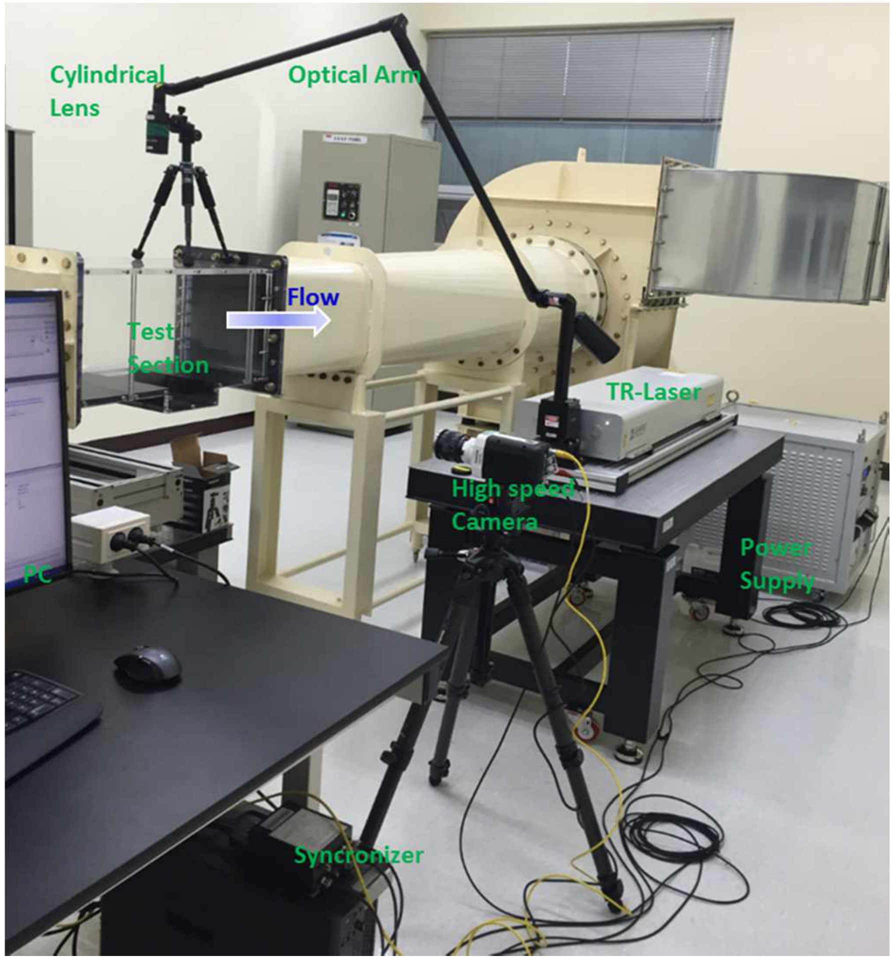
Particle Image Velocimetry(PIV)

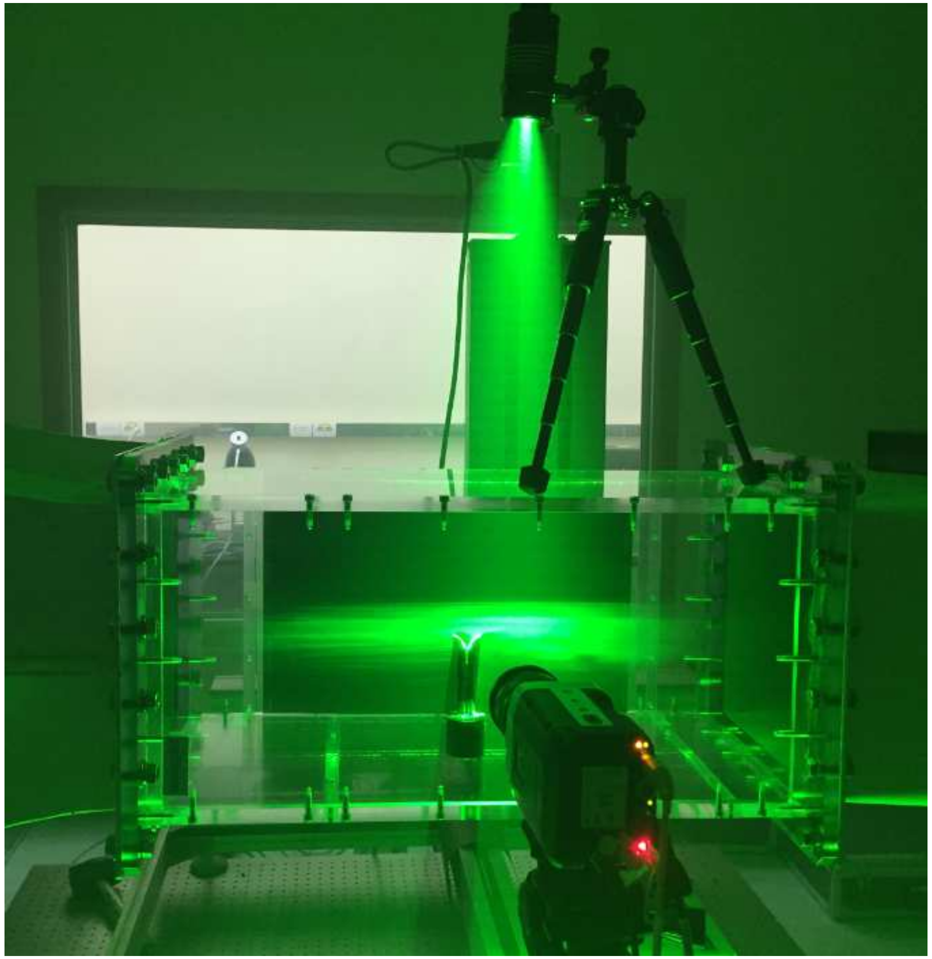
- Quantitative visualization of flow phenomenon around S-type Pitot tube
- Time-resolved laser (20mJ), High-speed camera(3200 fps), Time interval = 1ms between two-consequent velocity image



Particle Image Velocimetry(PIV)

- Field of view was 150 mm x 100 mm with 16 X 16 pixels 50% overlaps
- 5000 instantaneous PIV images were acquired with cross correlation algorithm

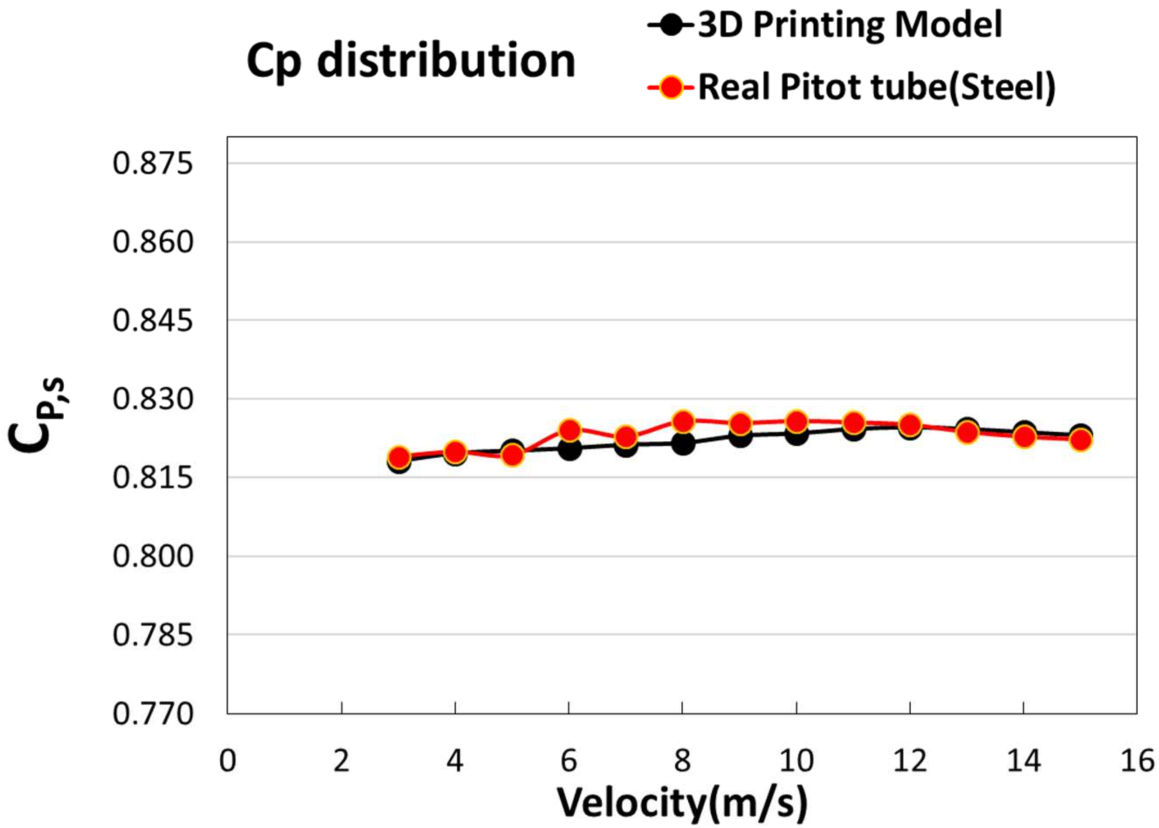




Contents

Verification of 3D Printing model

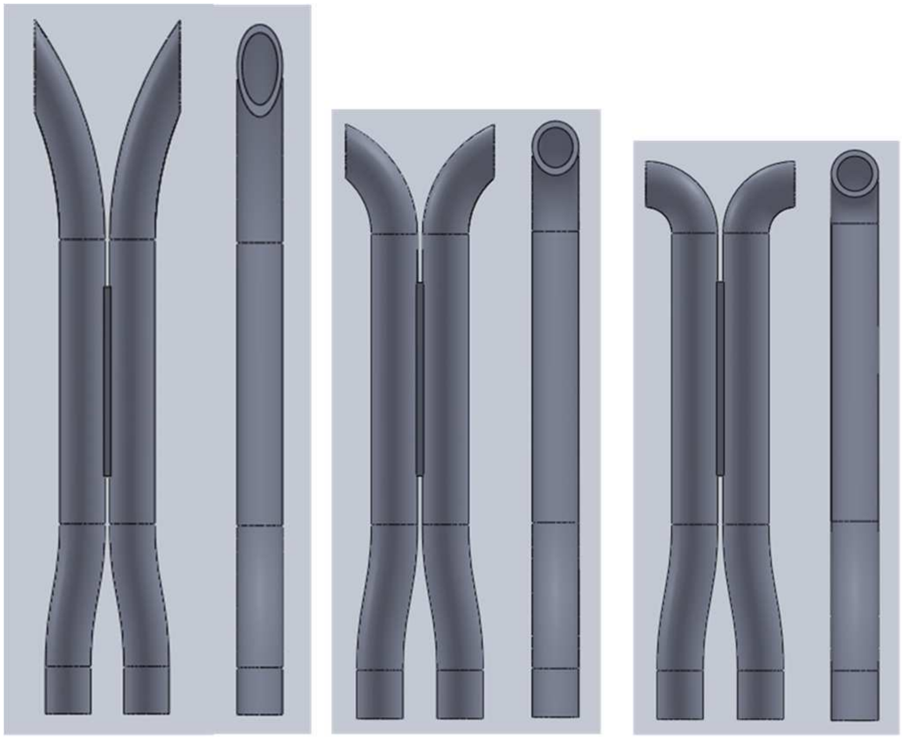
- Compare Cp distribution according to velocity change for 3D printing model and real S-type Pitot tube(Steel)



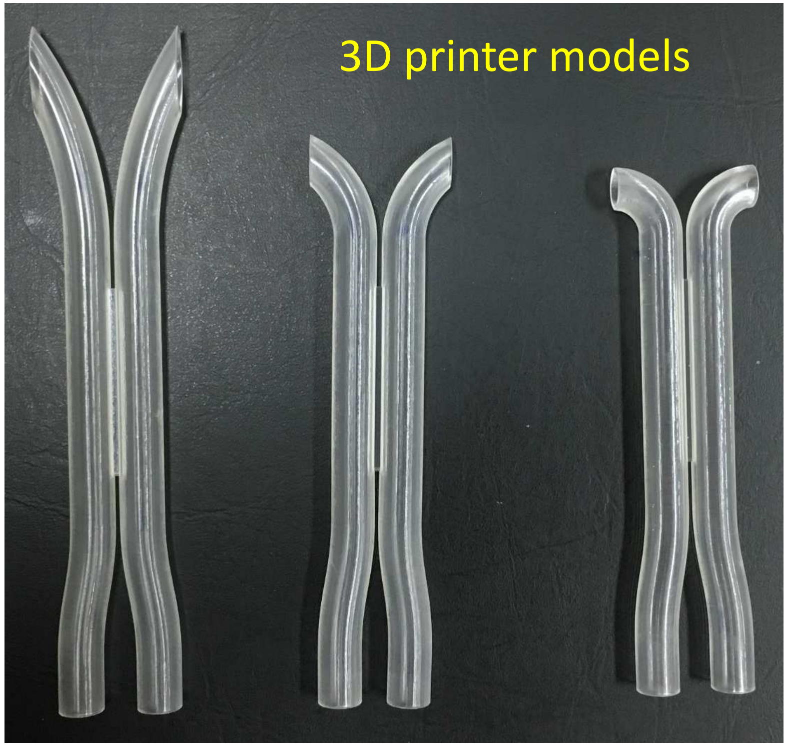
- Two pitot tubes show almost similar results in yaw and pitch angle change

Effect of velocity changes on Cp

- Compare L=1.6D models (α = 15 Deg., 30 Deg. and 45 Deg.)



