Improving Measurements for Smokestack Emissions 2017

Experimental Investigation on Geometric Parameters of S-type Pitot tube for GHGs Emission monitoring

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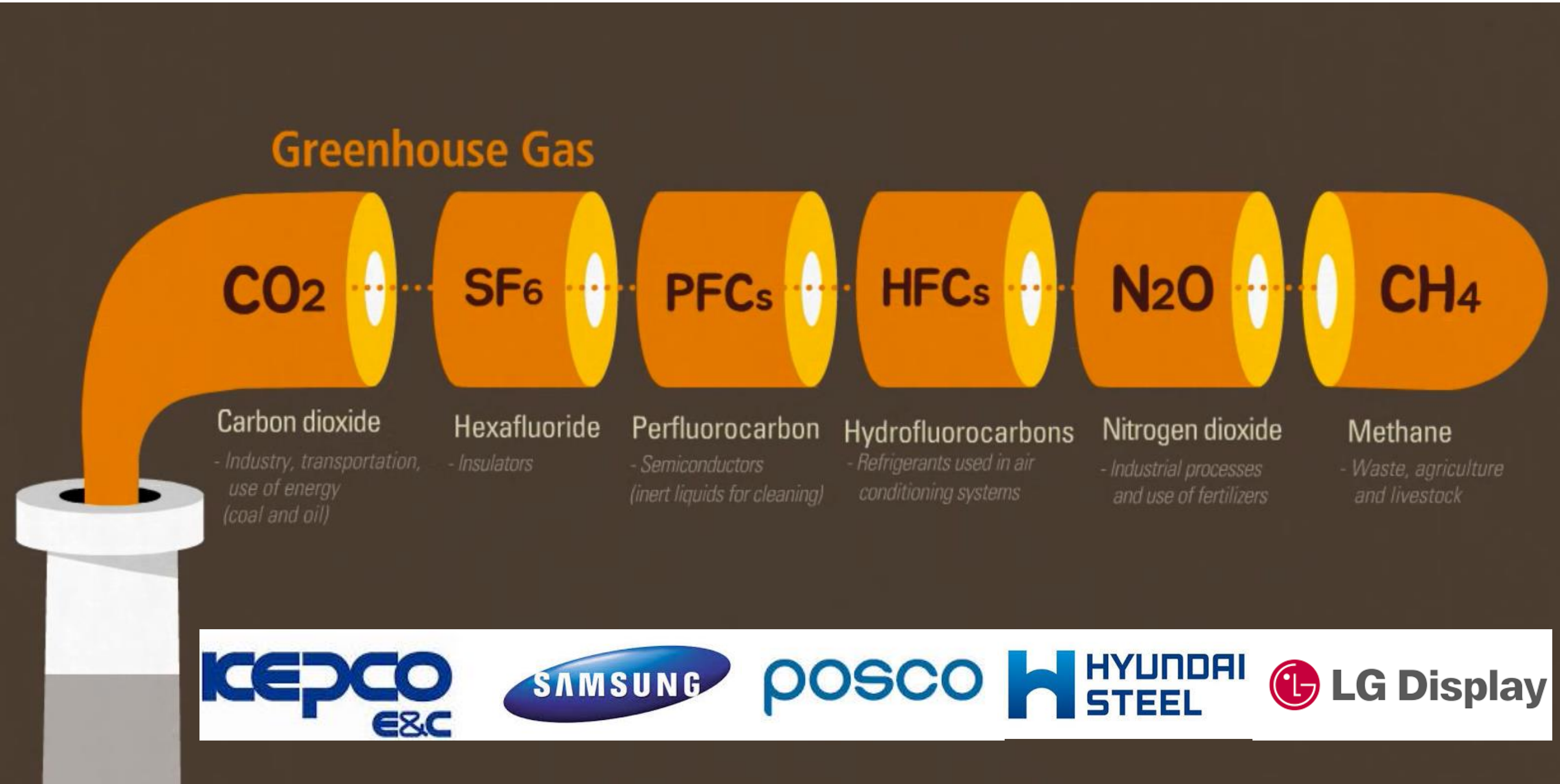
Contents

KRISS

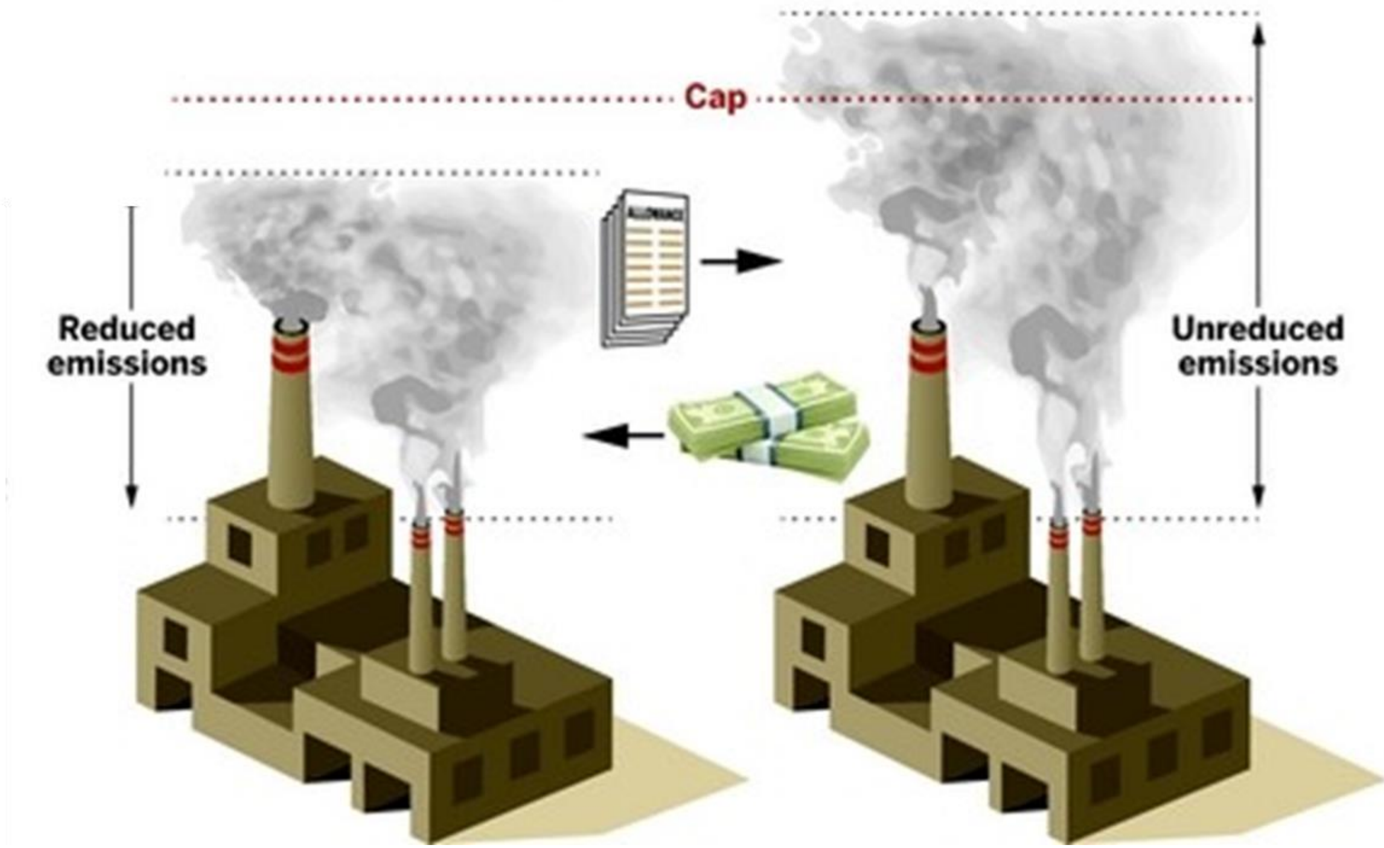
Korea GHG Inventory

- 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



Estimation method of GHG emissions in KOREA

Activity-based method

$$E = FC \times EF$$

E : estimated emission (kg)
FC : fuel consumption (TJ)
EF : emission factor (kg/TJ)

Fuel consumption (Tier 1) by IPCC guidelines

$$E = FM \times CC \times \frac{M_{CO_2}}{M_C}$$

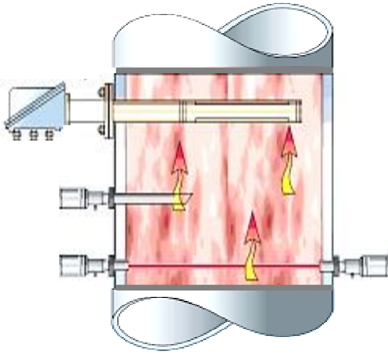
CC : fuel carbon content(kg/kg)
M_{CO2} : molecular mass of carbon dioxide
M_C : atomic mass of carbon

Carbon content (Tier 3) by IPCC guidelines

Continuous emission measurement(CEM)

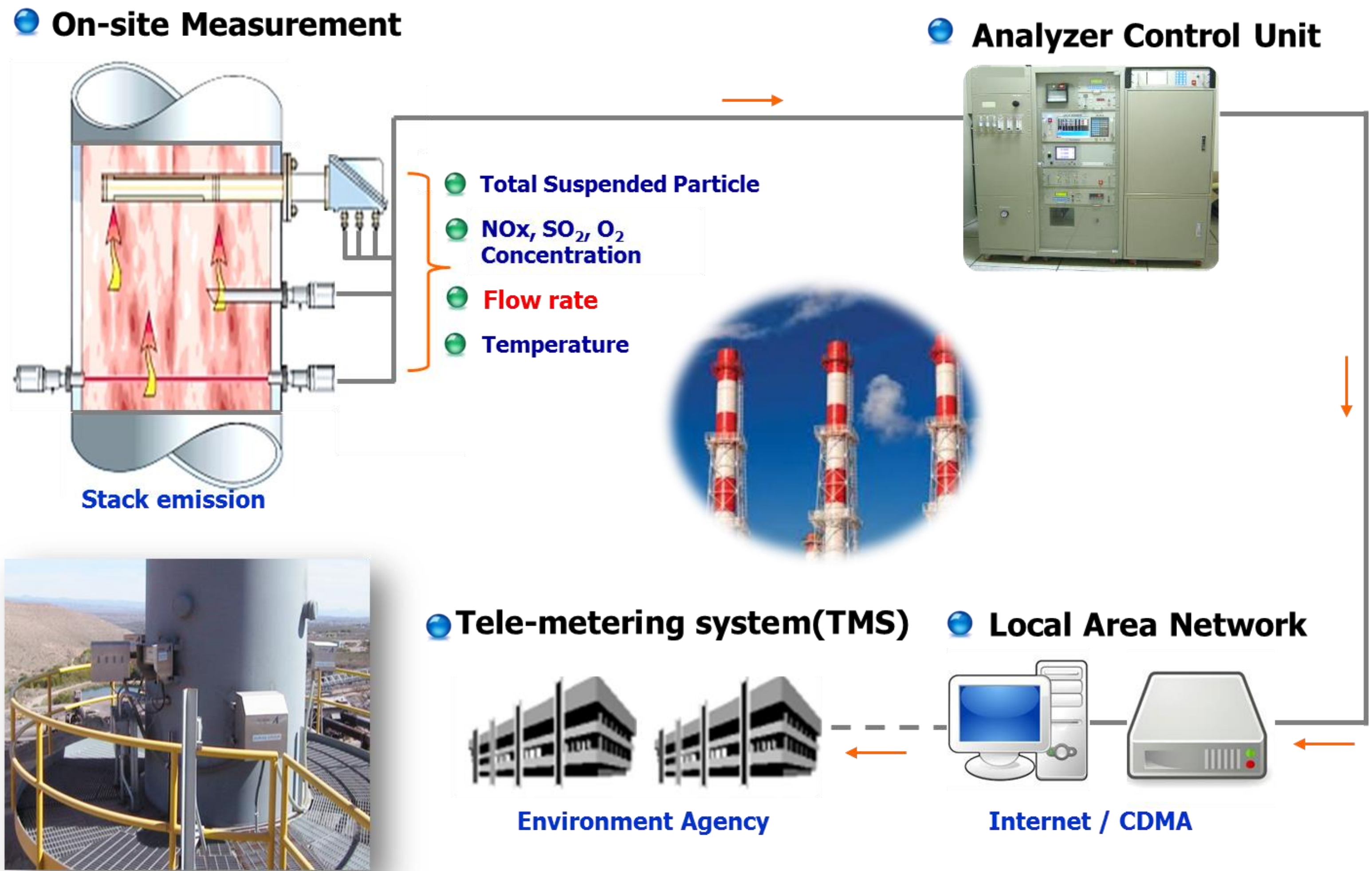
$$E_{CEM} = \sum_{i=1}^{N} E_{5min,i} = \sum_{i=1}^{N} (K \times \overline{C}_i \times Q_{5min,i} \times \frac{MW_{gas}}{22.4L})$$

CEMS (Tier 4) by EPA



- Depending on combustion source and unit size, facilities can select estimate methods, but CEMs is not Mandatory in the Environ. Law of Korea

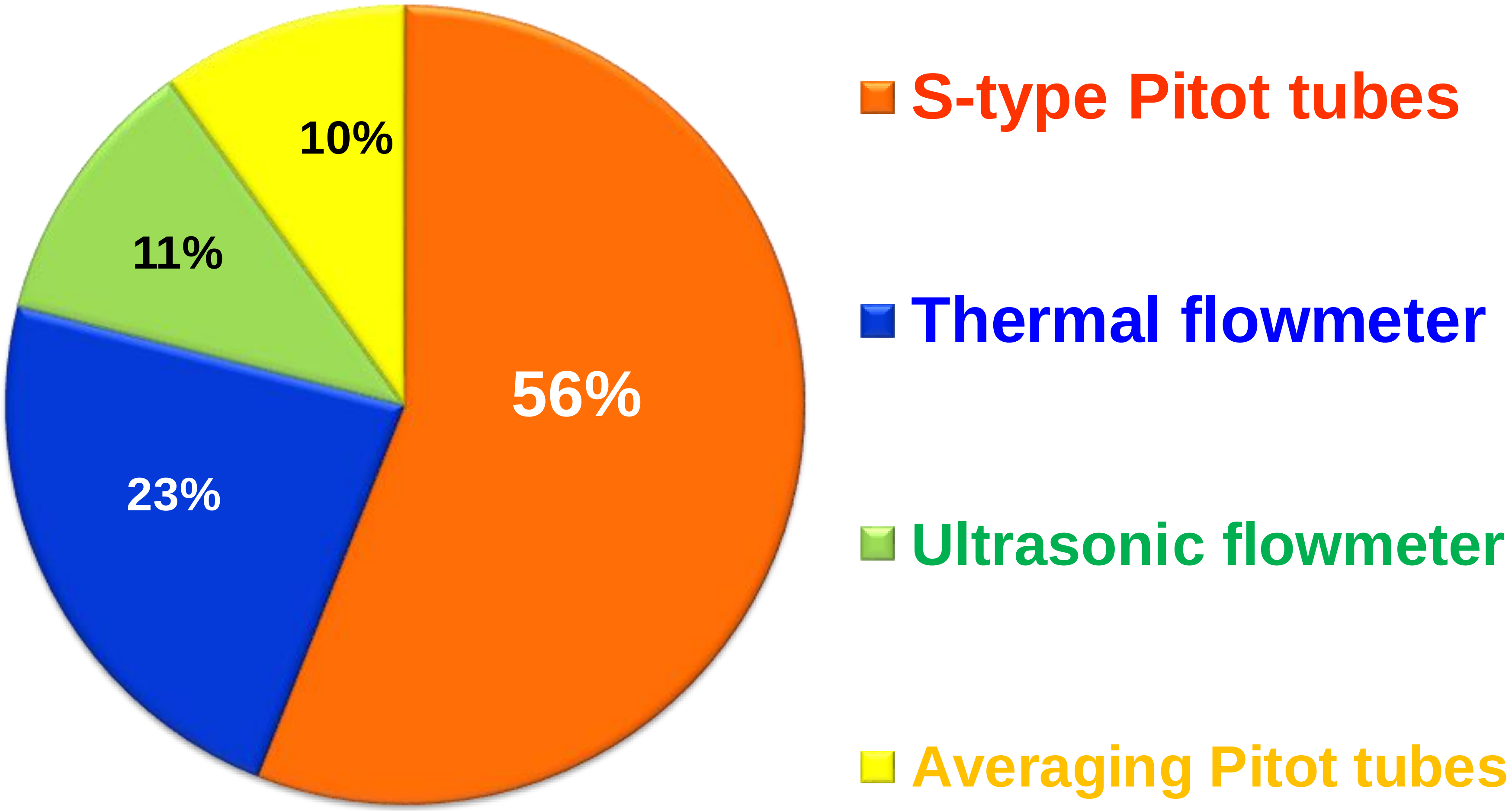
Smoke Stack Tele-Monitoring System(TMS)



- National Ambient Air Monitoring System operated by Ministry of S. Korea
- Measure and monitor the pollutant items(SOX, NOX,..)and non-pollutant item(Temp., Flow rate and O2) from large-scale emission facilities

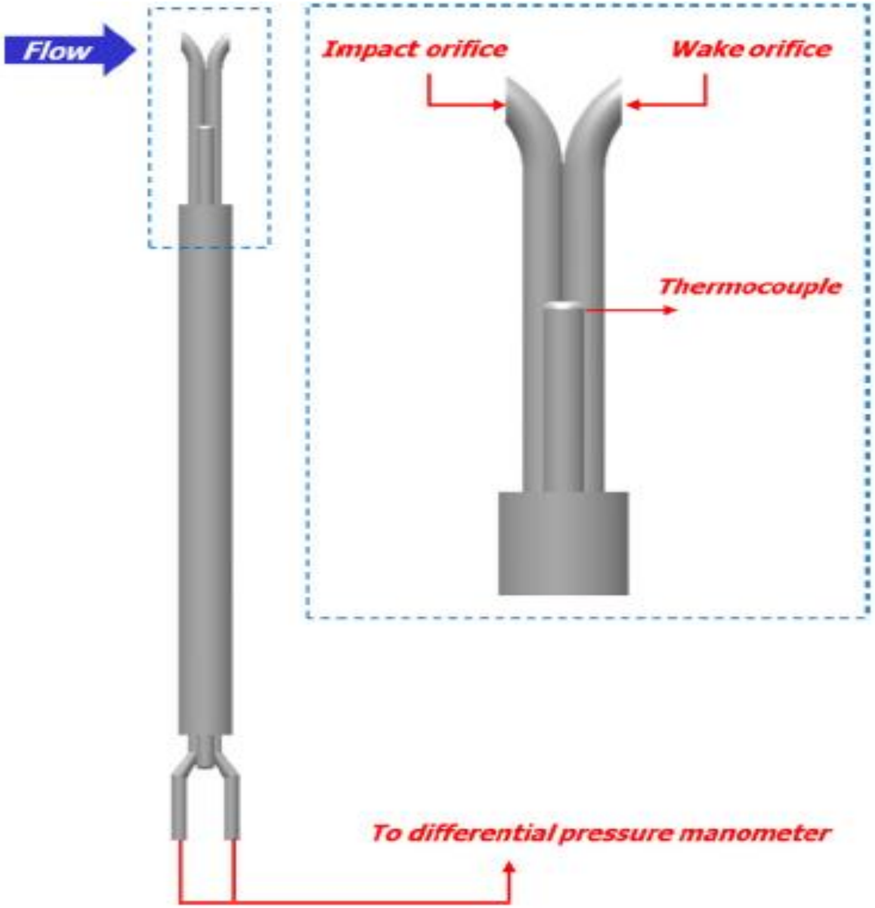
Contents

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)

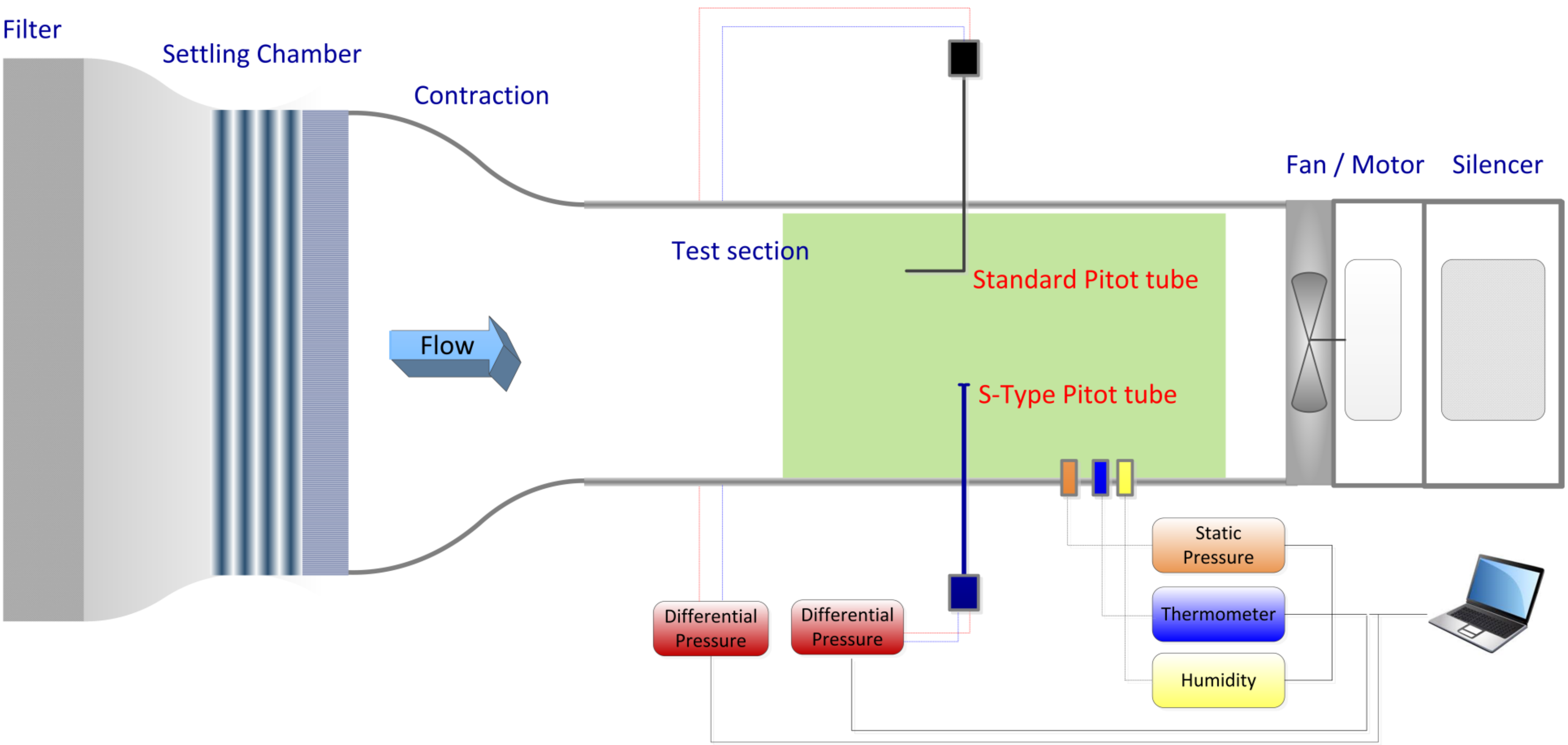
$C_{P,S}$: S type Pitot tube coefficient

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)

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



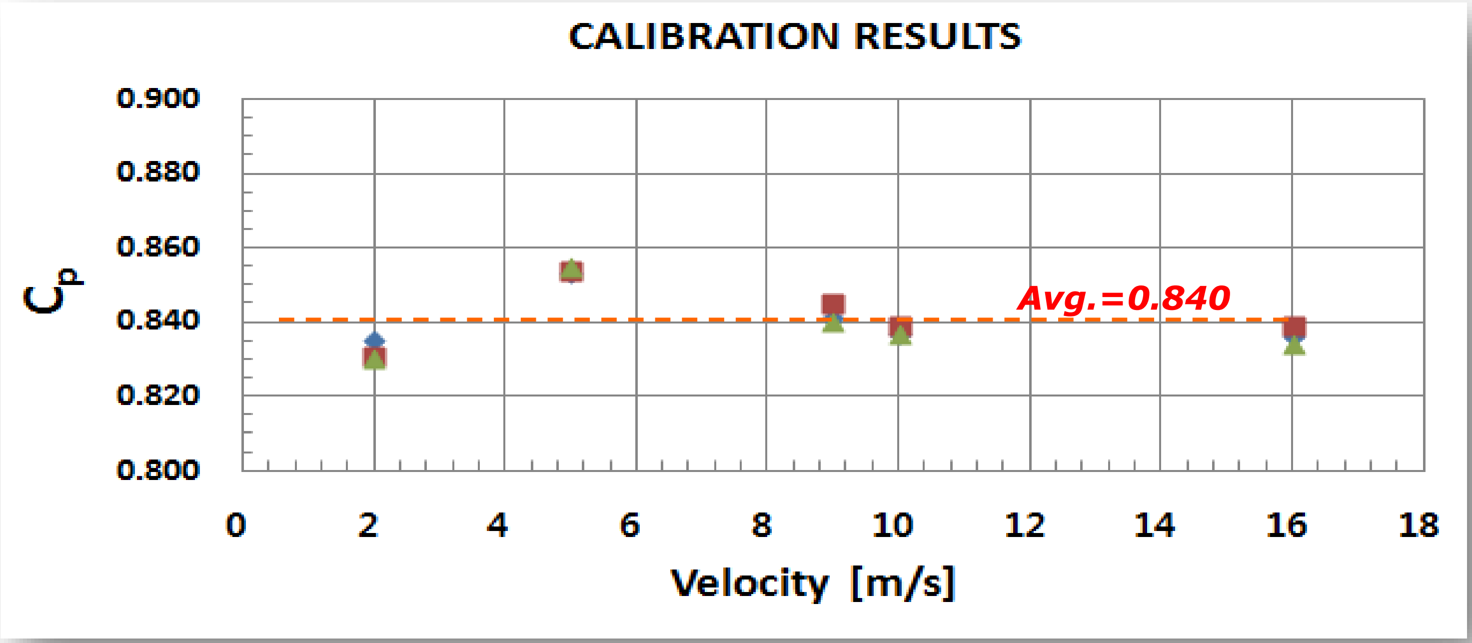
Calibration for S Pitot Tube Coefficient (C_p)

- 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



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

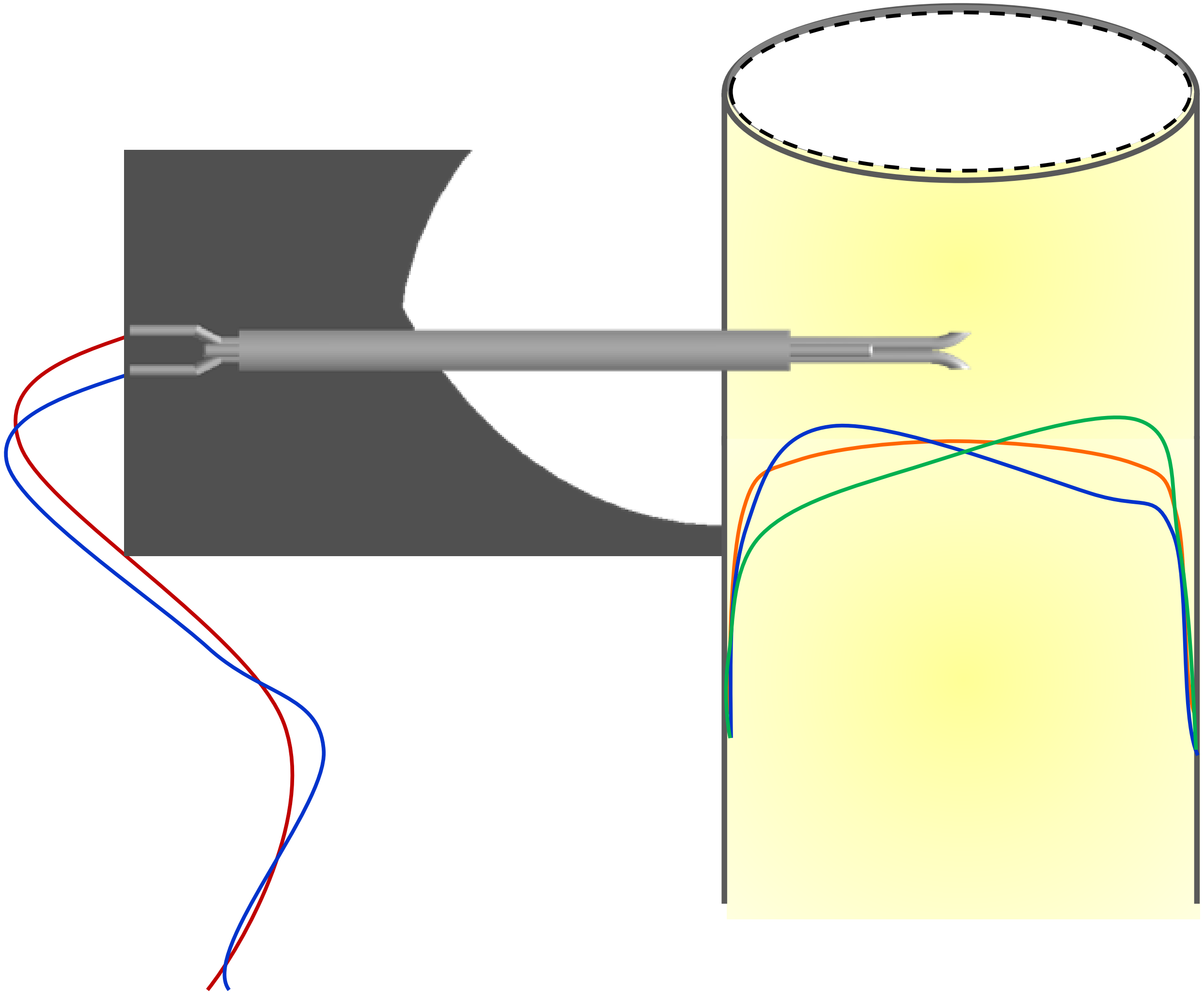
On-site Measurement

- 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

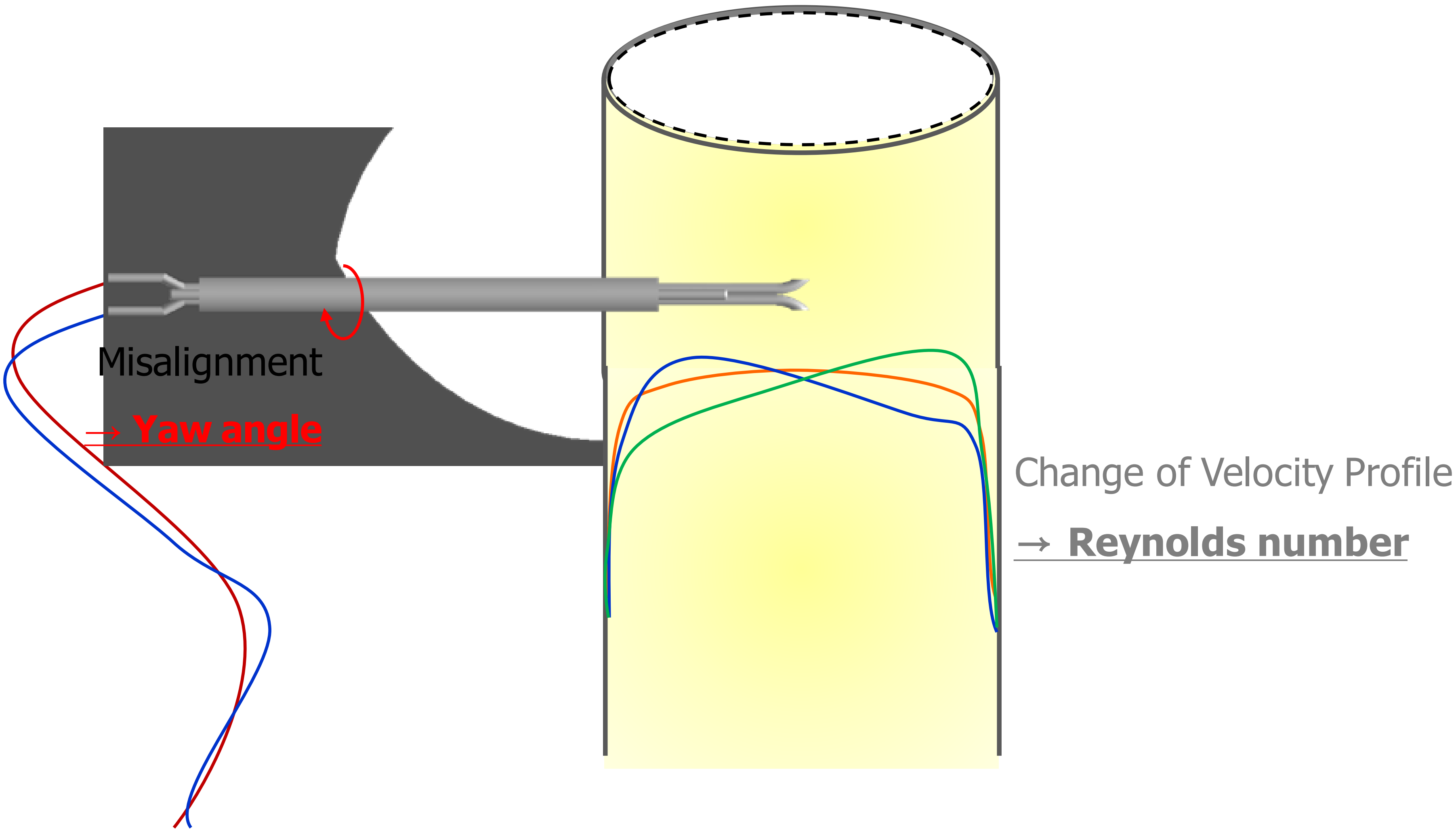


Change of Velocity Profile

→ Reynolds number

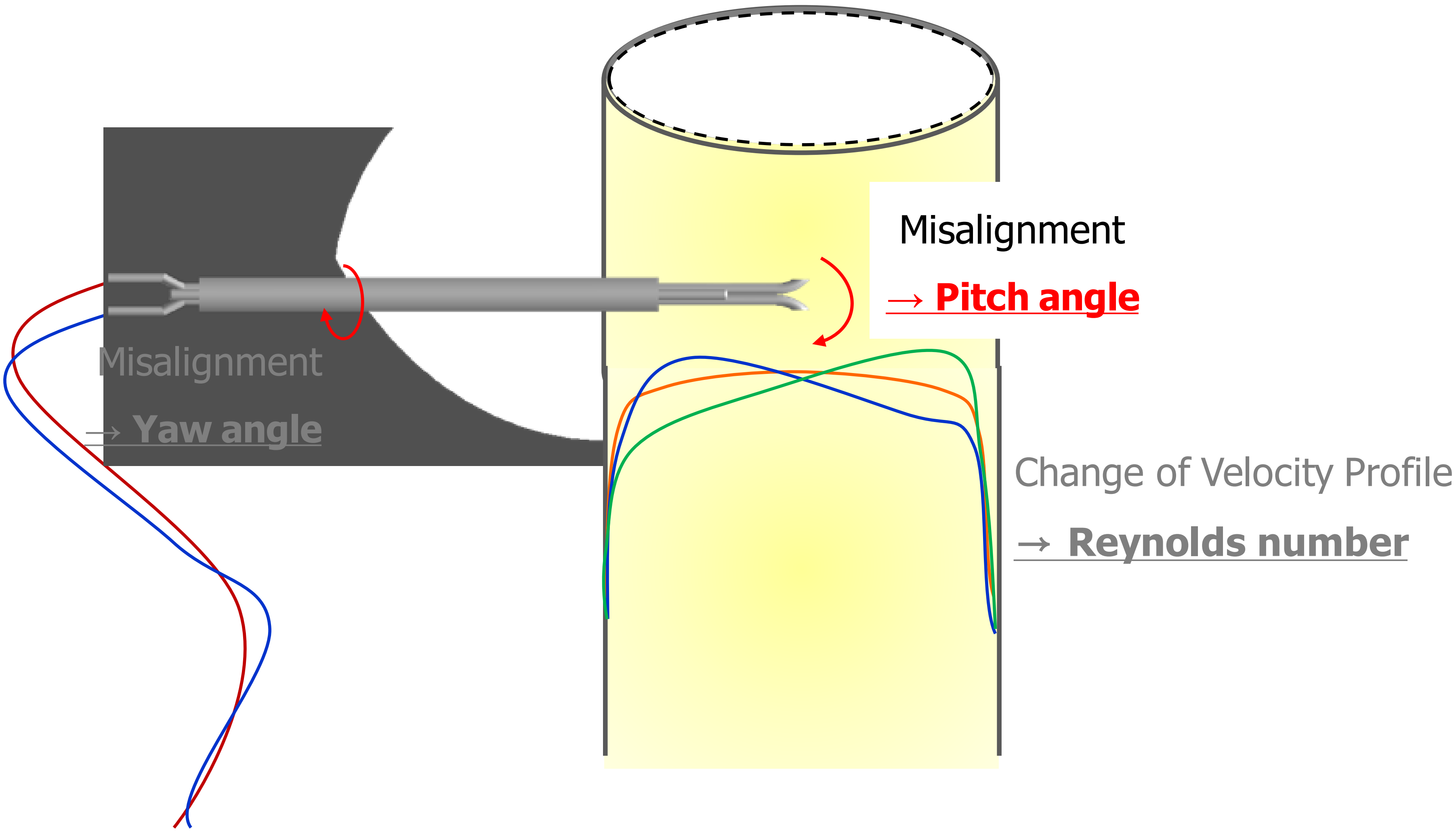
What Happens Inside the Stack?