α = 15°, L = 1.6D　　α = 30°, L = 1.6D　　α = 45°, L = 1.6D



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

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

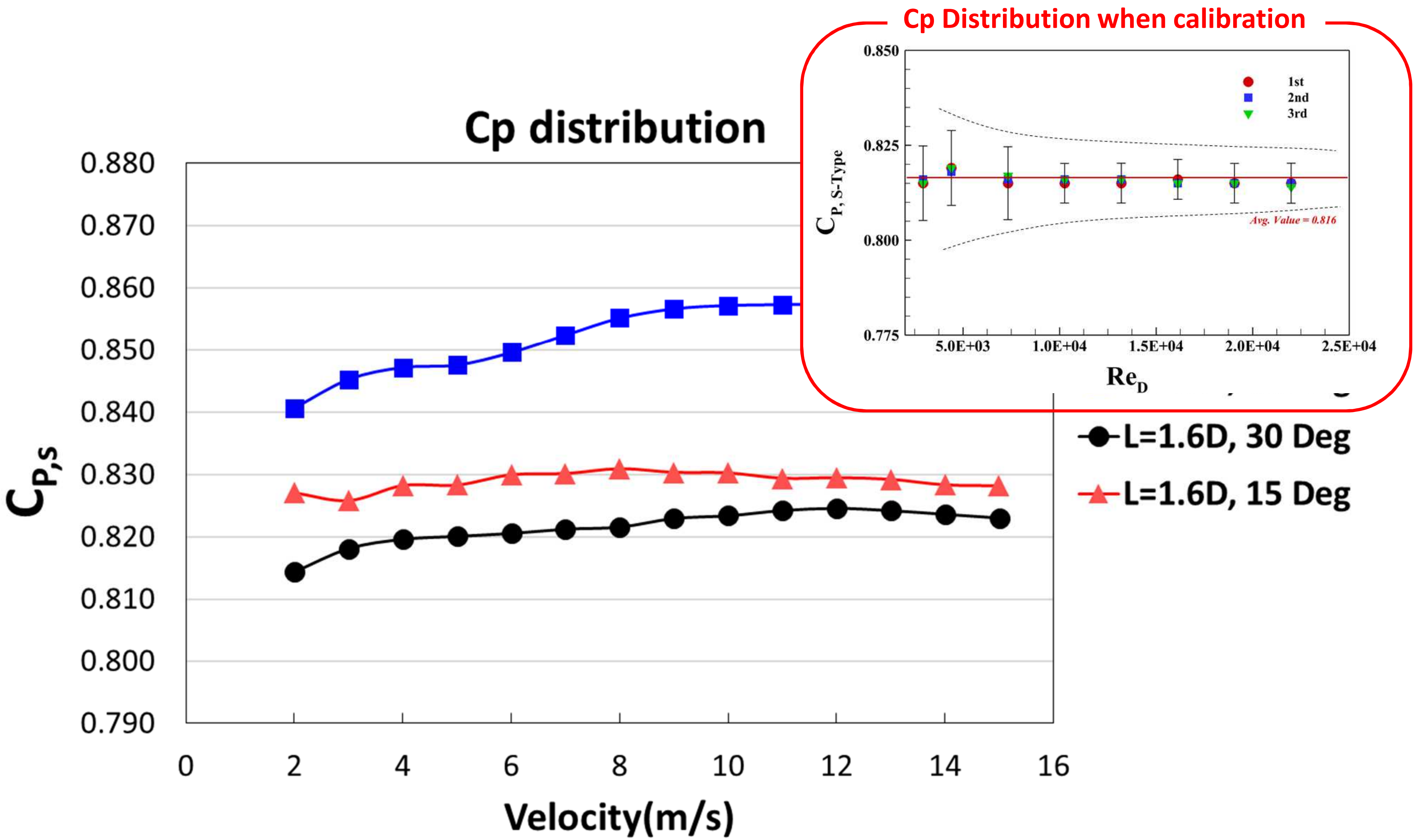
$C_{p,std}$: Stadard Pitot tube coefficient

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

ΔP_{std}: differential pressure of Standard tube

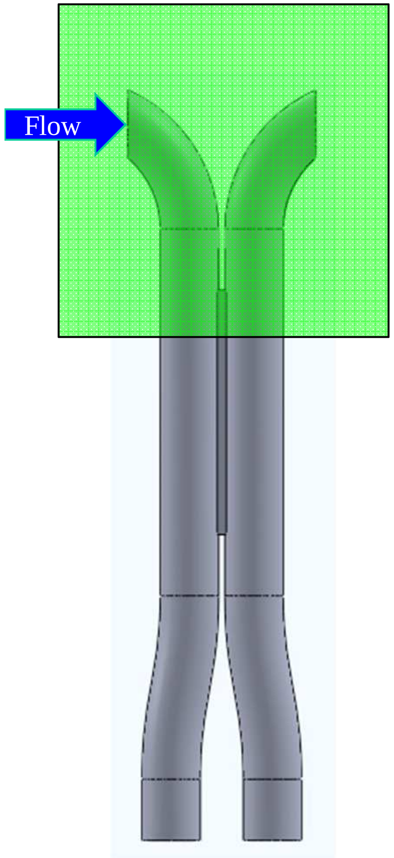
Effect of velocity changes on Cp

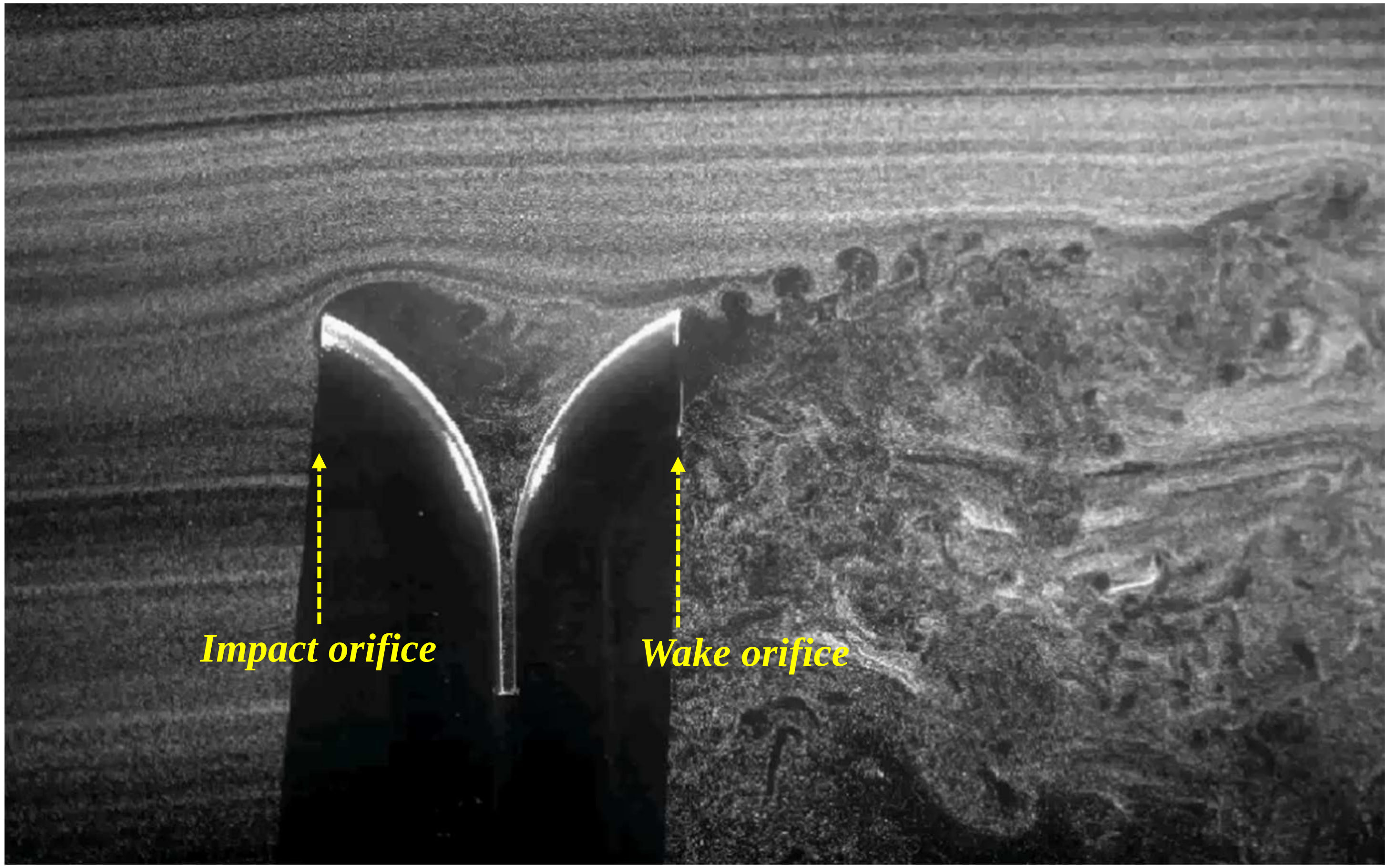
- The α=45°(L=1.6D) S Pitot has Cp larger than others 4%, Cp is increasing as incoming velocity increases up 15 m/s



L=1.6D, α=30˚ Model(PIV)