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



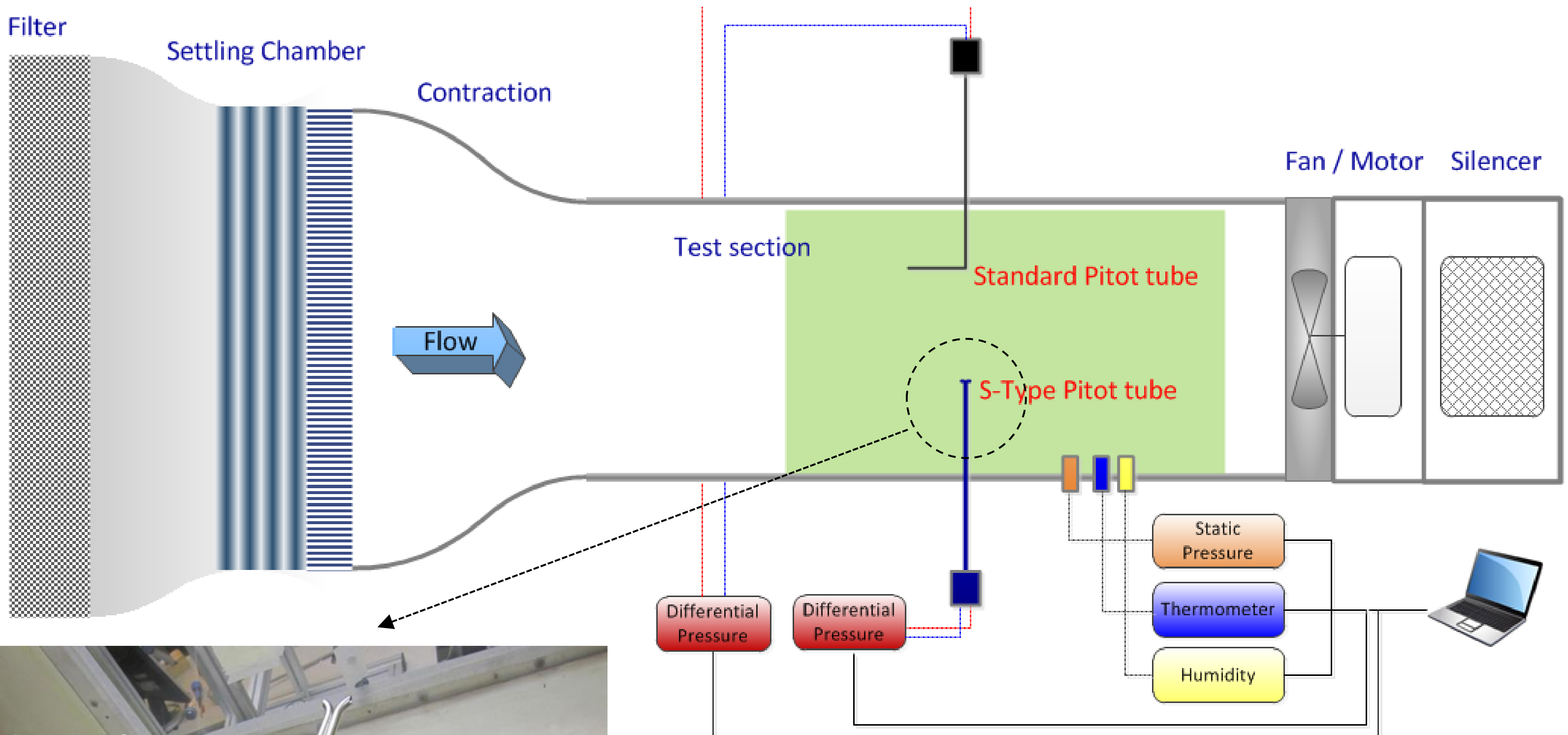
What Happens Inside the Stack?

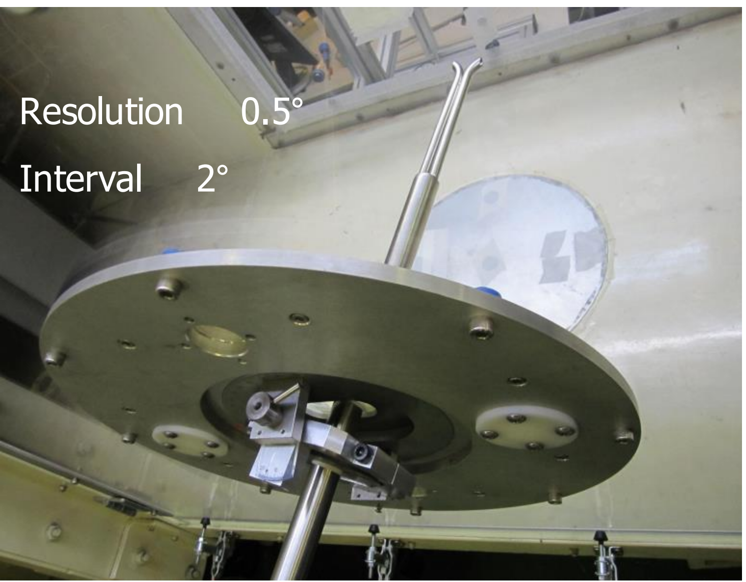
- Pitch angle misalignment of S-type Pitot tube can result due to the deflection of the long S-type Pitot tube in large diameter stacks.

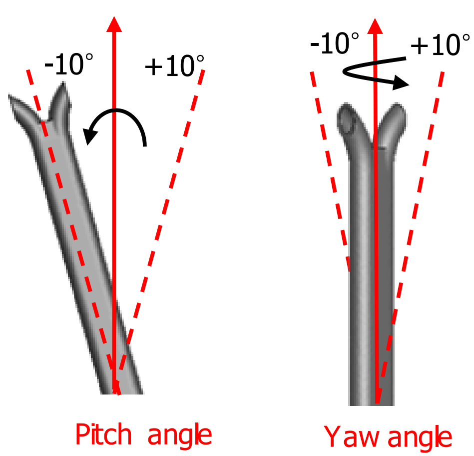


Experimental Studies (2015)

- Flow Measurement and Instrumentation, Kang et al. 2015





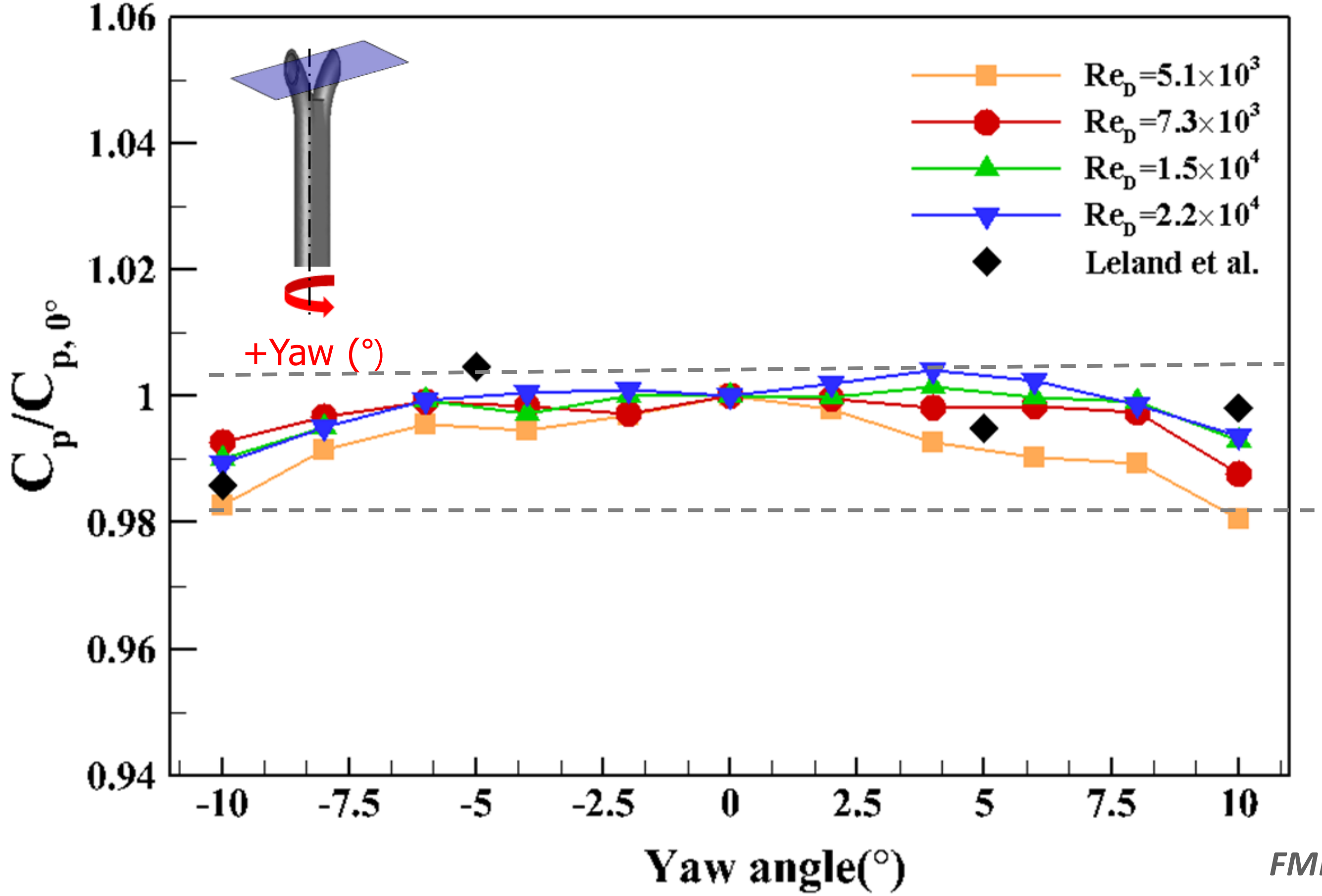


KRISS Subsonic Wind Tunnel	
Wind tunnel Type	Open-Suction type
Velocity range	2 m/s to 15 m/s
Test section area	0.9 m X 0.9 m
Uncertainty (%)	0.60 % to 1.1%

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

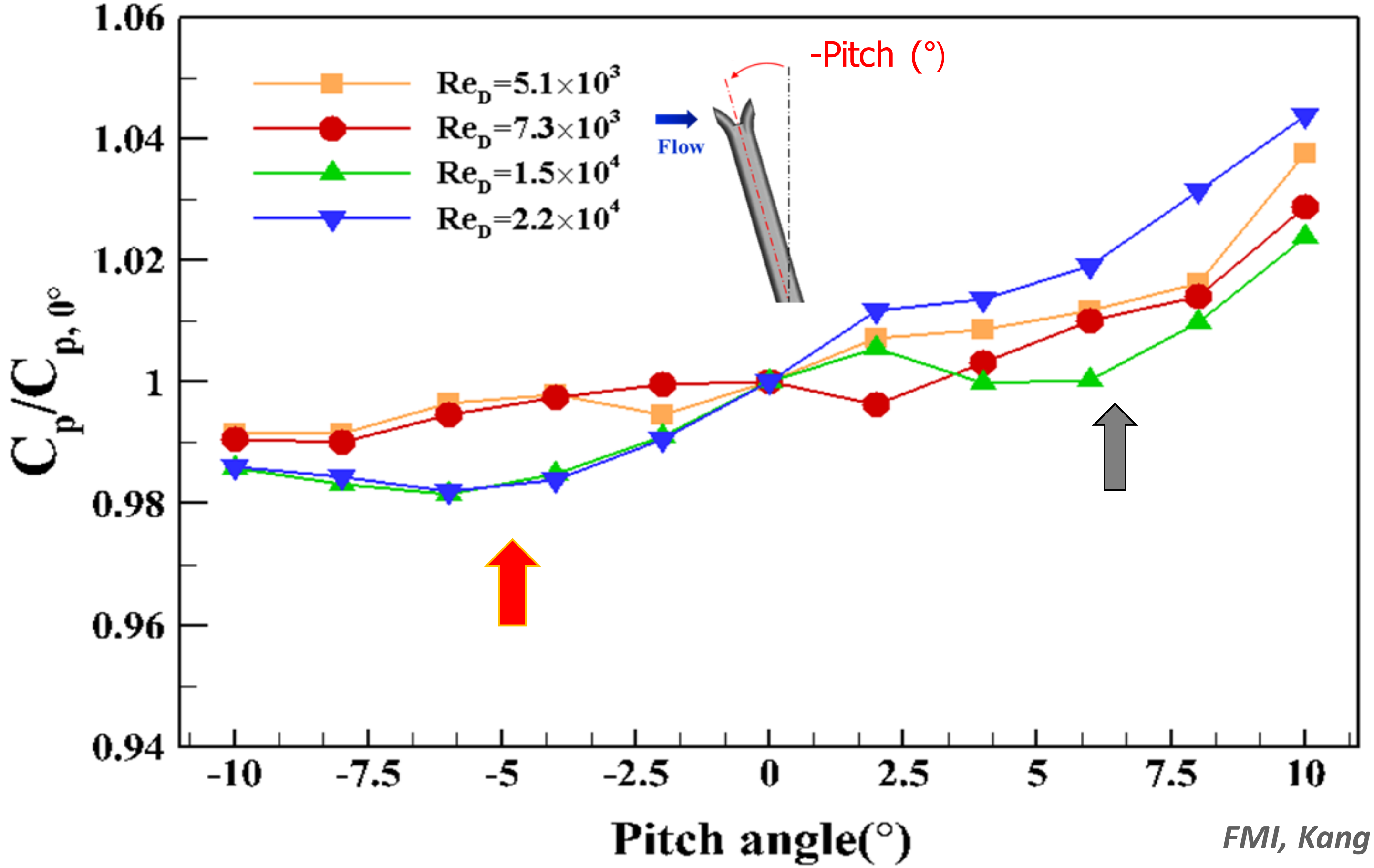


FMI, Kang et al. 2015

The effects of Pitch angle misalignment

The effects of Pitch angle misalignment

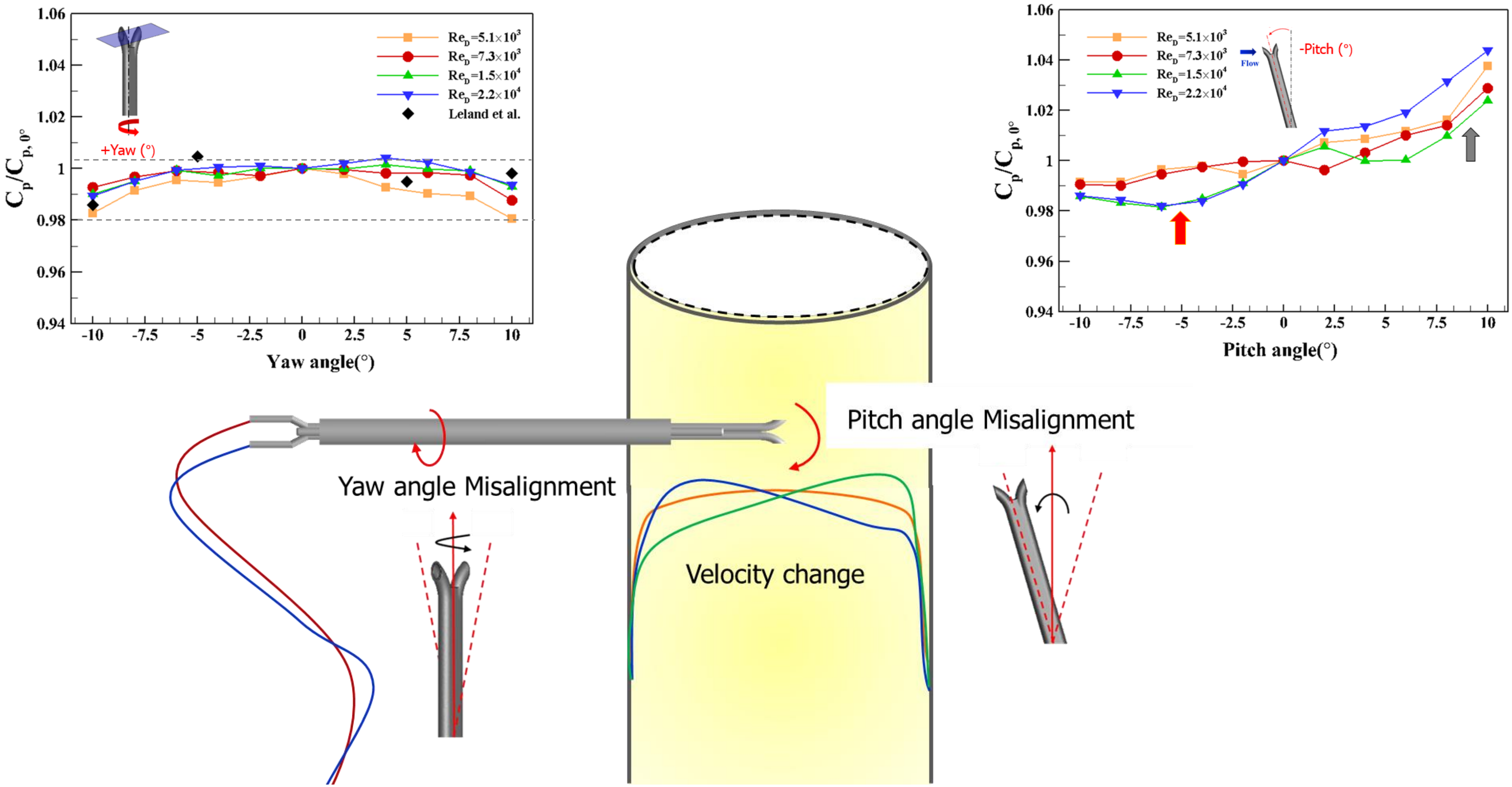
- The normalized S-type Pitot tube coefficients increase up to 4 % as the pitch angle increases to +10°
- In negative Pitch angles, S-type Pitot coefficients decrease to −2%, which can occur in industry stacks due to defection of long S type Pitot tube