- Flow phenomenon around S-type Pitot tube

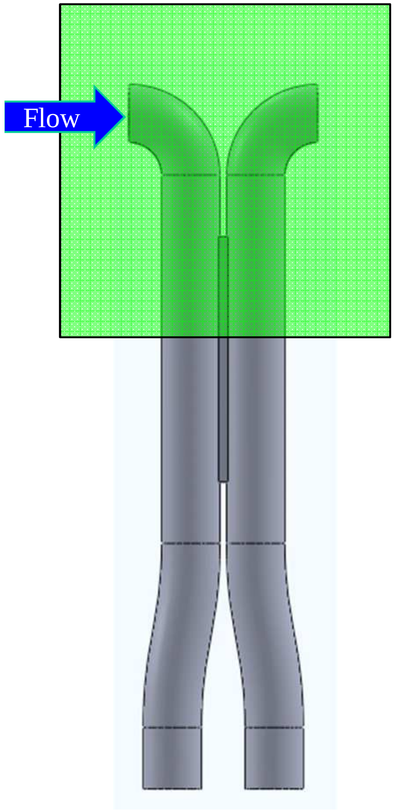


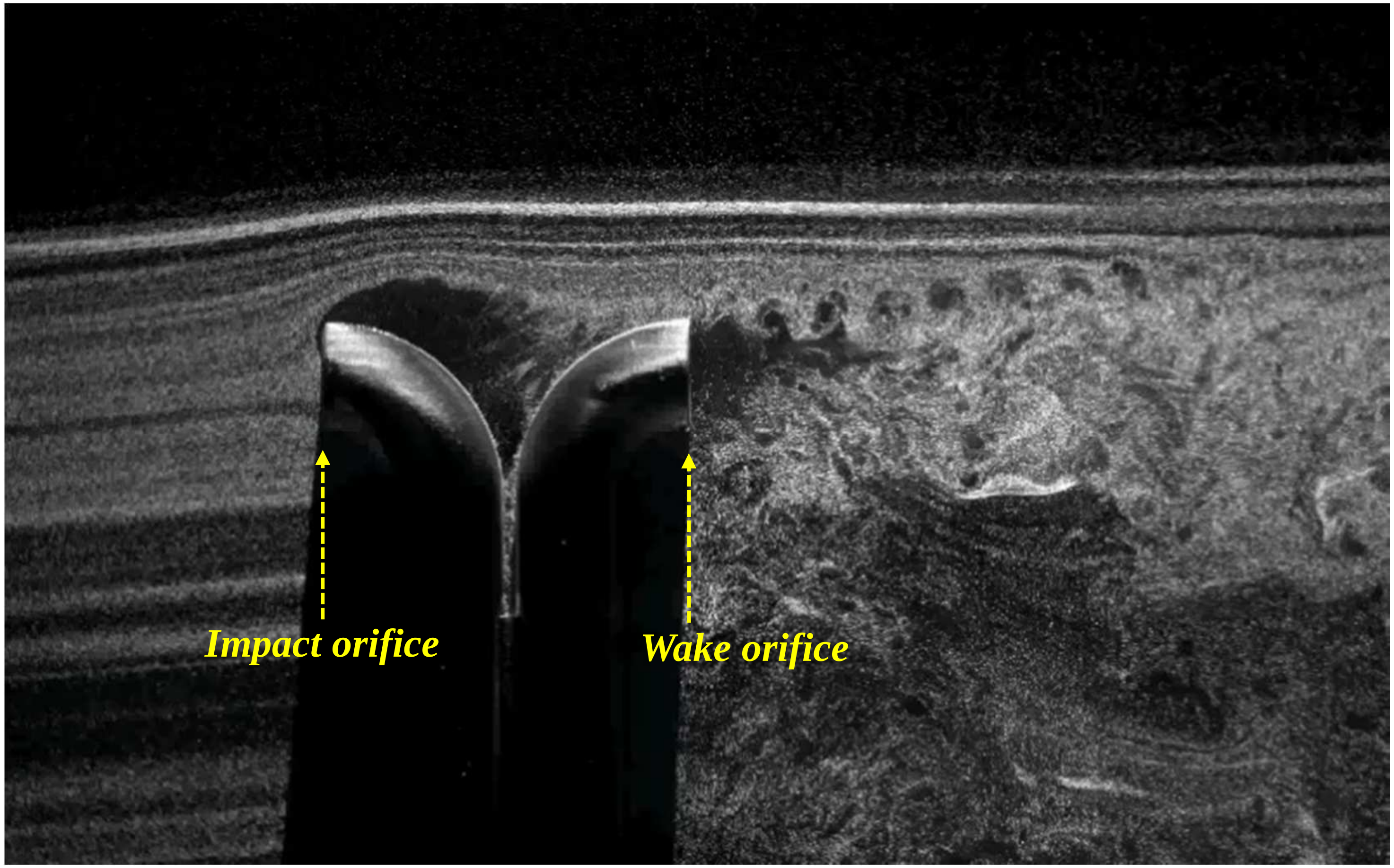


- Due to complicated geometry between the impact and wake orifices, the separated flows are developed to a vortical structure behind orifices

L=1.6D, α=45° Model(PIV)

- Flow phenomenon around S-type Pitot tube (L=1.6D, α=45°)

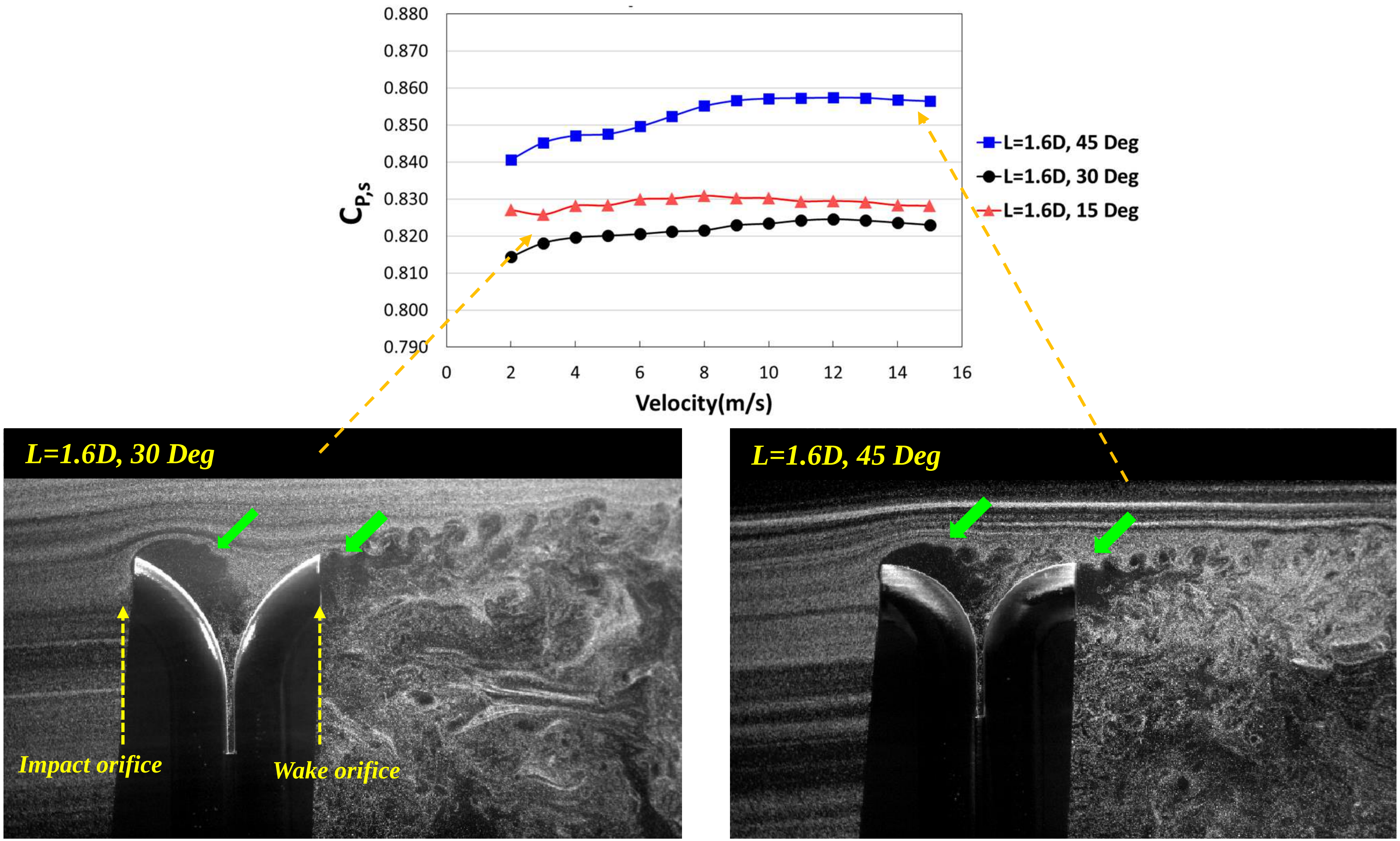




- Separated flow from wake orifice(downstream) were less developing due to short distance between two orifice and gradual change of curved surface compared to 30 deg model.

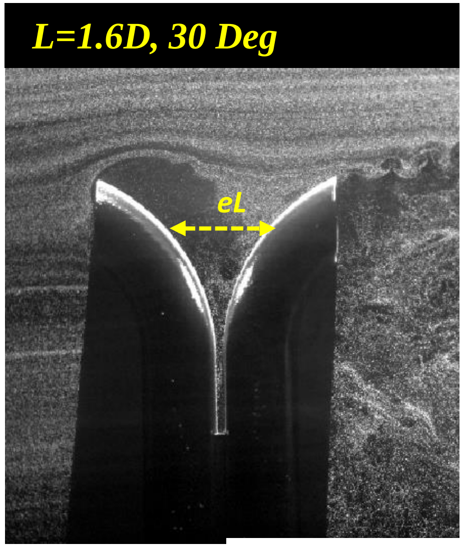
L=1.6D α=30° vs α=45°

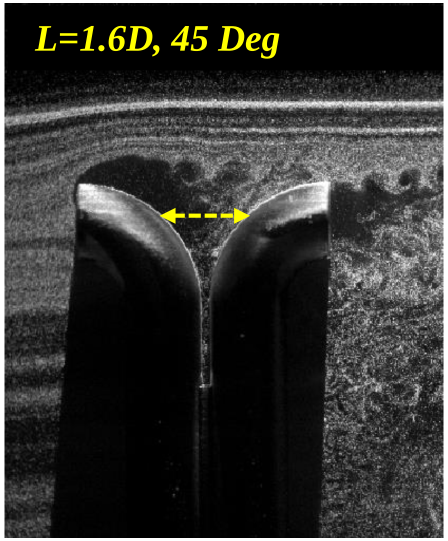
- Separated flow from wake orifice(downstream) were less developing due to short distance between two orifices and gradual change of curved surface
  → Cp,s increased (45 deg)

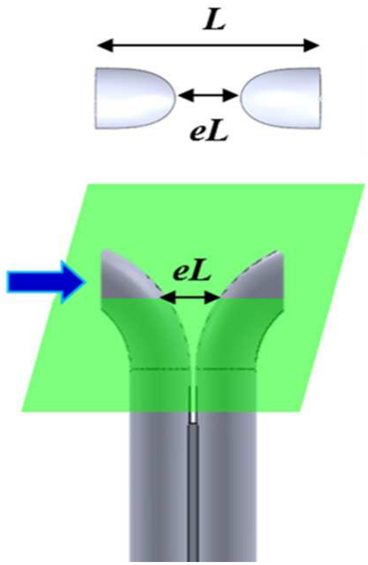


Effect of velocity changes on Cp

- actual contact distance of the flow between the two orifices is more important than the distance L **→ Effective length(eL)**



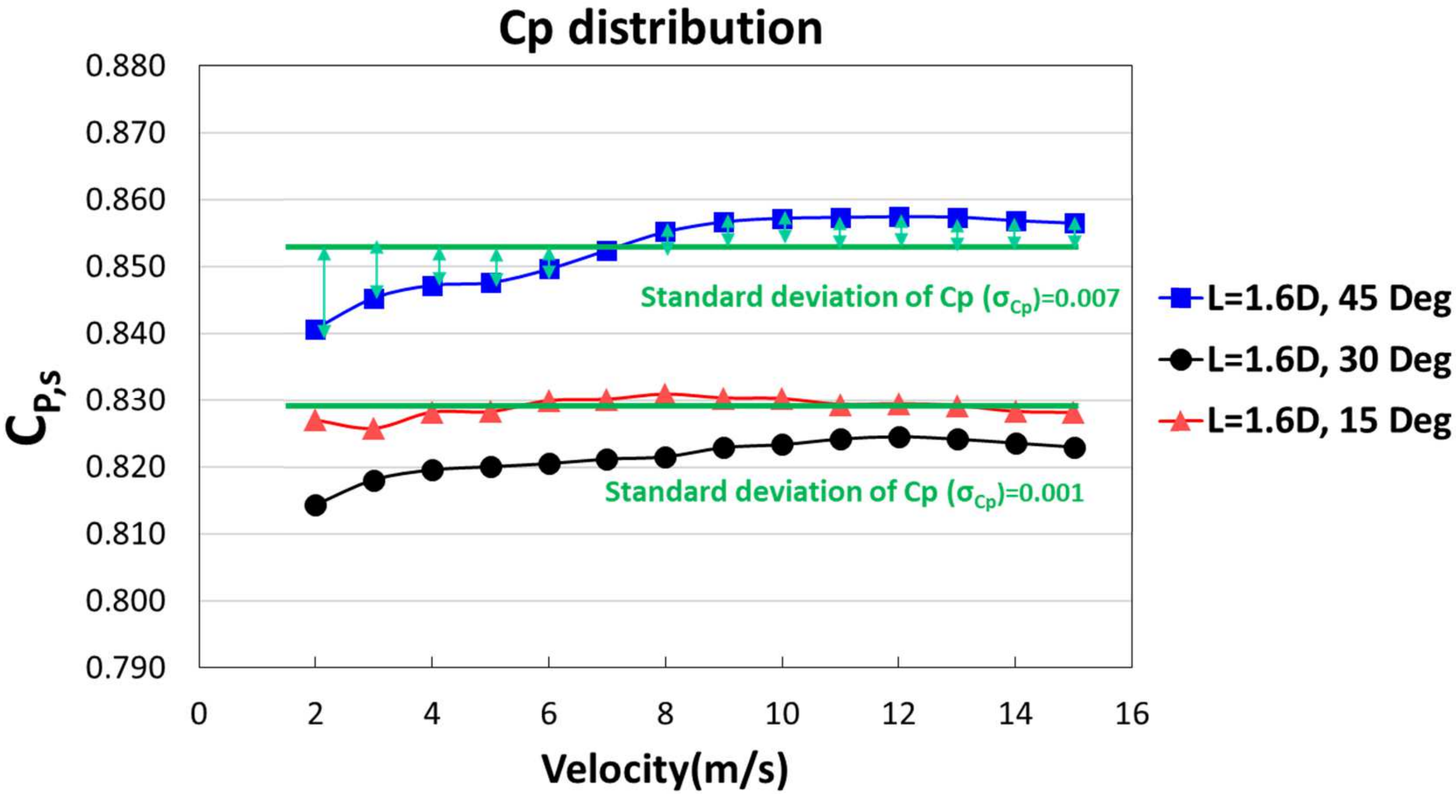




L (mm)	α (°)	eL (mm)	eL/D
1.05D	15	10.16	1.06
	30	6.54	0.68
	45	3.16	0.32
1.6D	15	20.68	2.16
	30	15.90	1.66
	45	8.76	0.92
3D	15	47.64	4.98
	30	41.82	4.38
	45	26.64	2.78