FMI, Kang et al. 2015

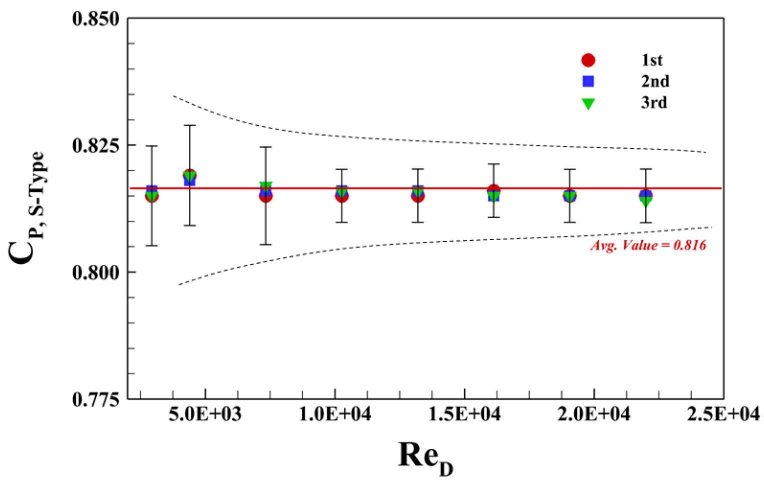
S-type Tube for Smokestack

- 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.

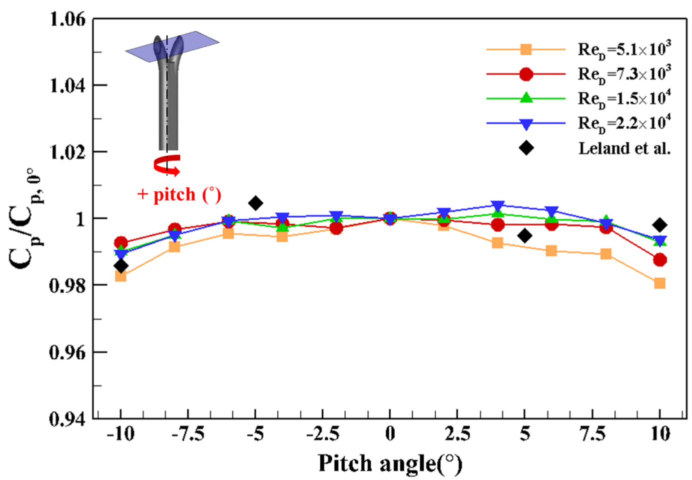


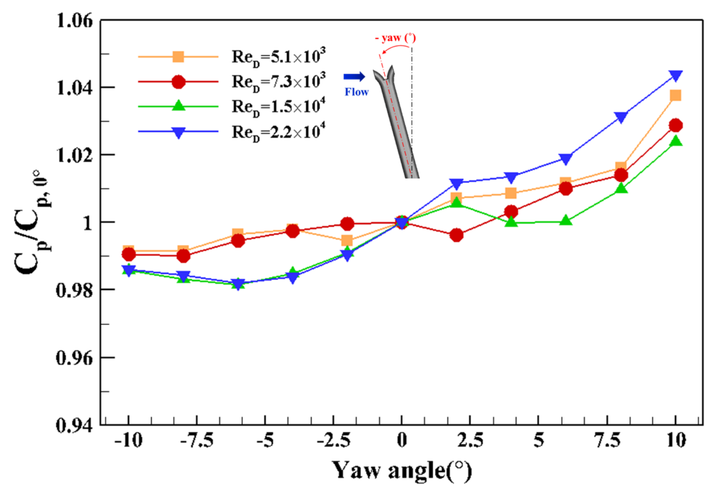
What is Ideal S-Type Pitot tube ?

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



- Less (more) 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)

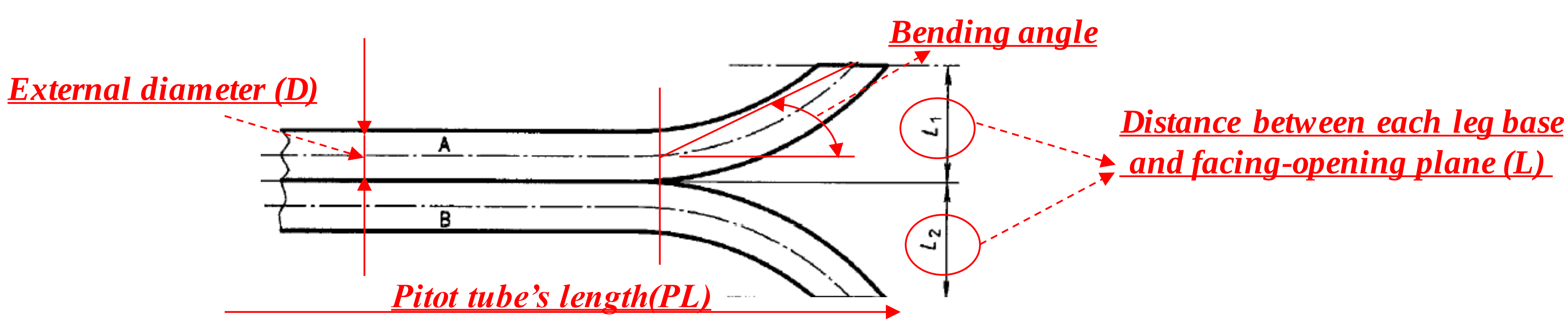
Recommended Configuration of S Pitot tube

International Organization for Standardization

ASTM INTERNATIONAL

EPA United States Environmental Protection Agency

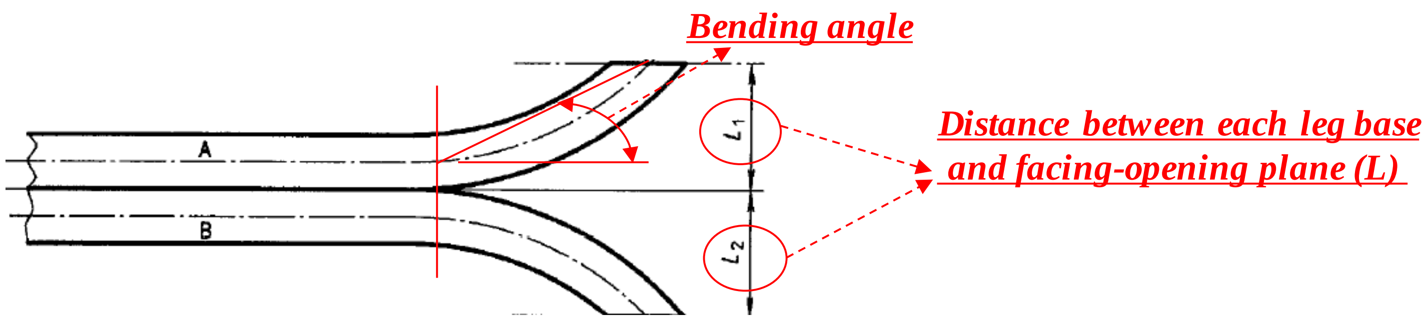
ISO 10780	ASTM D3796(Ref. 1)	EPA
External diameter of leg (D) : 4 mm to 10 mm Distance between the base of each leg of the Pitot tube and its face-opening plane : 1.05D ≤ L ≤ 10D This distance shall be equal for each leg	Bending a 45° angle on the end of 0.95 cm stainless steel tube The Pitot tube's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



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



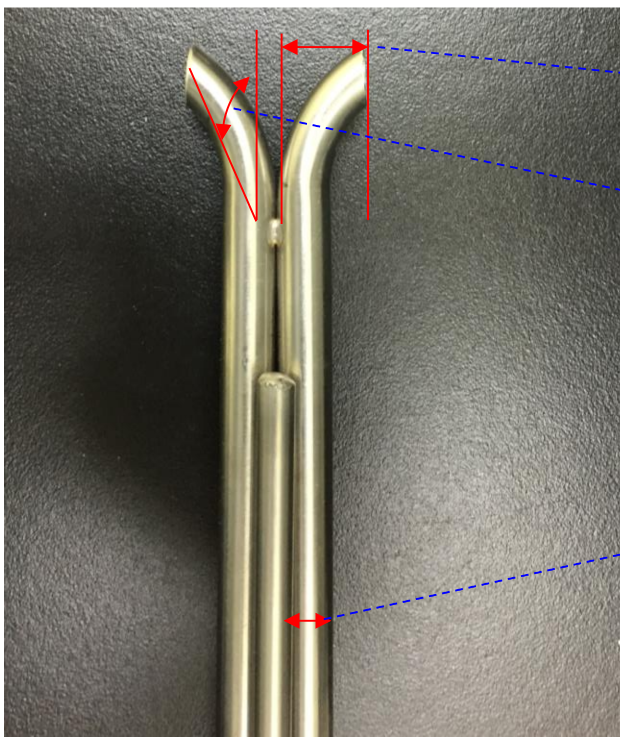
1. Distance between leg base and facing-opening plane (L)
   - ISO: 1.05D ≤ L ≤ 10D, EPA: 1.05D ≤ L ≤ 1.5D

2. Bending Angle of opening parts (α)
   - ASTM: 45° (KRISS S Pitot tube = 30 °)

3. Shape of opening parts
   - Curved / Straight

Configuration of S-type Pitot tube

- S-type Pitot tube KRISS used



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

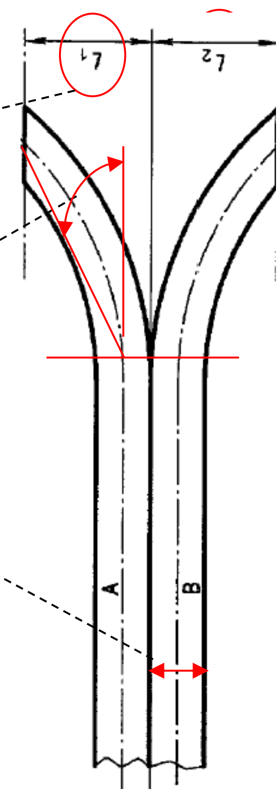
→L=1.6D

Bending angle

→α= 30 °

External diameter (D)

→D=9.5 mm



Configuration of S-type Pitot tube

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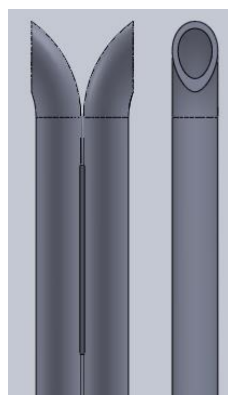
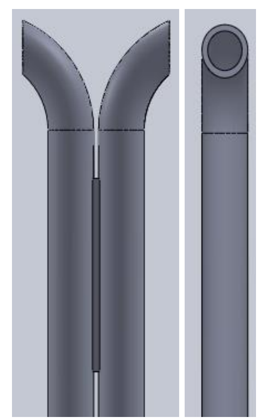
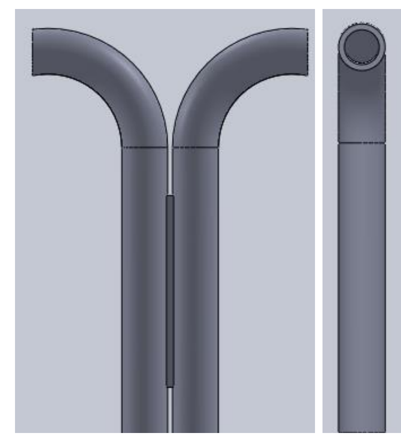


L =1.05D, α = 30°



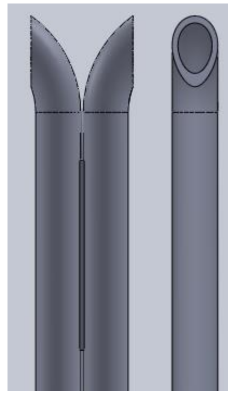
L = 1.6D, α = 30°



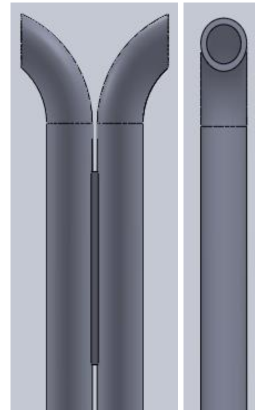
L = 3D, α = 30°

S-type Pitot tube Manufacturing

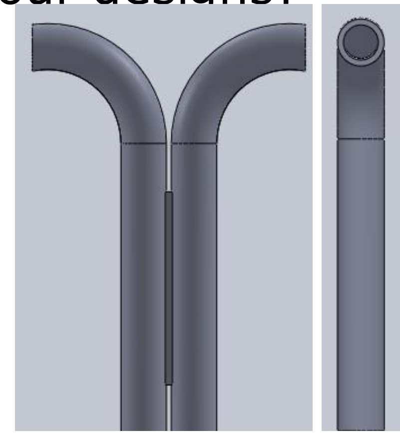
- How to manufacture S-type Pitot tube model for our designs?



L =1.05D, α = 30°

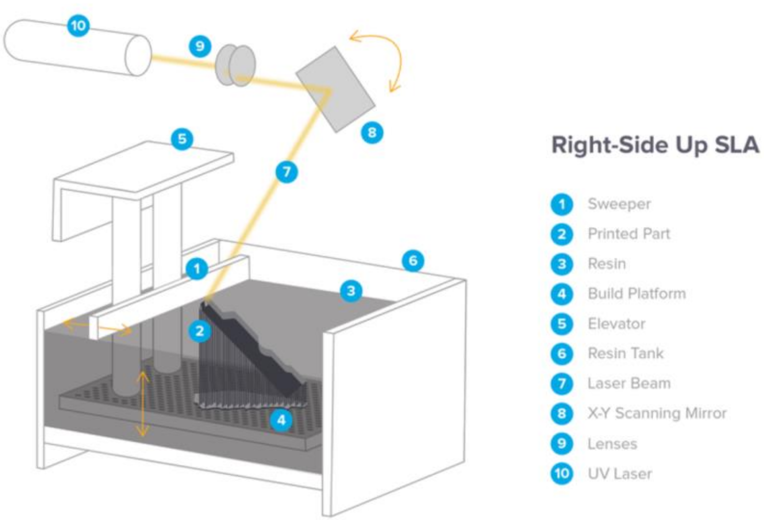


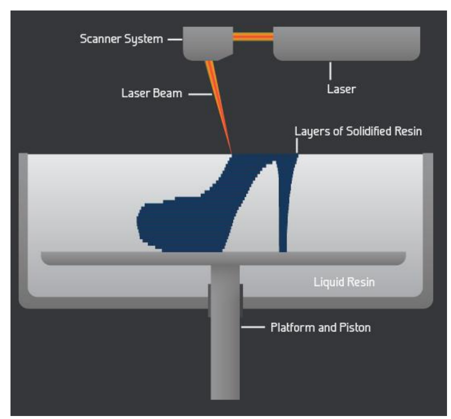
L = 1.6D, α = 30°

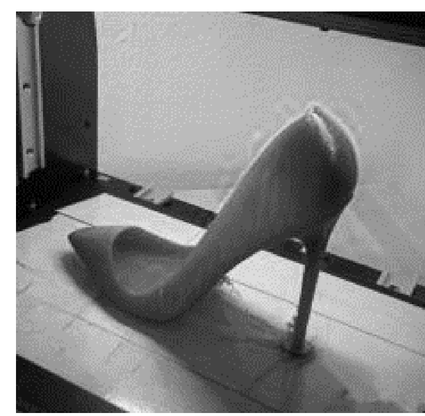


L = 3D, α = 30°

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



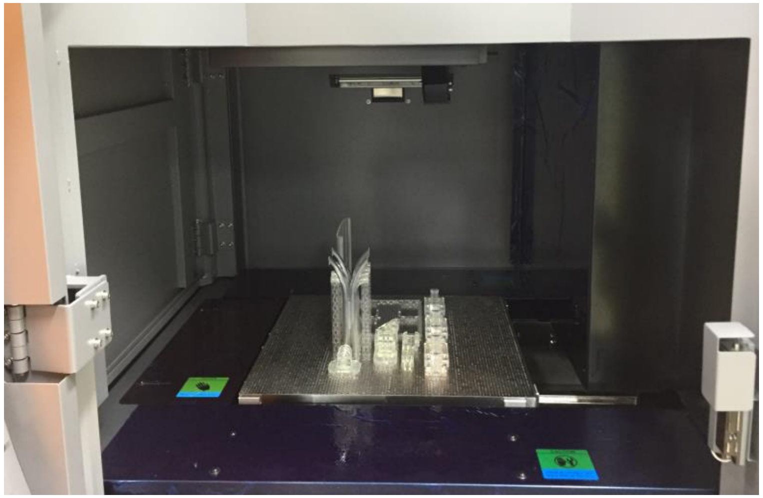


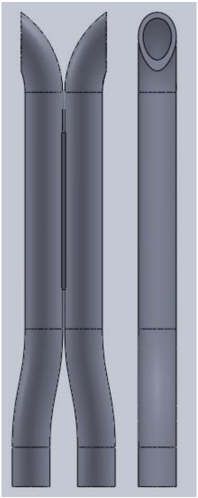


3D Printing for S-type Pitot tube

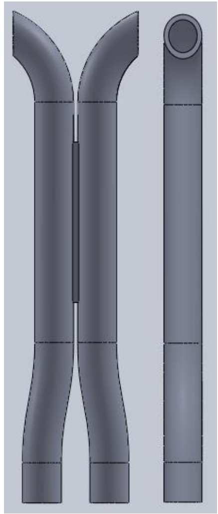
- 3D Printing S-type Pitot tube for our design(Daejeon Techno-park)

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

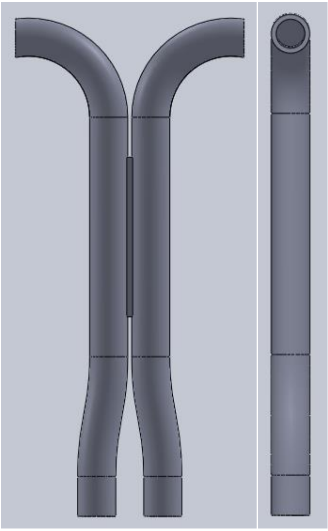




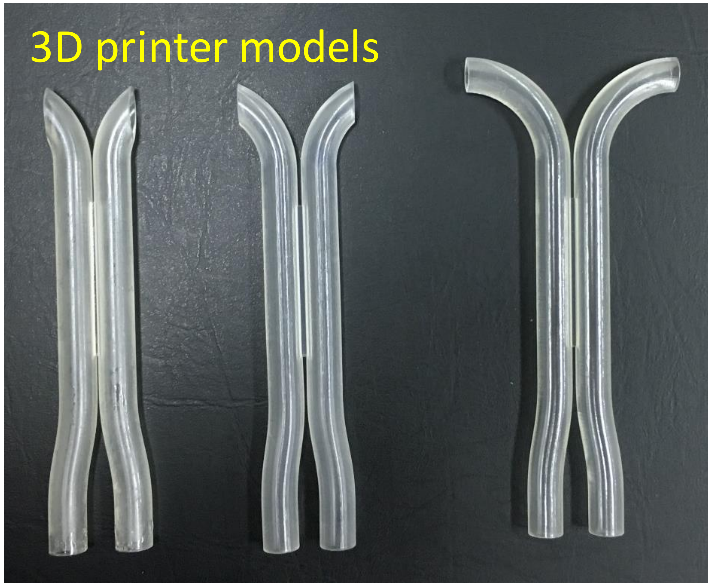
L =1.05D, α = 30°



L = 1.6D, α = 30°



L = 3D, α = 30°



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

   → **L = 1.05D, 1.6D, 3D**

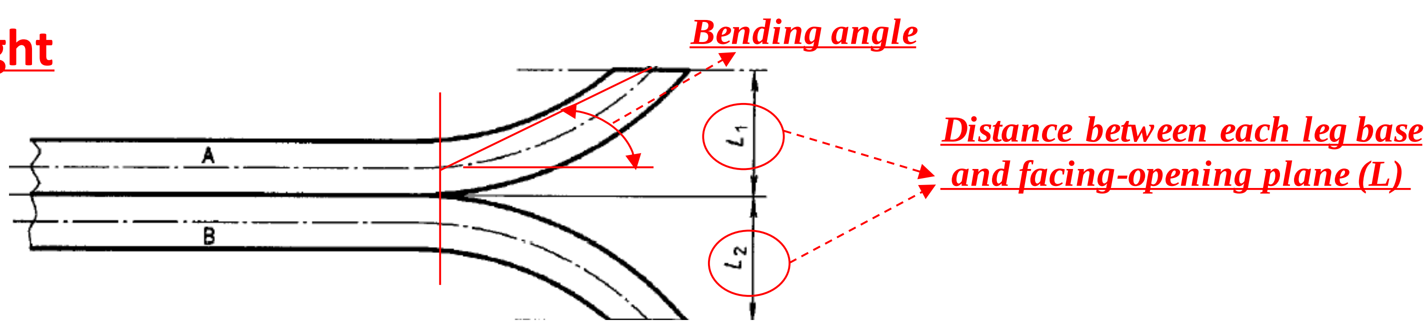
2. Bending Angle of opening parts

   - ASTM: 45° (KRISS S Pitot = 30 °)

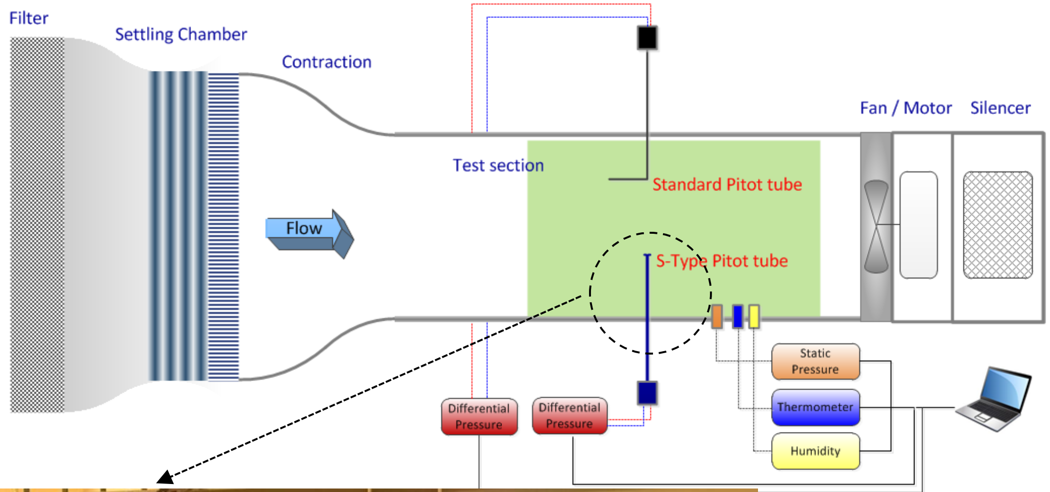
   → **α = 15°, 30°, 45°**

3. Shape of opening parts

   → **Curved, Straight**



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
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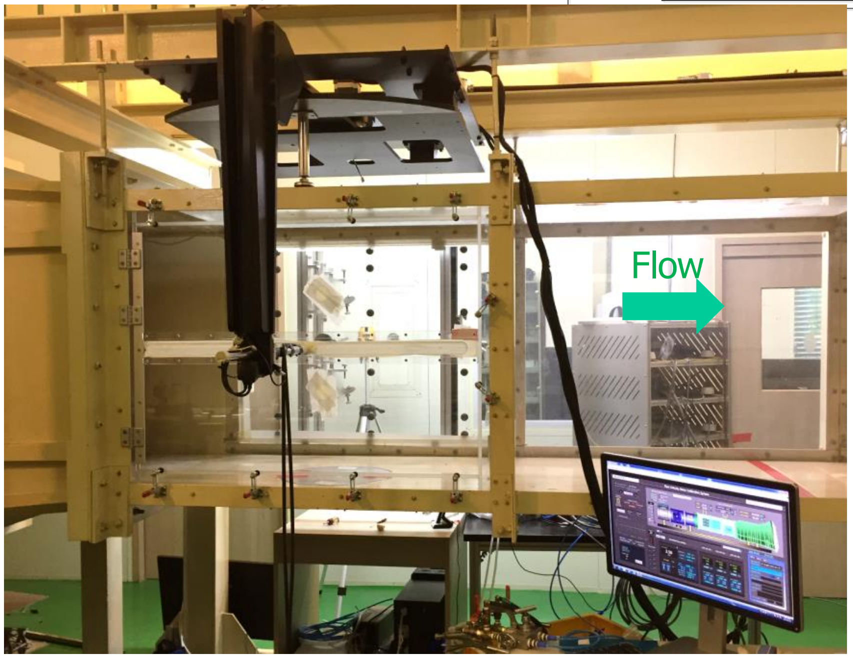
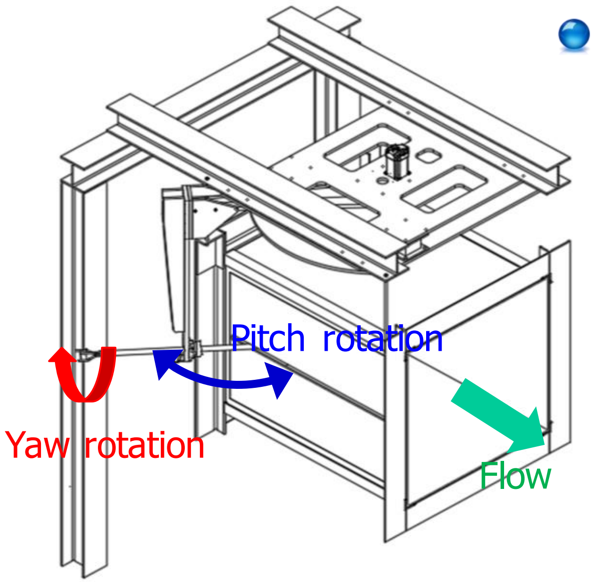


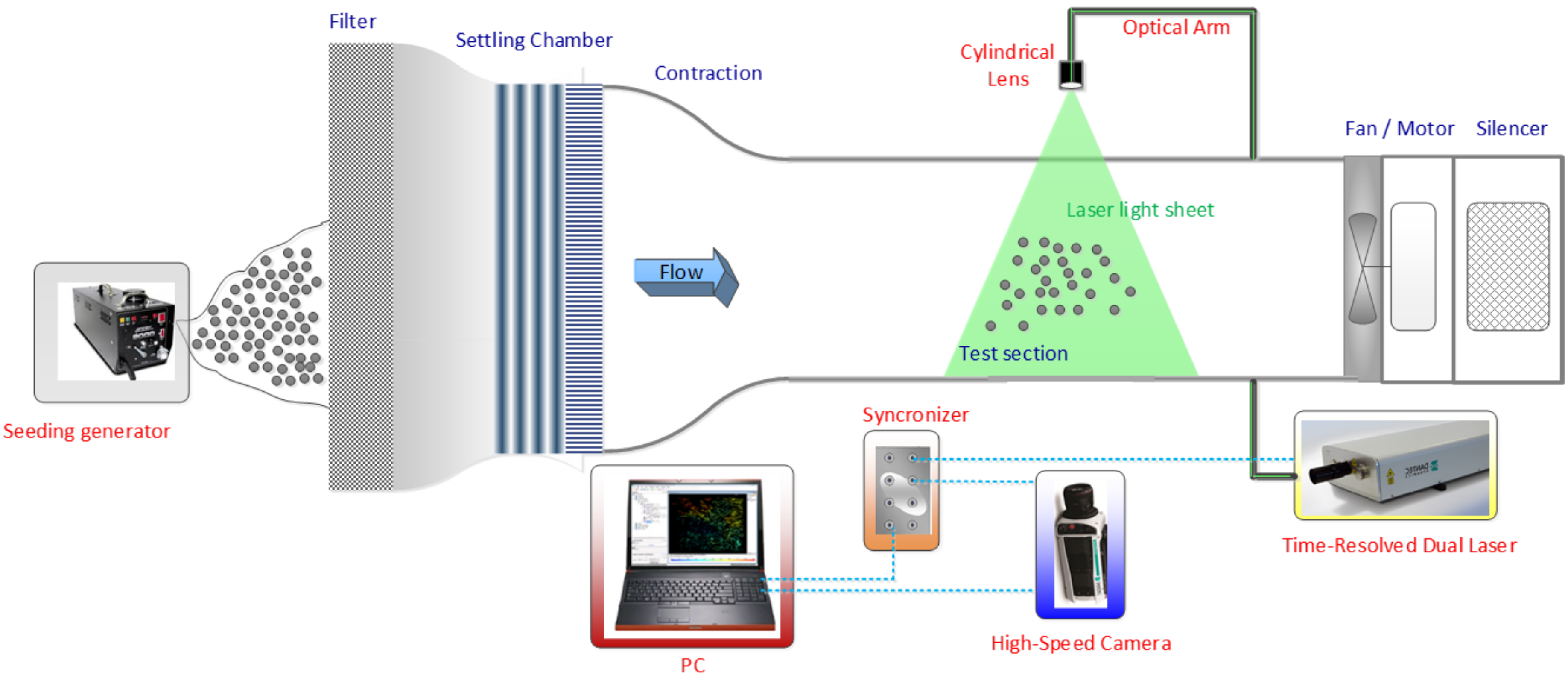


New rotating device

- 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



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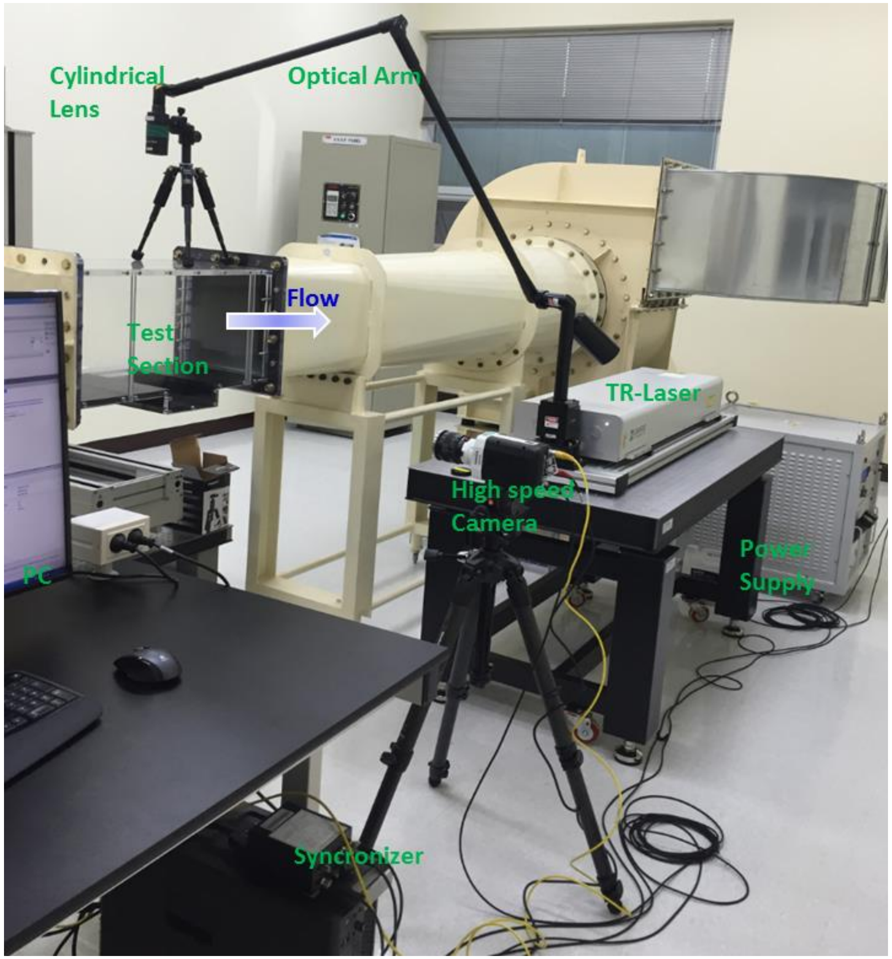
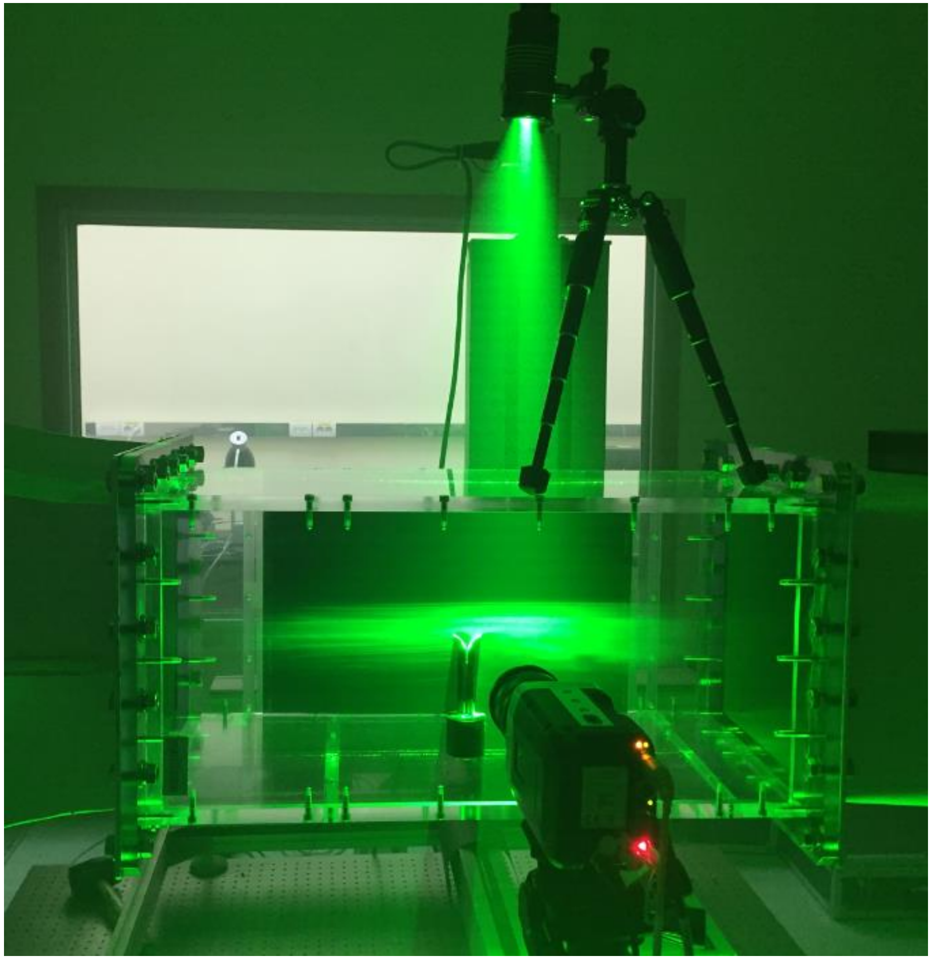