Uncertainty of Cp for S-type Pitot tube models

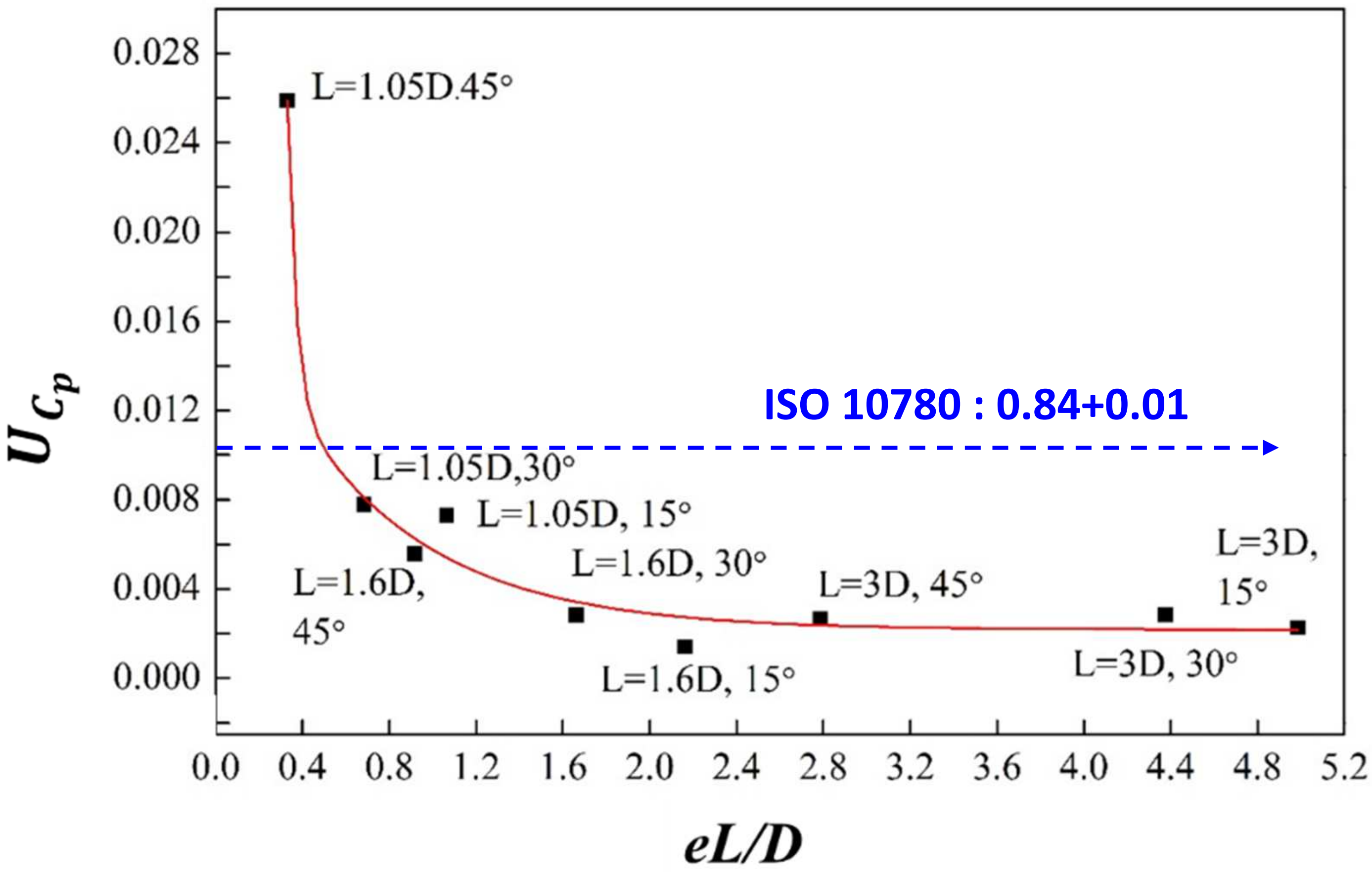
- Uncertainty can be calculated by the standard deviation and the difference with ISO 10780's Cp value (0.84, recommended)



$$U_{C_p} = \sqrt{\sigma_{C_p}^2 + \frac{(C_p - 0.84)^2}{2\sqrt{3}}}$$

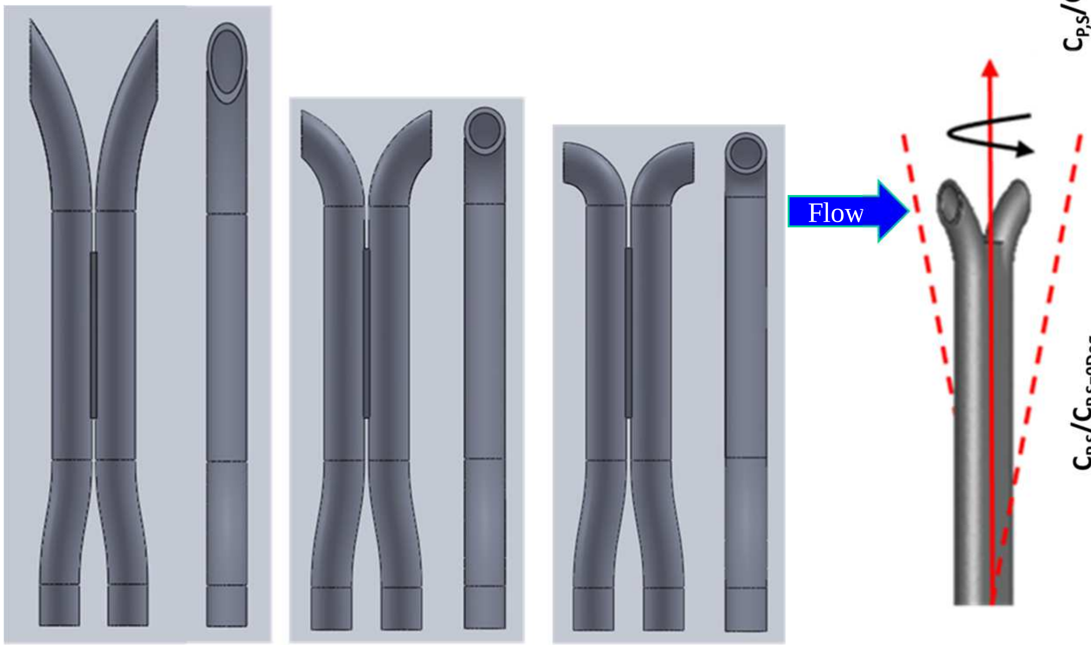
Uncertainty of Cp for S-type Pitot tube models

- Uncertainty of the S-type Pitot tube coefficients decreases as the effective length(eL/D) increases.
- the S-type Pitot tube models with long effective lengths have more constant distributions of the S-type Pitot tube coefficients with respect to the velocity changes



Effect of Yaw angle misalignment on Cp

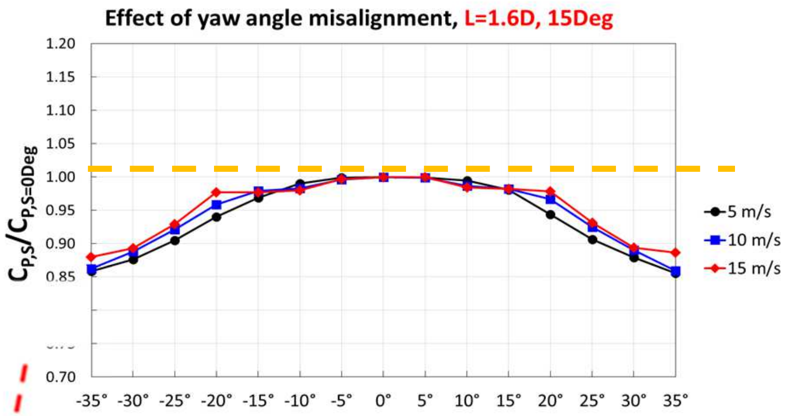
- Compare L=1.6D models
  (α = 15 Deg., 30 Deg. and 45 Deg.)