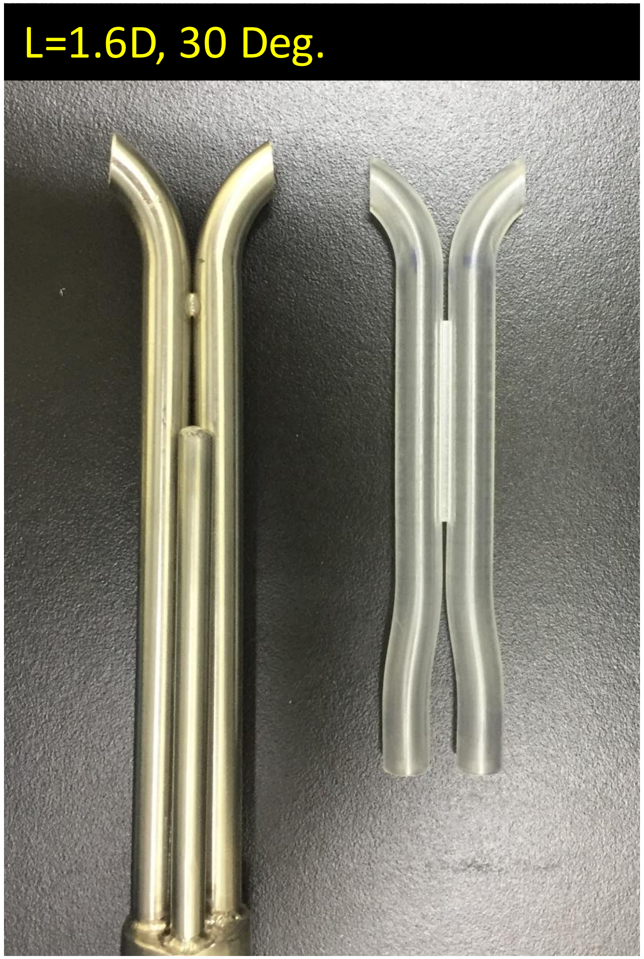


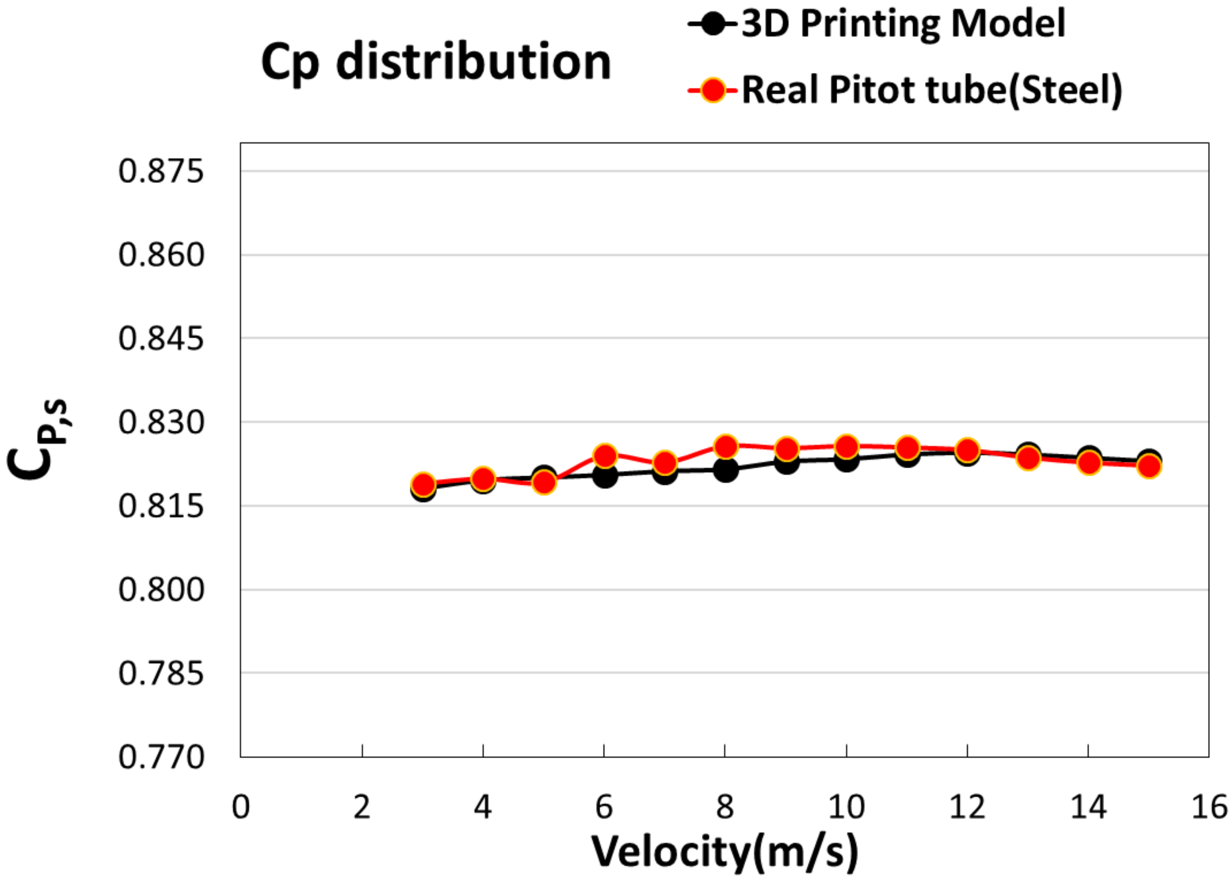
KRISS

Contents

Verification of 3D Printing model

- Compare Cp distribution according to velocity change





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

Experiments for the effect of S pitot geometry I

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

→ **L = 1.05D, 1.6D, 3D**

2. Bending Angle of opening parts

→ **α = 15°, 30°, 45°**

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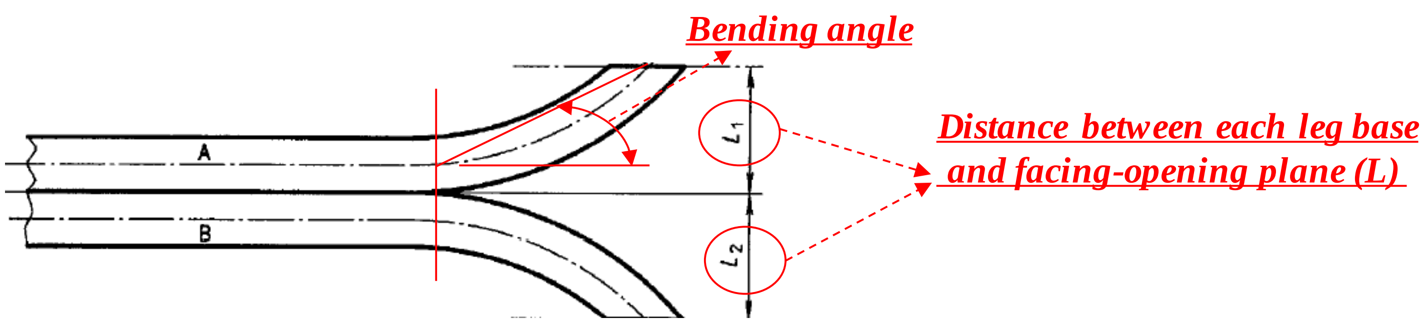
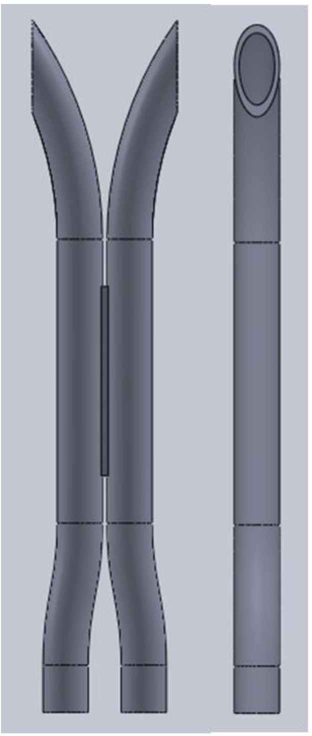
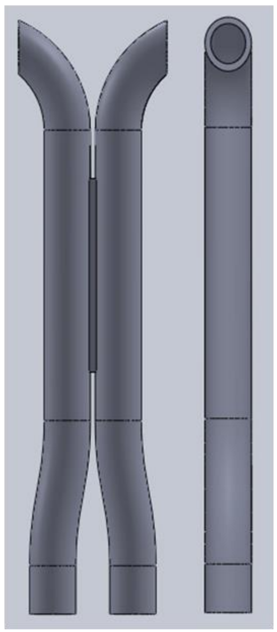


L=1.6D Models

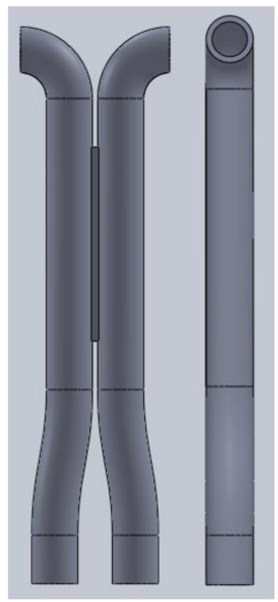
- Compare L=1.6D models (α = 15 Deg., 30 Deg. and 45 Deg.)



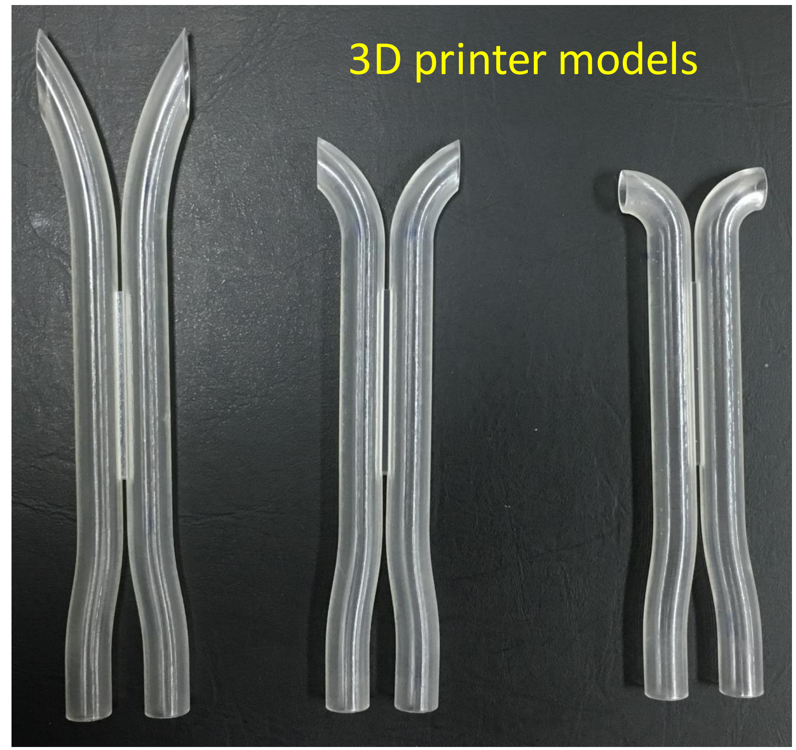
α = 15°, L = 1.6D



α = 30°, L = 1.6D

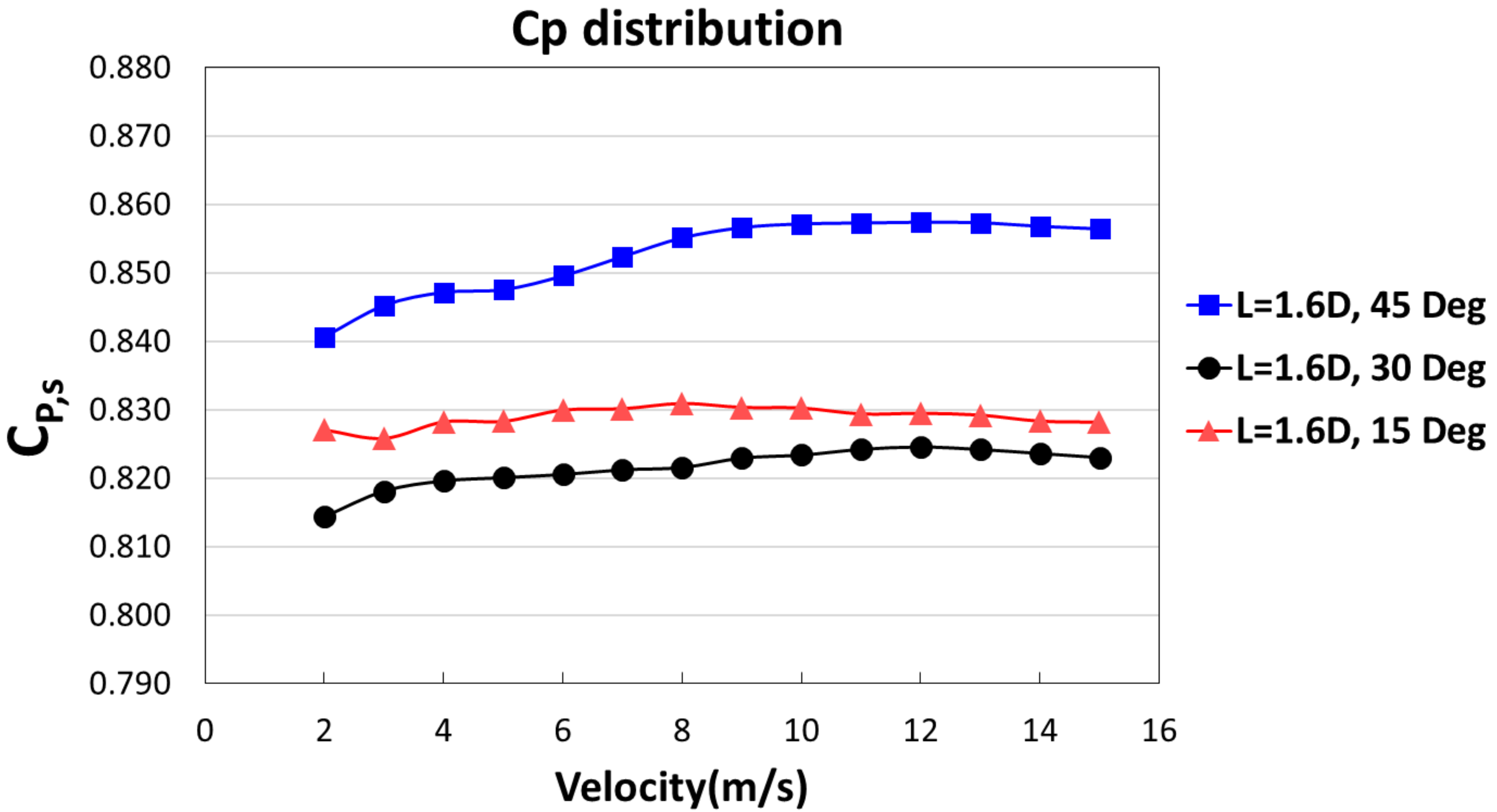


α = 45°, L = 1.6D



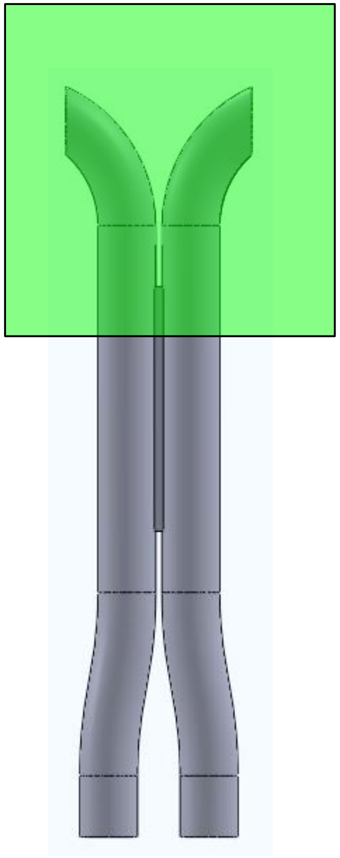
L=1.6D Models(Cp distribution)

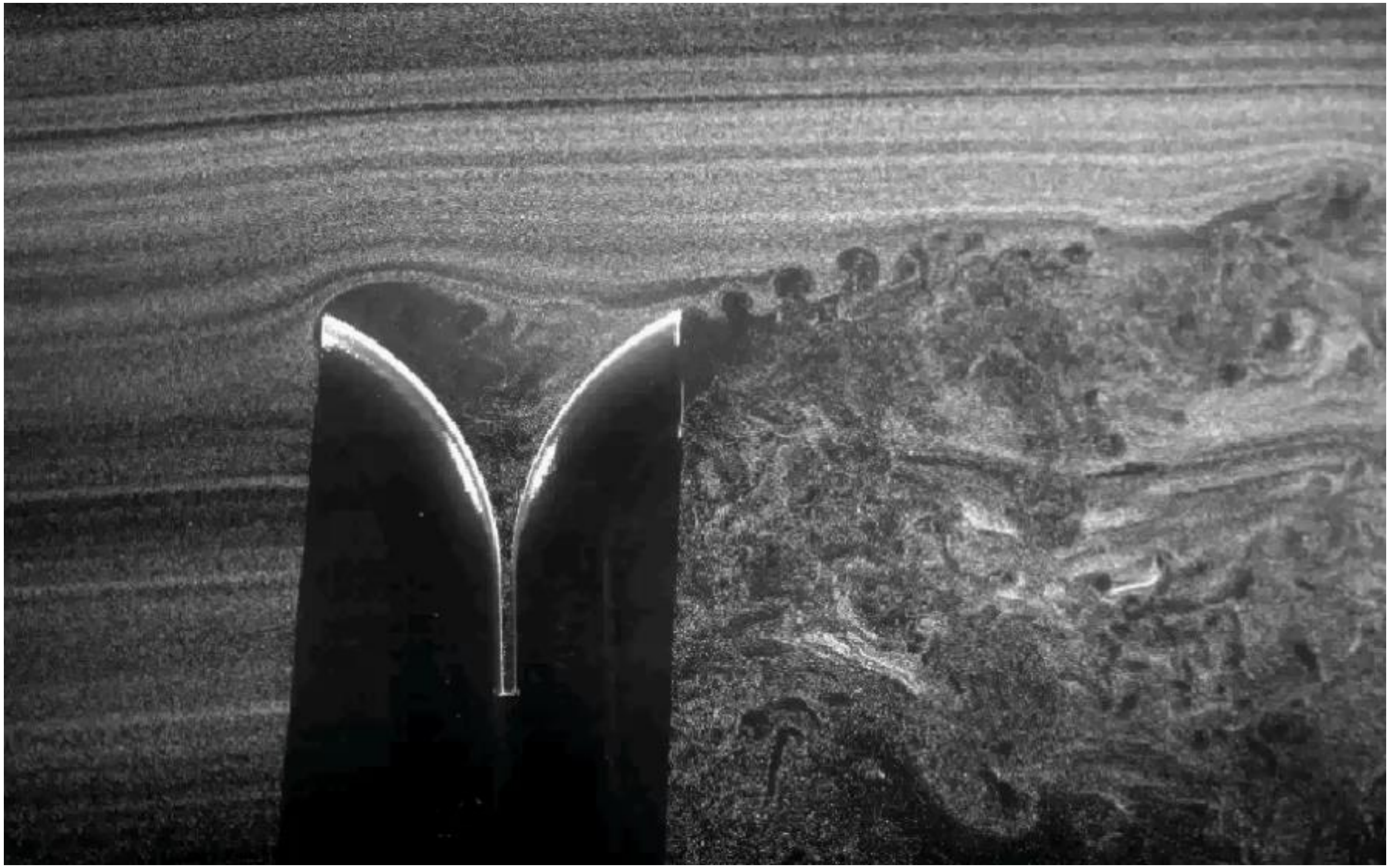
- The α=45°(L=1.6D) S Pitot has Cp larger than others 4%, Cp is increasing as incoming velocity increases up 15 m/s



L=1.6D, 30 Deg Model(PIV)

- Flow phenomenon around S-type Pitot tube

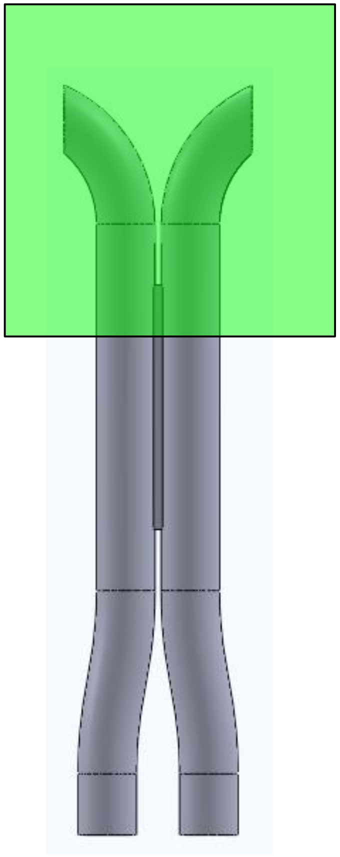


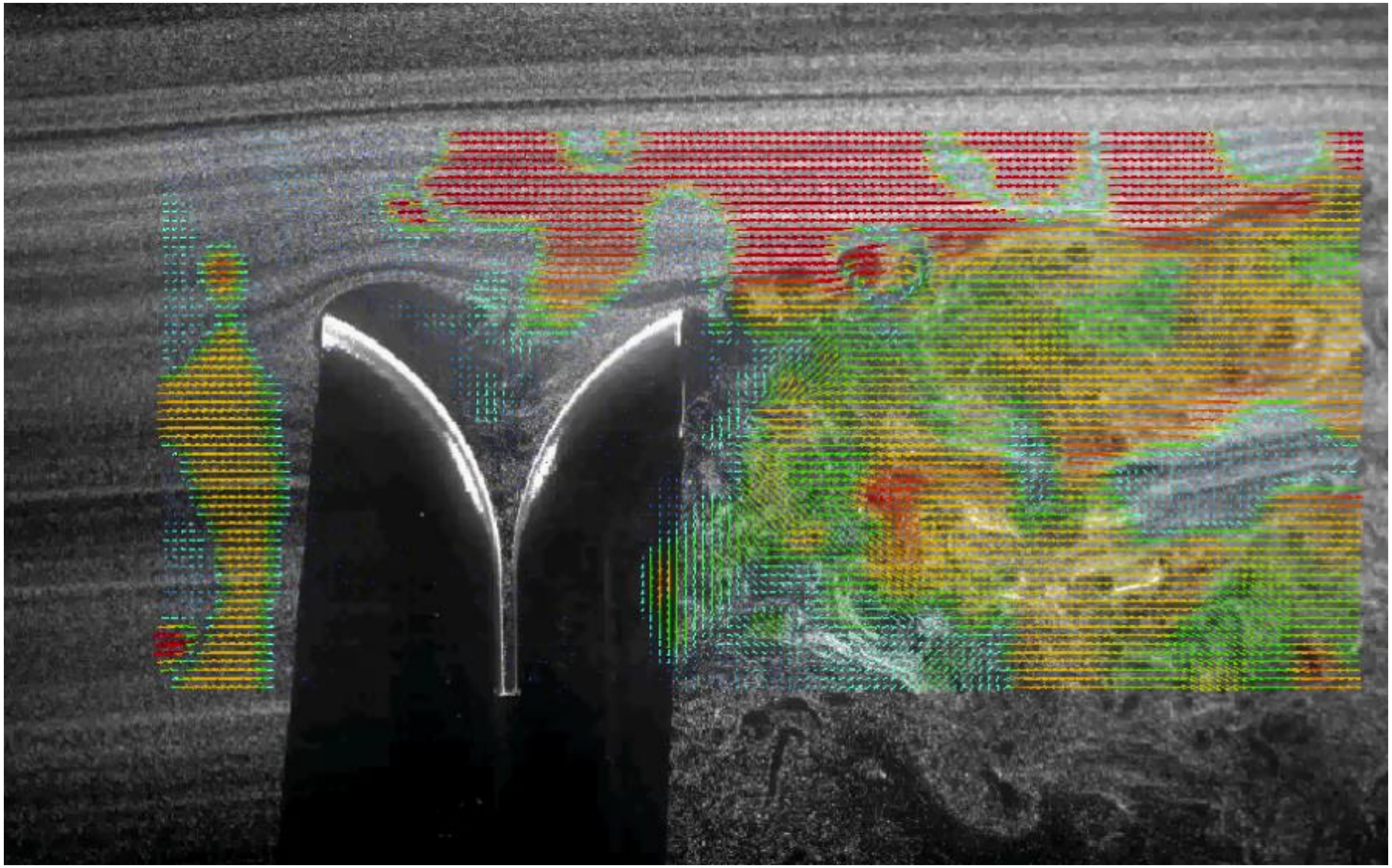


- Due to complicated geometry between the impact and wake orifices, the separated flows are developed to a vortical structure behind orifices

L=1.6D, 30 Deg Model(PIV)

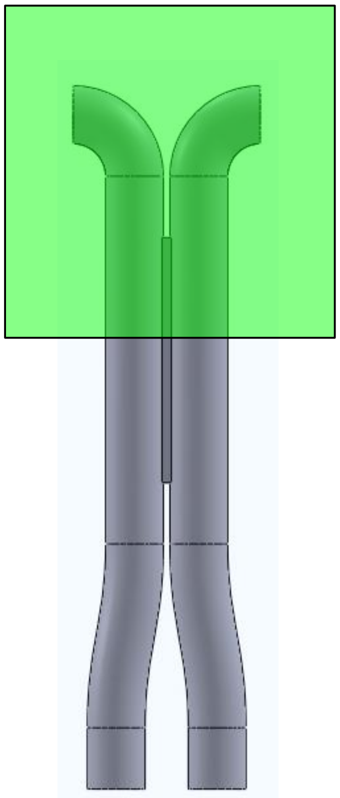
- Velocity vector distribution around S-type Pitot tube

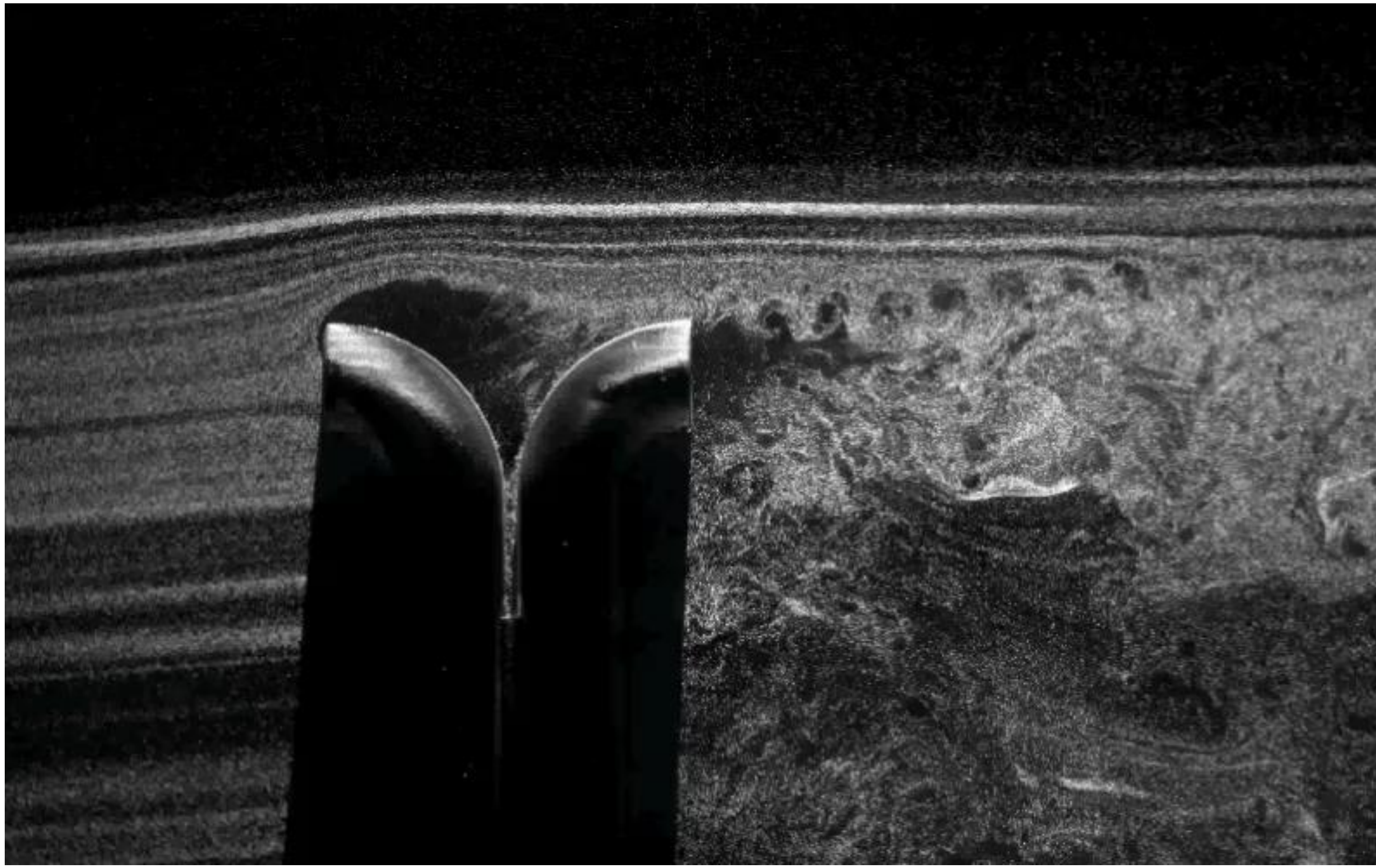




L=1.6D, 45 Deg Model(PIV)

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

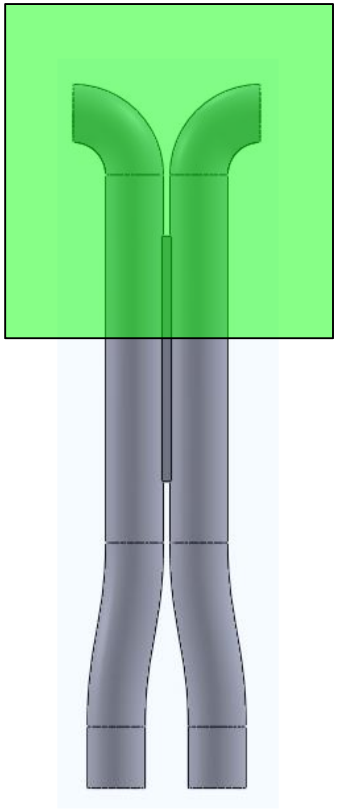


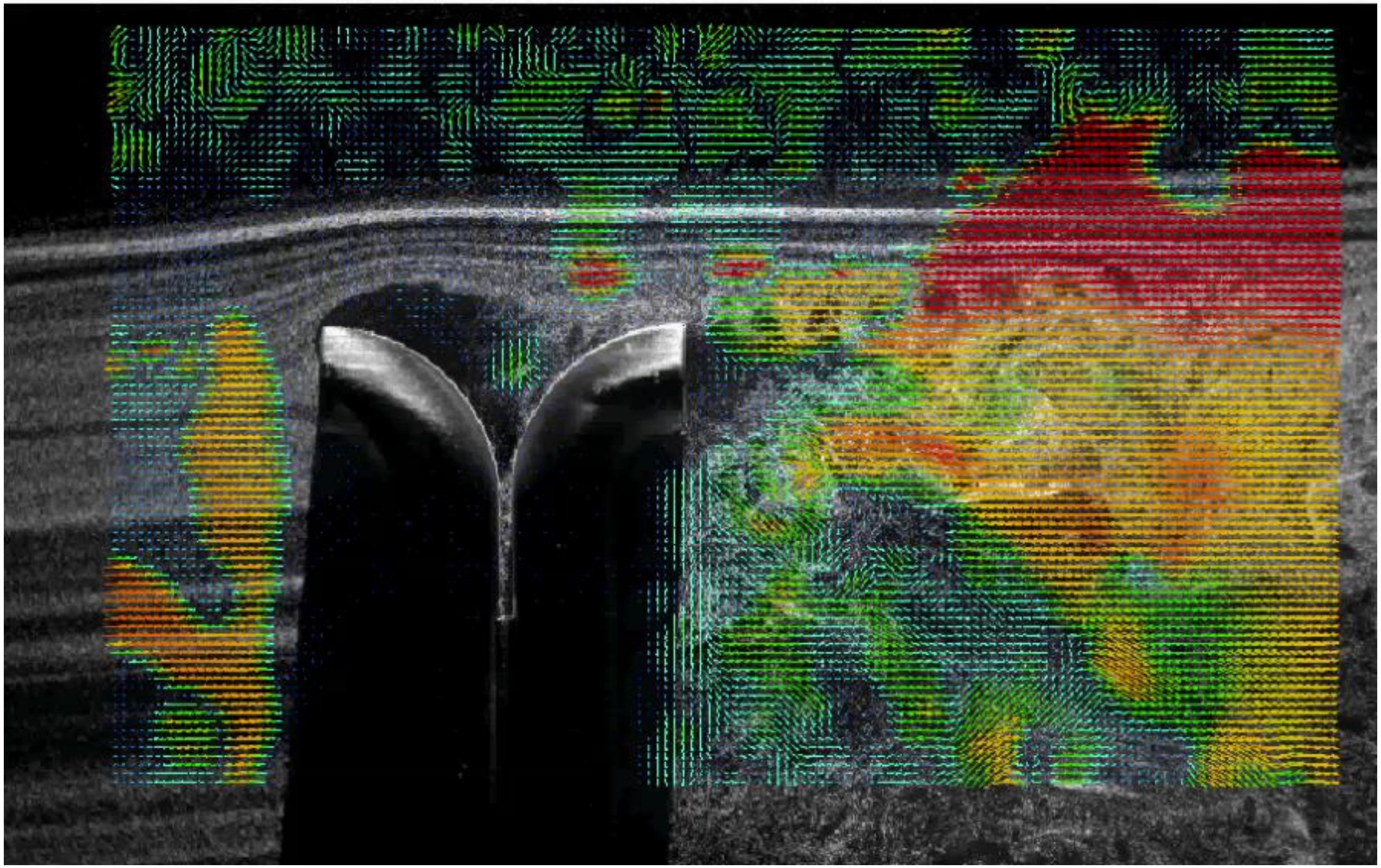


- Separated flow from wake orifice(downstream) were developing less due to gradual change of curved surface compared to 30 deg model.