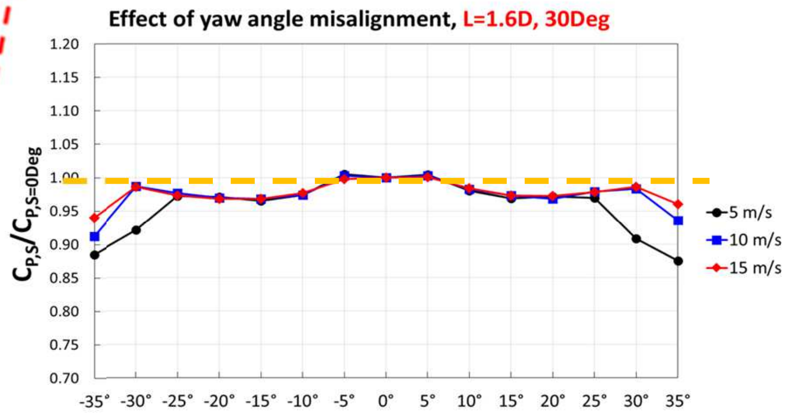


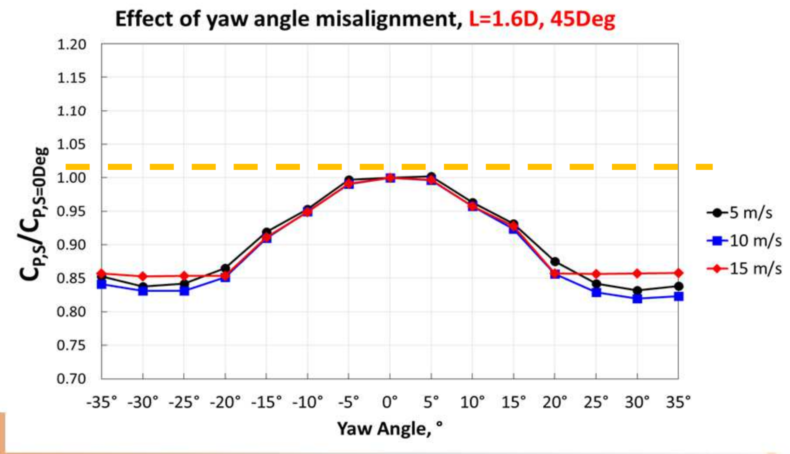
α = 15°, L = 1.6D

α = 30°, L = 1.6D

α = 45°, L = 1.6D

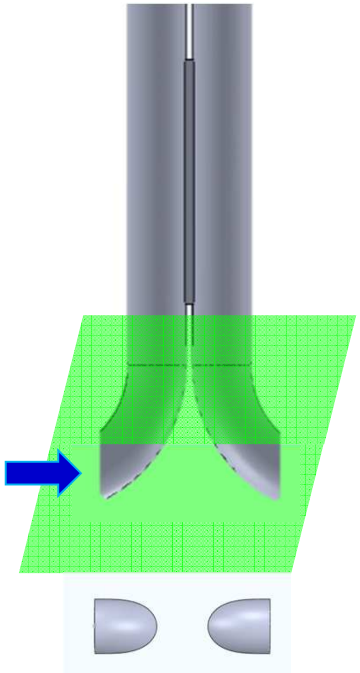


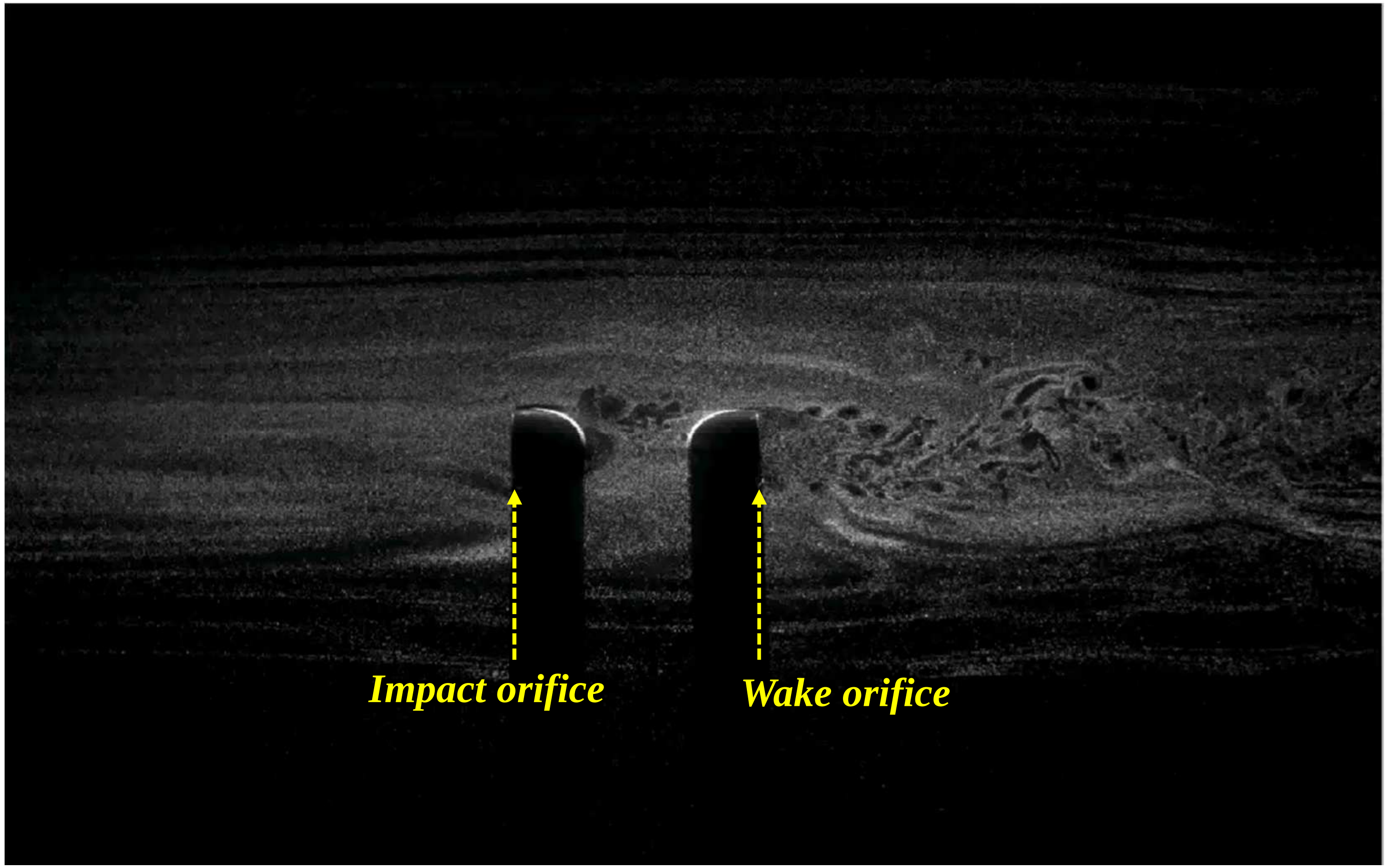




L=1.6D, α=30° (Yaw=0°) PIV

- Flow phenomenon around S-type Pitot tube (L=1.6D, 30 Deg.)

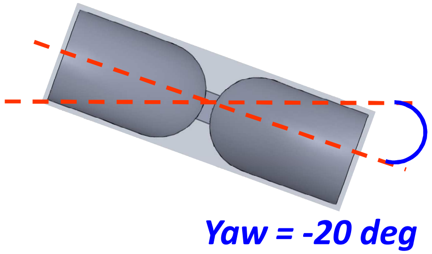


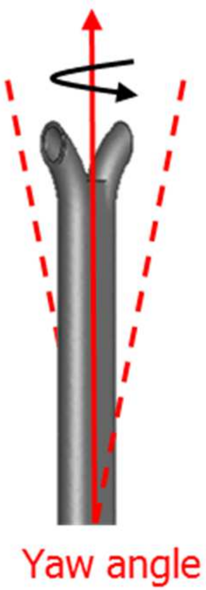


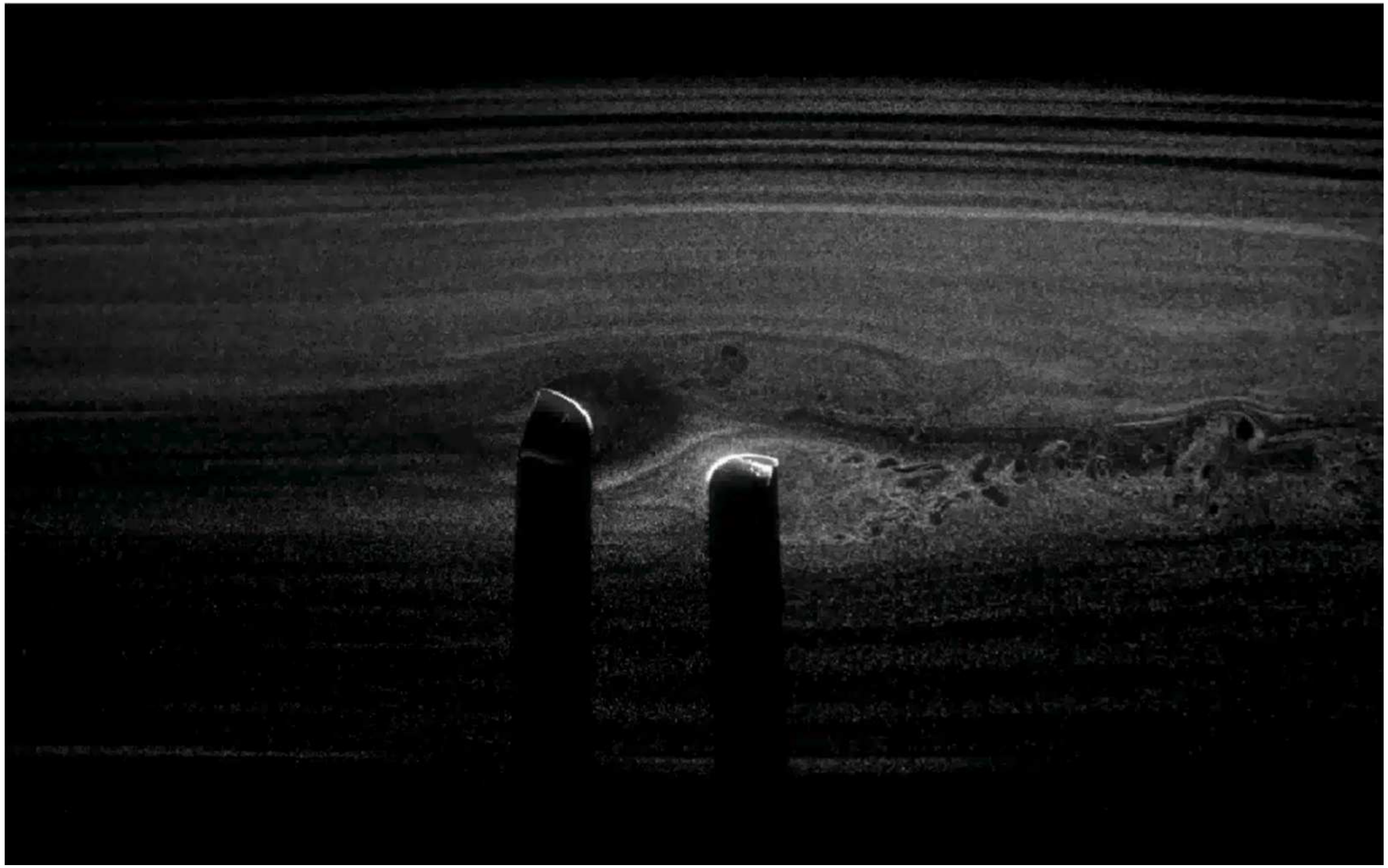
- Each vortical structures from impact and wake orifices are observed

L=1.6D, α=30˚ (Yaw=-20°) PIV

- Flow phenomenon around S-type Pitot tube (L=1.6D, **30 Deg.**)



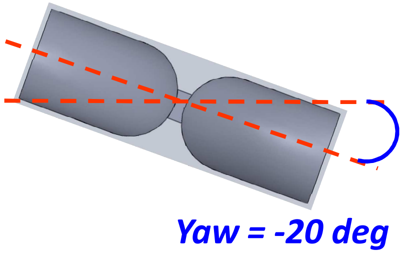


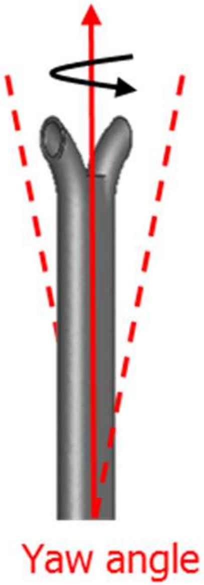


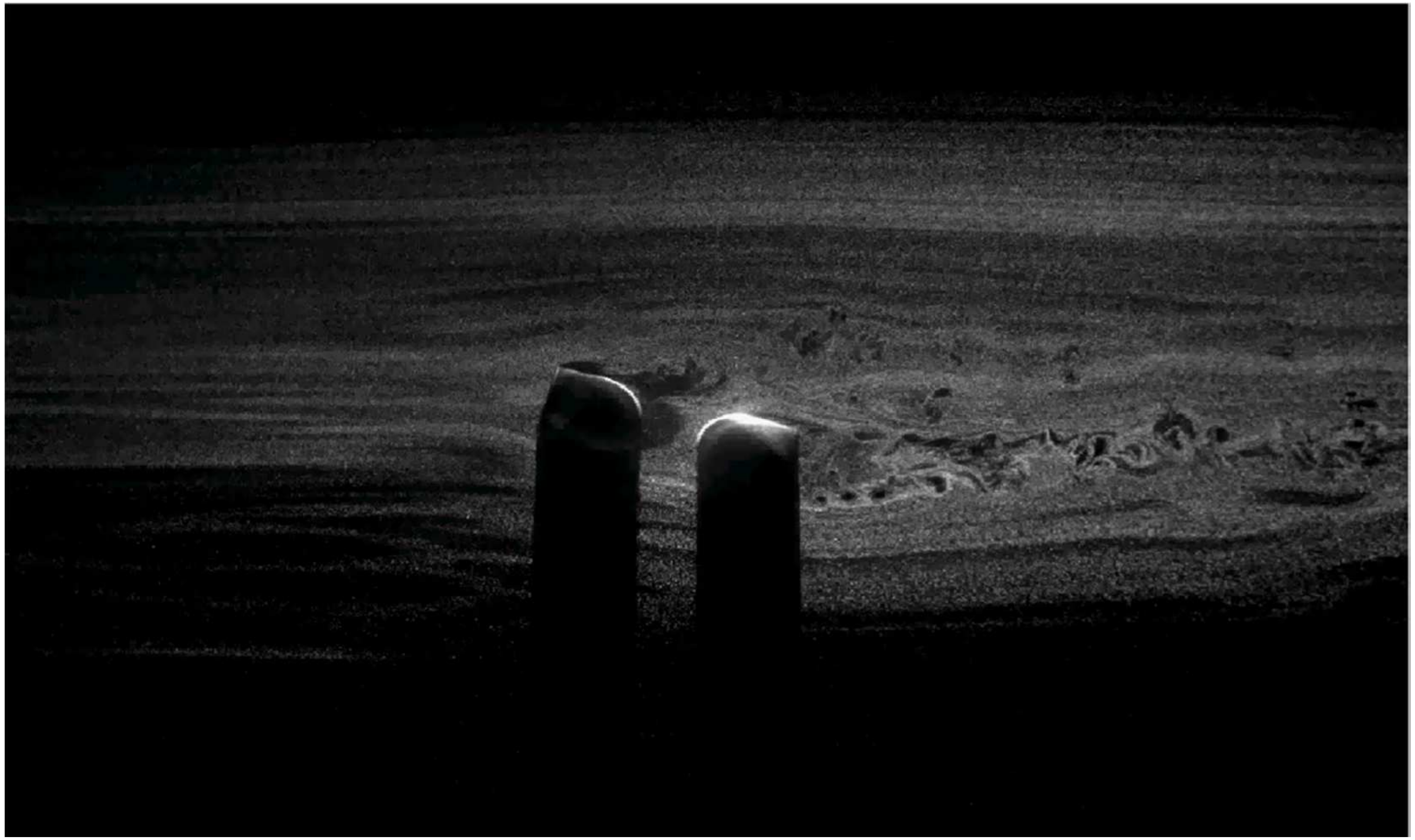
- No interference between the separated flow from the impact orifice and the flows near the wake orifice due to the long distance between the two orifices.

L=1.6D, α=45° (Yaw=-20°) PIV

- Flow phenomenon around S-type Pitot tube (L=1.6D, **45 Deg.**)





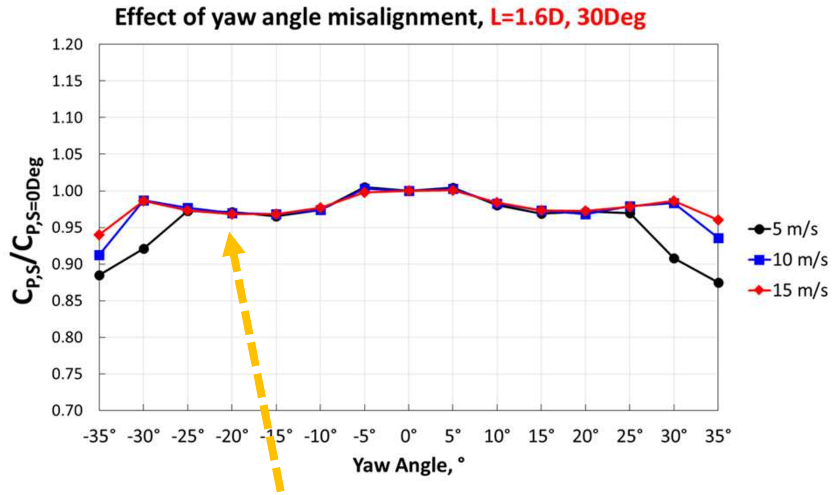


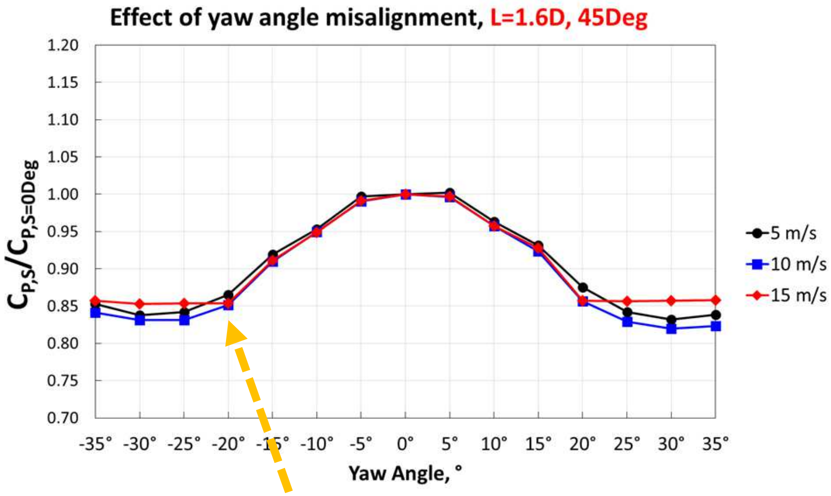
- Separated flow from impact orifice(upstream) interfere with vortical structures of wake orifices(downstream) due to the proximity of two orifices
- Actual contact distance of the flow between the two orifices is also an important parameter

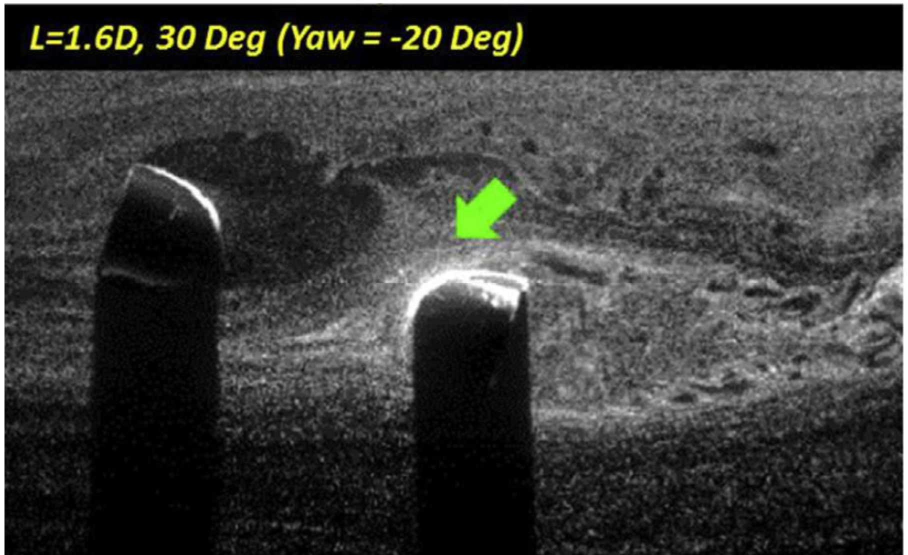
L=1.6D, α=30˚ vs α=45˚ (Yaw angle)

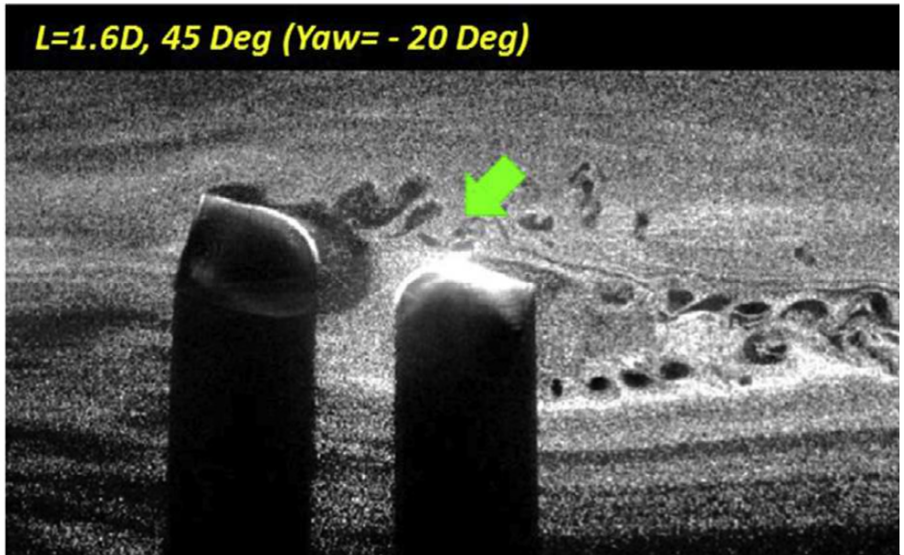
- When vortical structure behind the wake orifice were interfered with upstream separated flow, lower pressure near wake orifice

→ Cp,s deceresed (45 deg)









Effect of Yaw angle misalignment on Cp

- To quantify the effects of the geometry of models on the S-type Pitot tube coefficients under yaw angle misalignments,

→ Error index $I_{yaw\ error}$ was defined by the ratio of area between yaw curves

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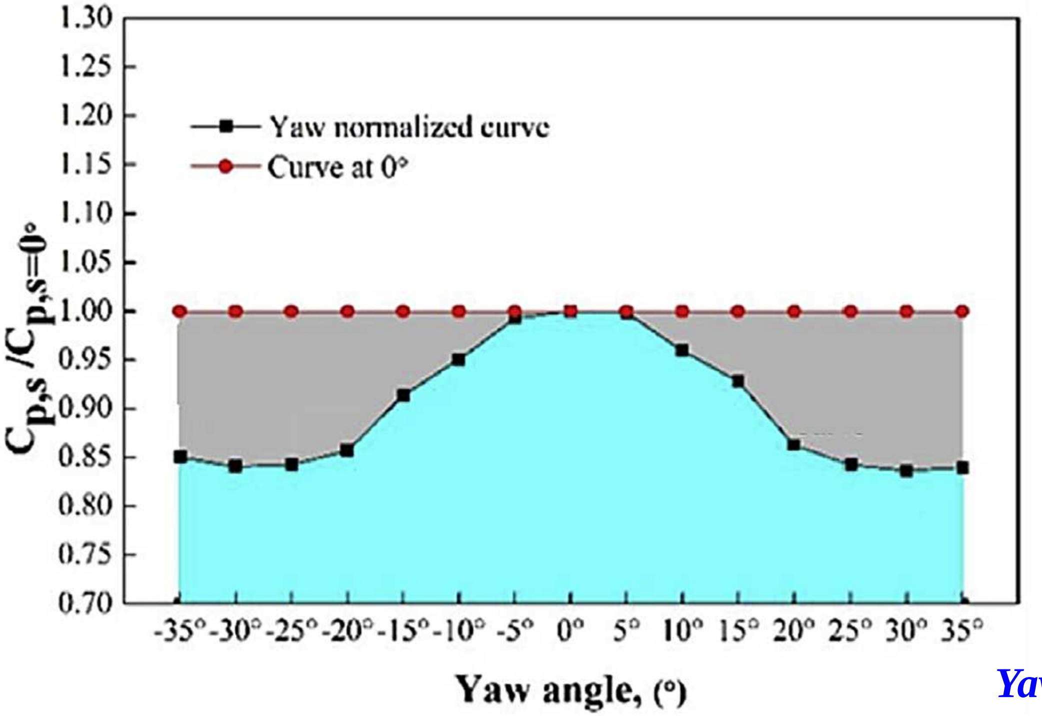
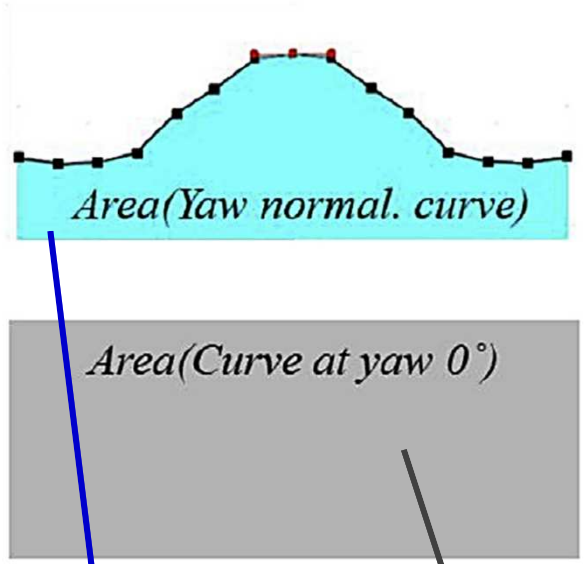




Yaw angle misalignment

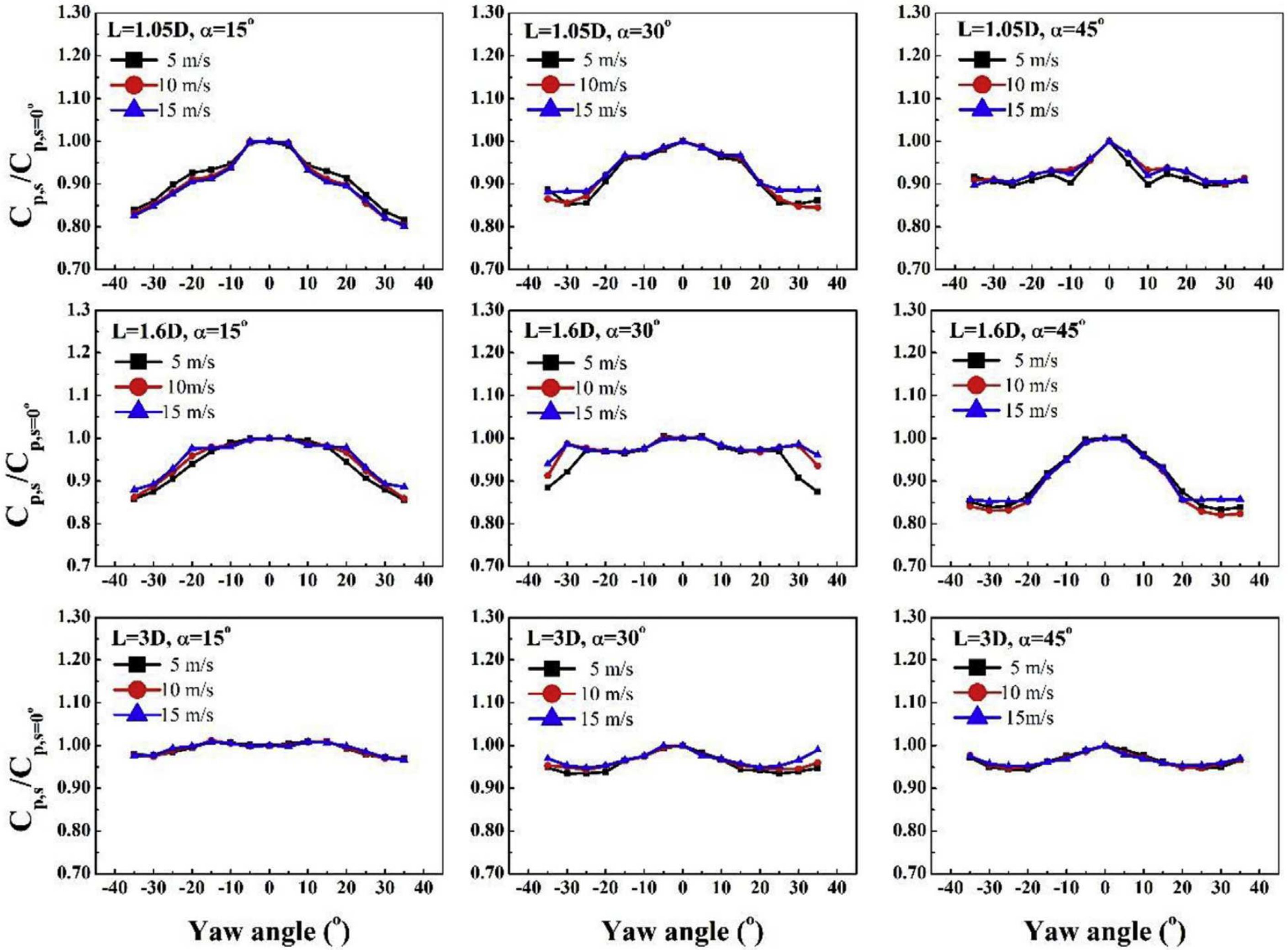
$$I_{yaw\ error} = \frac{Area\ of\ yaw\ normalized\ curve}{Area\ of\ curve\ at\ yaw = 0^{\circ}}$$

No misalignment

- Error index closed to the 1 indicates that the S-type Pitot tube models were less affected by the yaw angle misalignments.

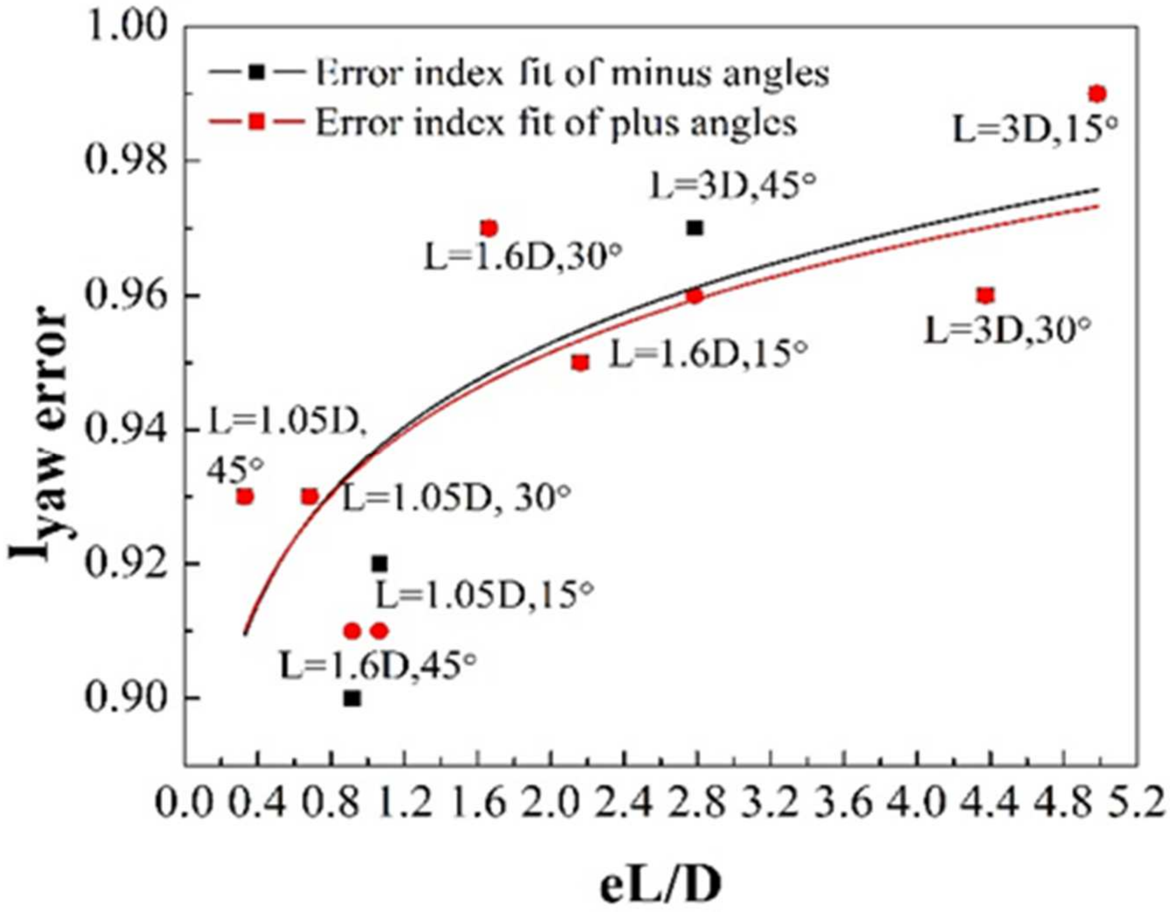
Effect of Yaw angle misalignment on Cp

- Yaw angle effect for L=1, 1.6 and 3D, α=15˚, 30˚ and 45 ˚)



Effect of Yaw angle misalignment on Cp

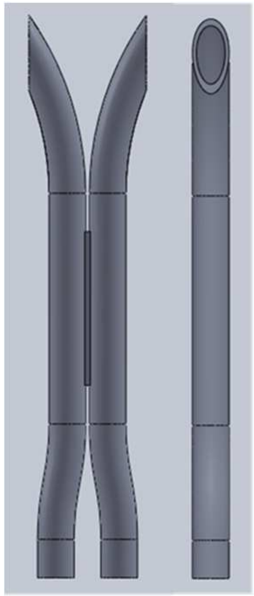
- Error index $I_{yaw\ error}$



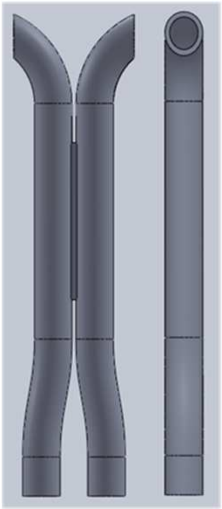
- The error index of the S-type Pitot tube models becomes close to 1 as the effective length, eL/D, increases.
- S-type Pitot tube models with long effective lengths are less affected by the yaw angle misalignments

Effect of Pitch angle misalignment on Cp

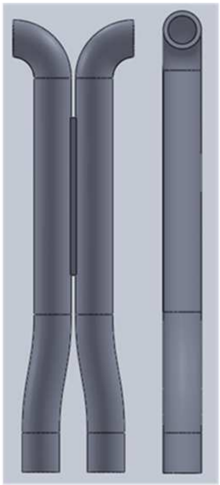
- Compare L=1.6D models
  (α = 15 Deg., 30 Deg. and 45 Deg.)



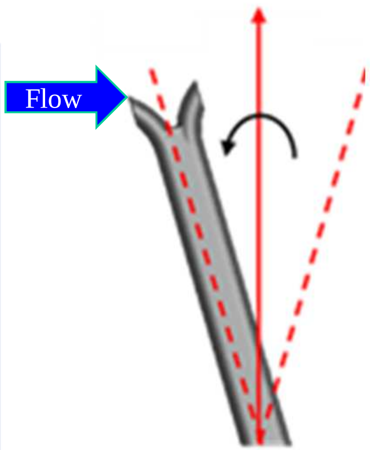
α = 15°, L = 1.6D

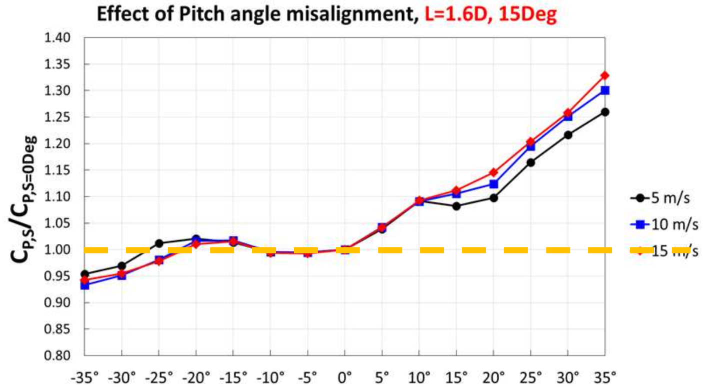


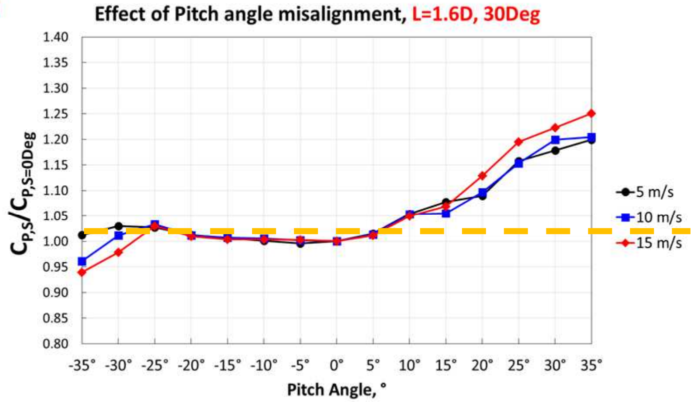
α = 30°, L = 1.6D

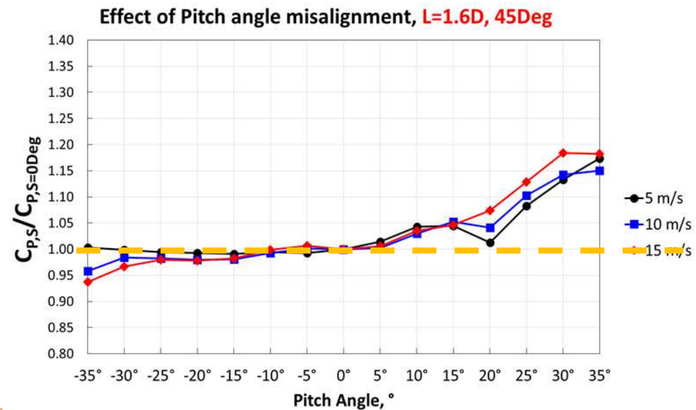


α = 45°, L = 1.6D









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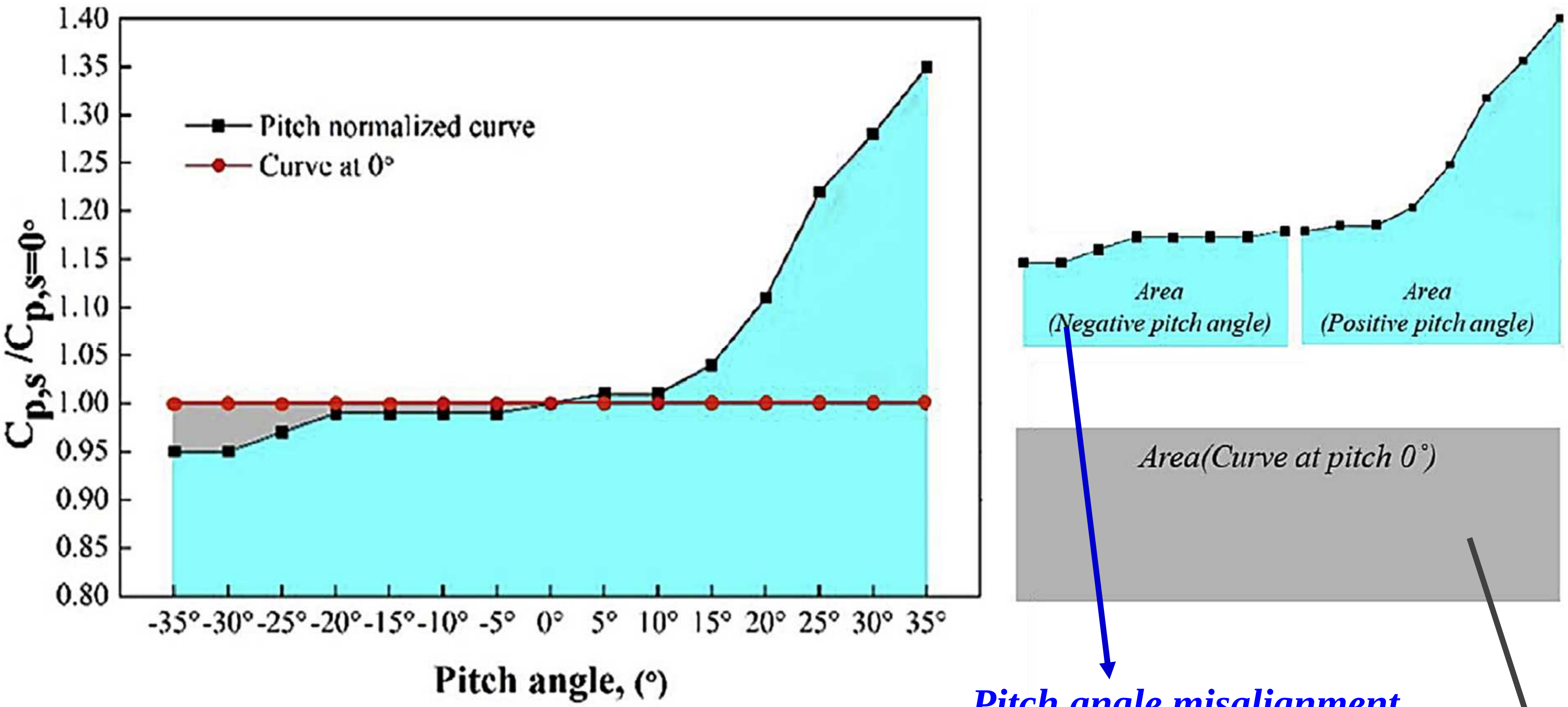


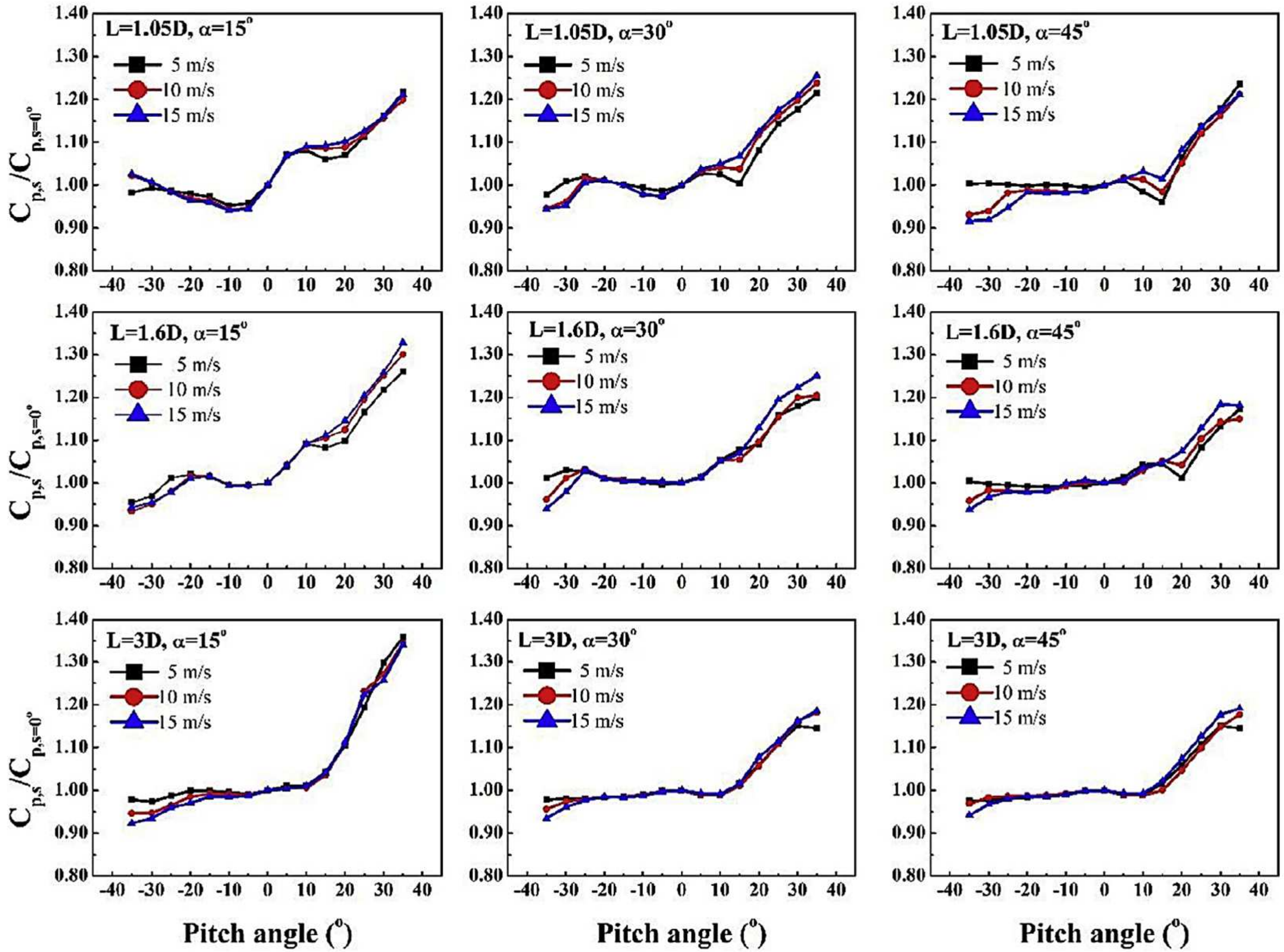
Pitch angle misalignment

$$I_{pitch\ error} = \frac{Area\ of\ pitch\ normalized\ curve}{Area\ of\ curve\ at\ pitch = 0^{\circ}}$$

No misalignment

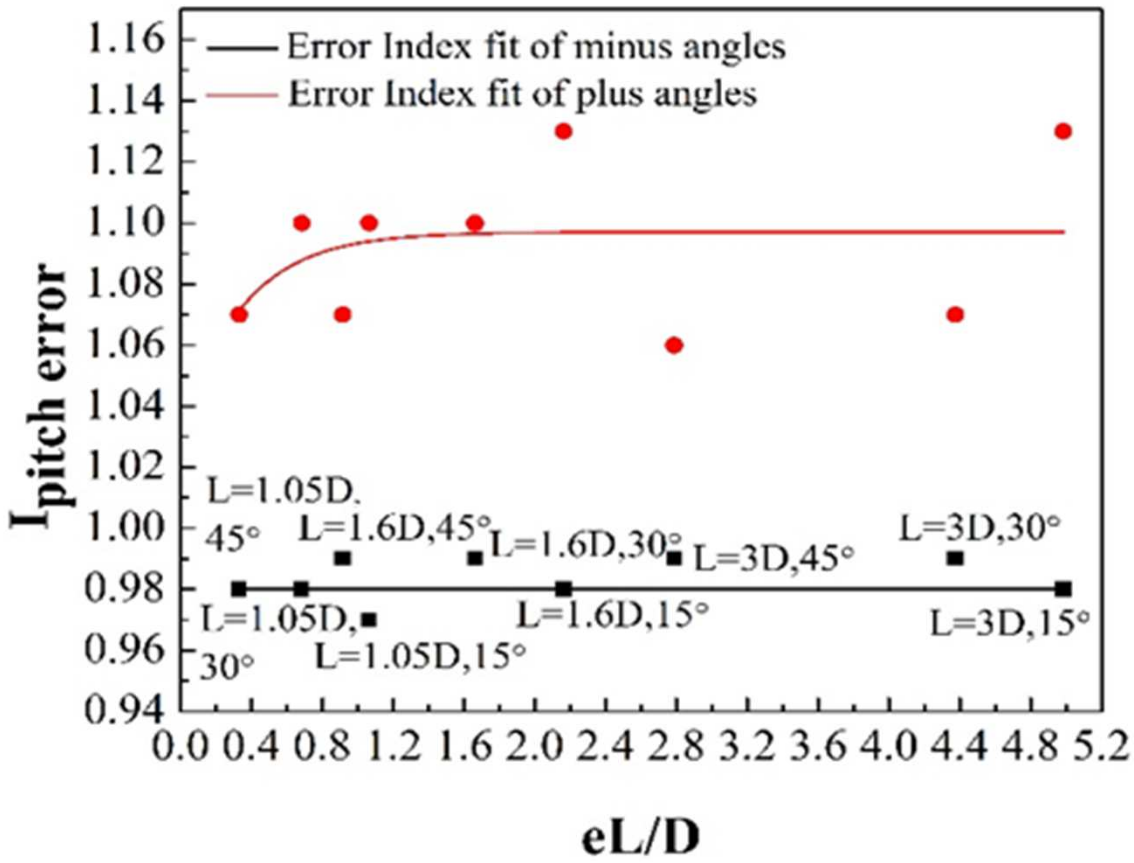
Effect of Pitch angle misalignment on Cp

- Pitch angle effect for L=1, 1.6 and 3D, α=15°, 30° and 45 °)



Effect of Pitch angle misalignment on Cp

- Error index I (Ratio of error area)



- The S-type Pitot tube coefficients were not correlated with the error index, which shows almost similar values of in the negative and positive pitch angle.

Conclusion

- S-type Pitot tube is mainly applied to measurement stack velocity for Smokestack in KOREA

- No detailed guidelines pertaining to the S-type Pitot tube geometry considering accurate and reliable measurements in the ISO, EPA and ASTM international standards

- Various geometric parameters on S-type Pitot tube coefficients with yaw and pitch misalignment were investigated by 3D printing and wind tunnel experiments

Conclusion

- S-type Pitot tube is mainly applied to measurement stack velocity for Smokestack in KOREA
- No detailed guidelines pertaining to the S-type Pitot tube geometry considering accurate and reliable measurements in the ISO, EPA and ASTM international standards
- Various geometric parameters on S-type Pitot tube coefficients with yaw and pitch misalignment were investigated by 3D printing and wind tunnel experiments
- The S-type Pitot tube with a long effective length has low uncertainty and constant distributions of the S-type Pitot tube coefficients
- S-type Pitot tube models with long effective lengths are less affected by the yaw angle misalignments, But in the real smokestack, it could be non-practical.
- The S-type Pitot tube coefficients were not correlated with the error index, which shows almost similar values of in the negative and positive pitch angle.

Thank you for your kind attention!