L=1.6D, 45 Deg Model(PIV)

- Velocity vector distribution around S-type Pitot tube



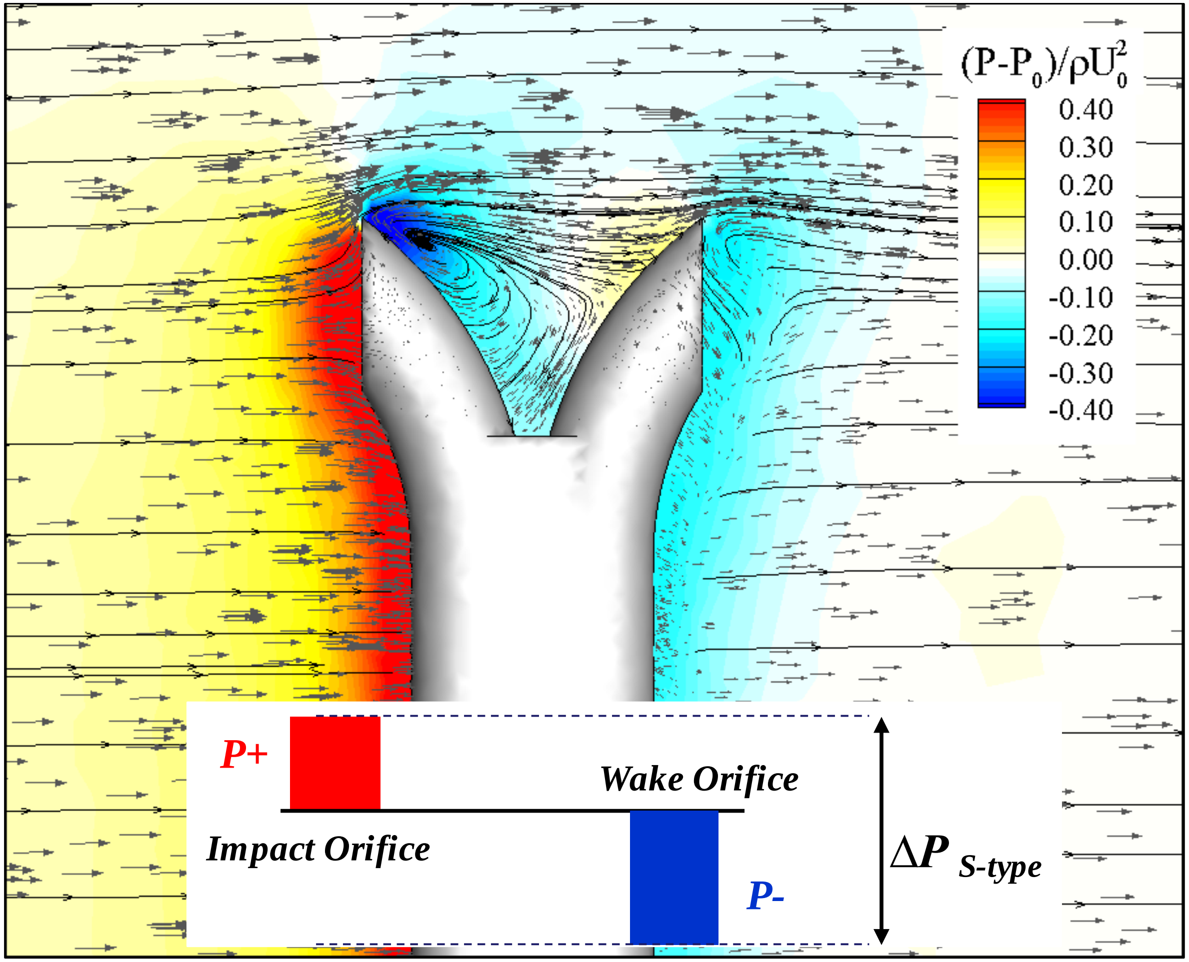


FMI, Kang et al. 2015

Cp,s-type coefficients

- When vortical structure behind the wake orifice developed well
  Lower pressure at wake orifice observed → Cp,s decreased

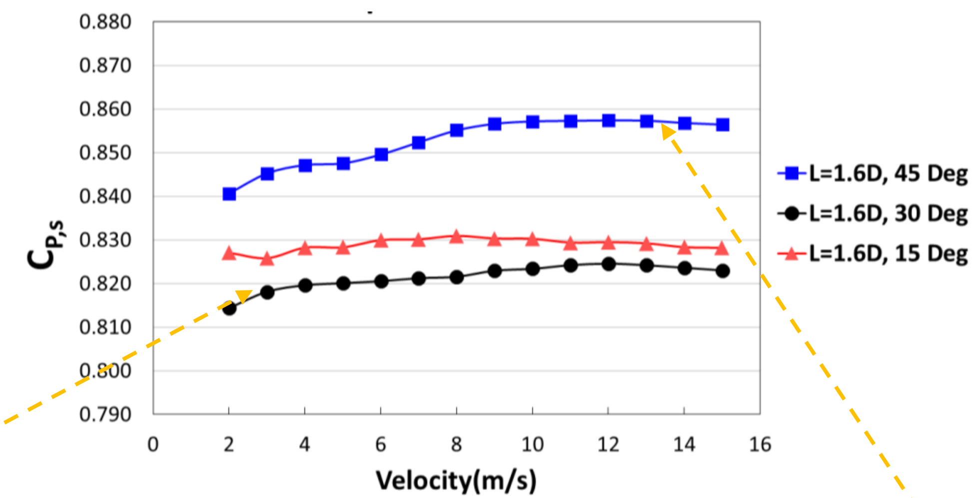
$$C_{P,S} = C_{P,Std}\left(\frac{\Delta P_{Std}}{\Delta P_{S\cdot type}}\right)$$

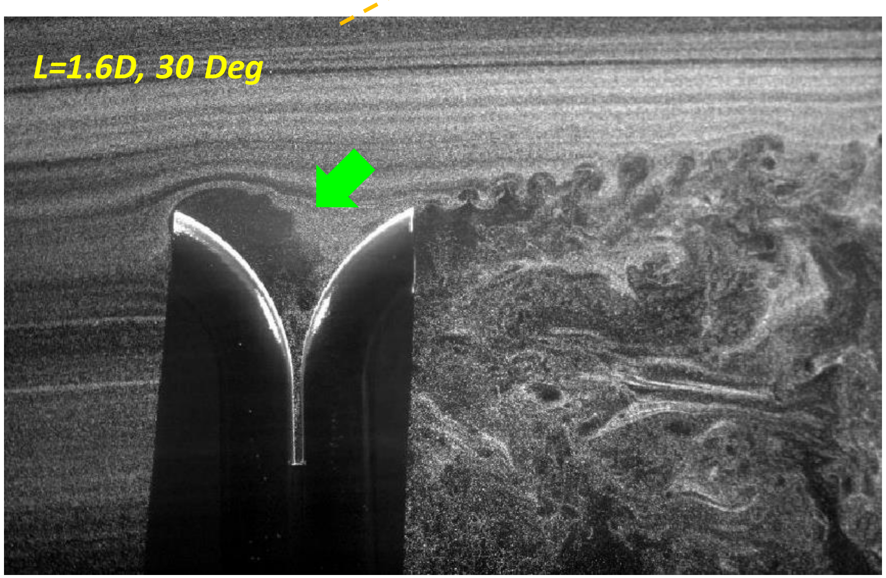


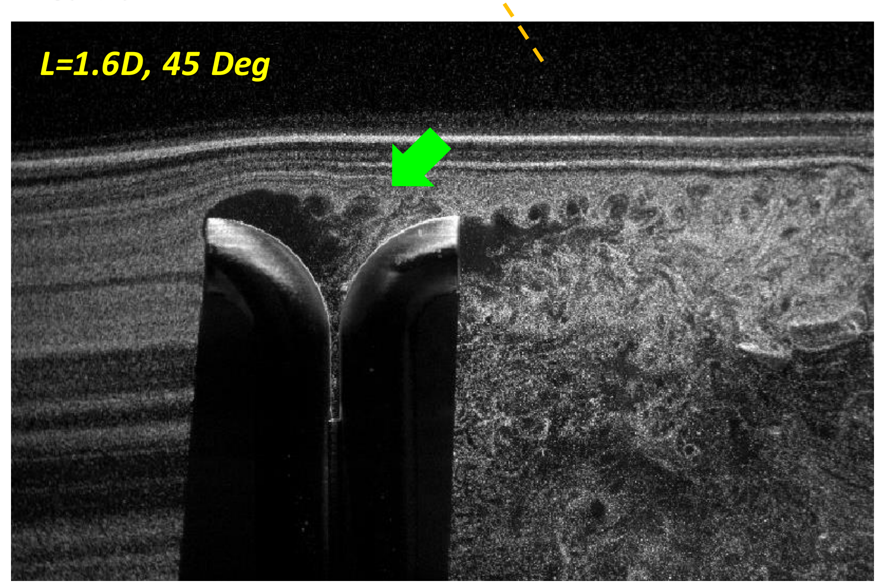
Numerical simulation
FMI, Kang et al. 2015

L=1.6D 30 Deg vs 45 Deg

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

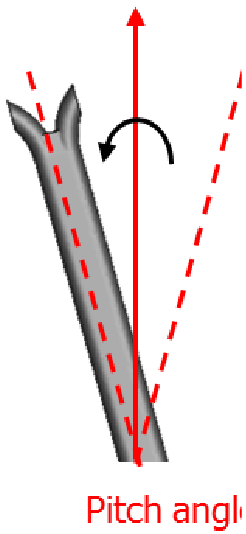


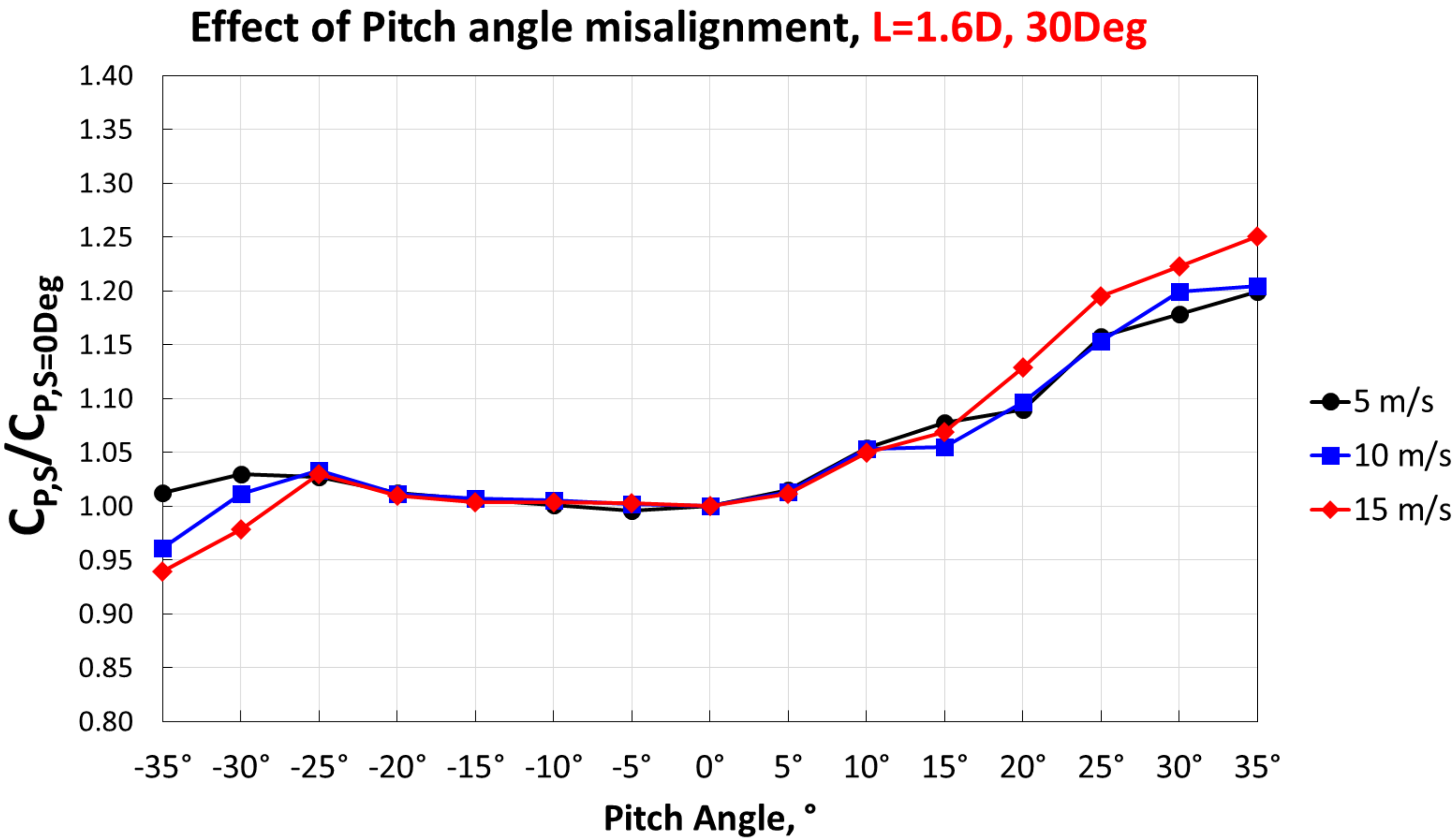




L=1.6D Model (Pitch angle)

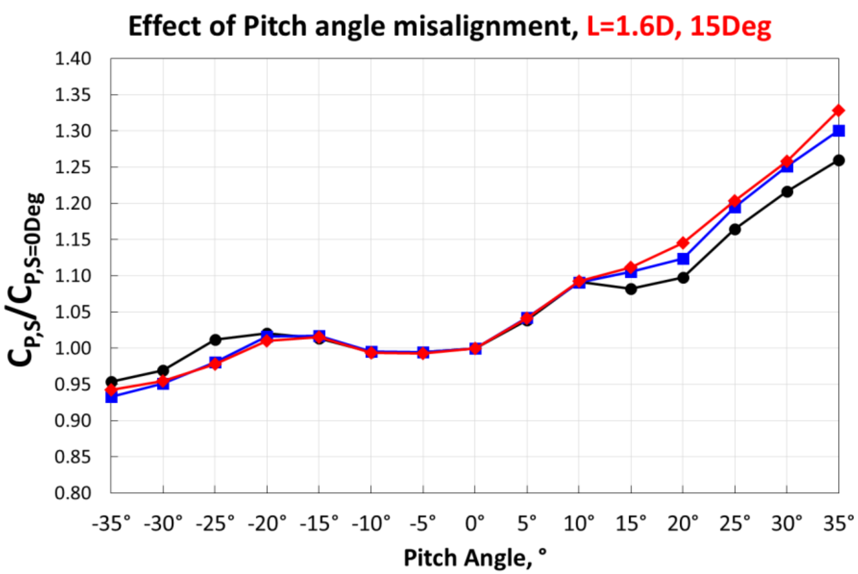
- The normalized S-type Pitot tube coefficients increase as the pitch angle increases

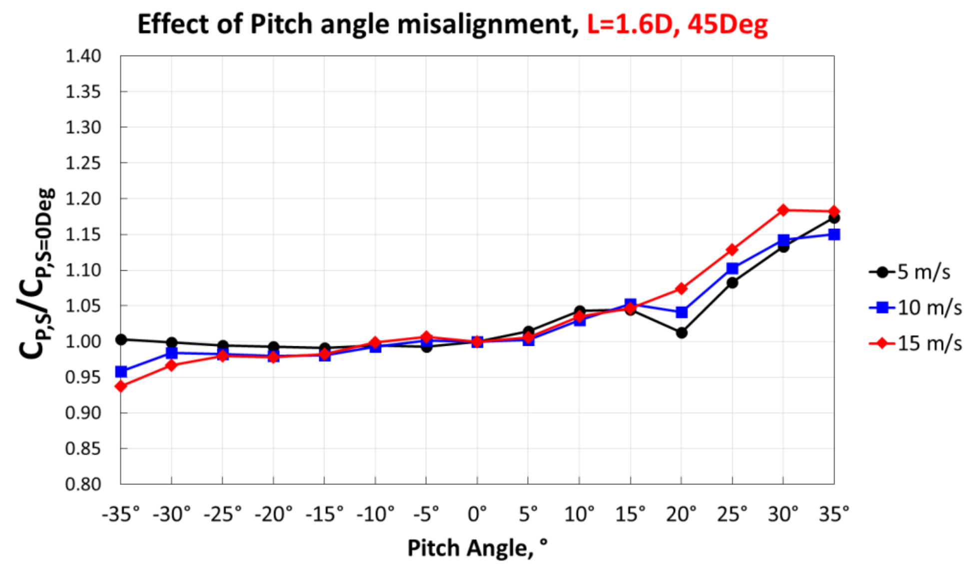


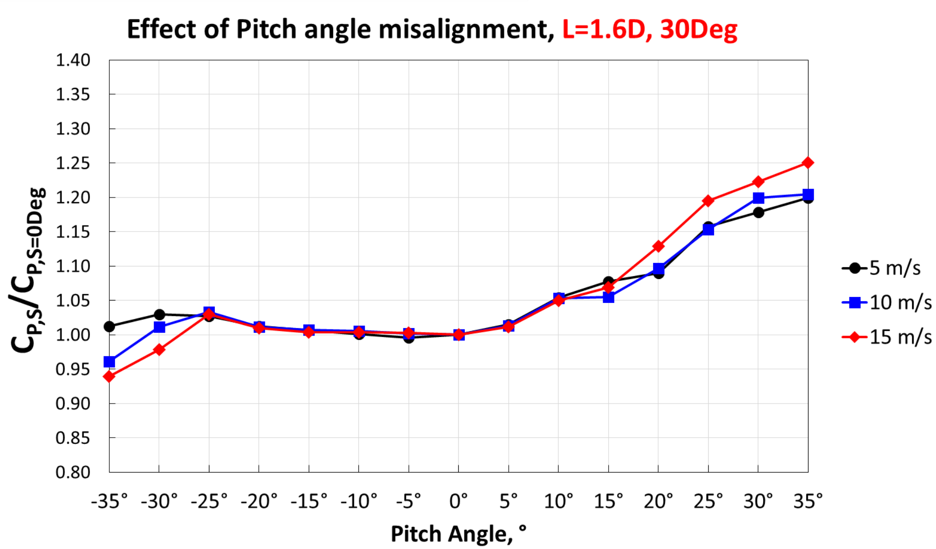


L=1.6D Model (Pitch angle)

- Three models(15, 30 and 45 Deg) show similar pattern to Pitch angle change

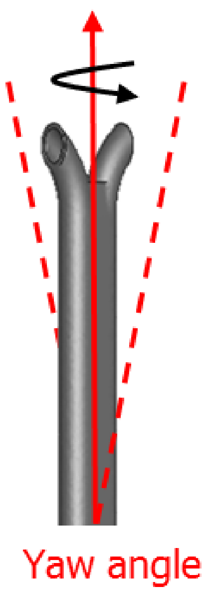


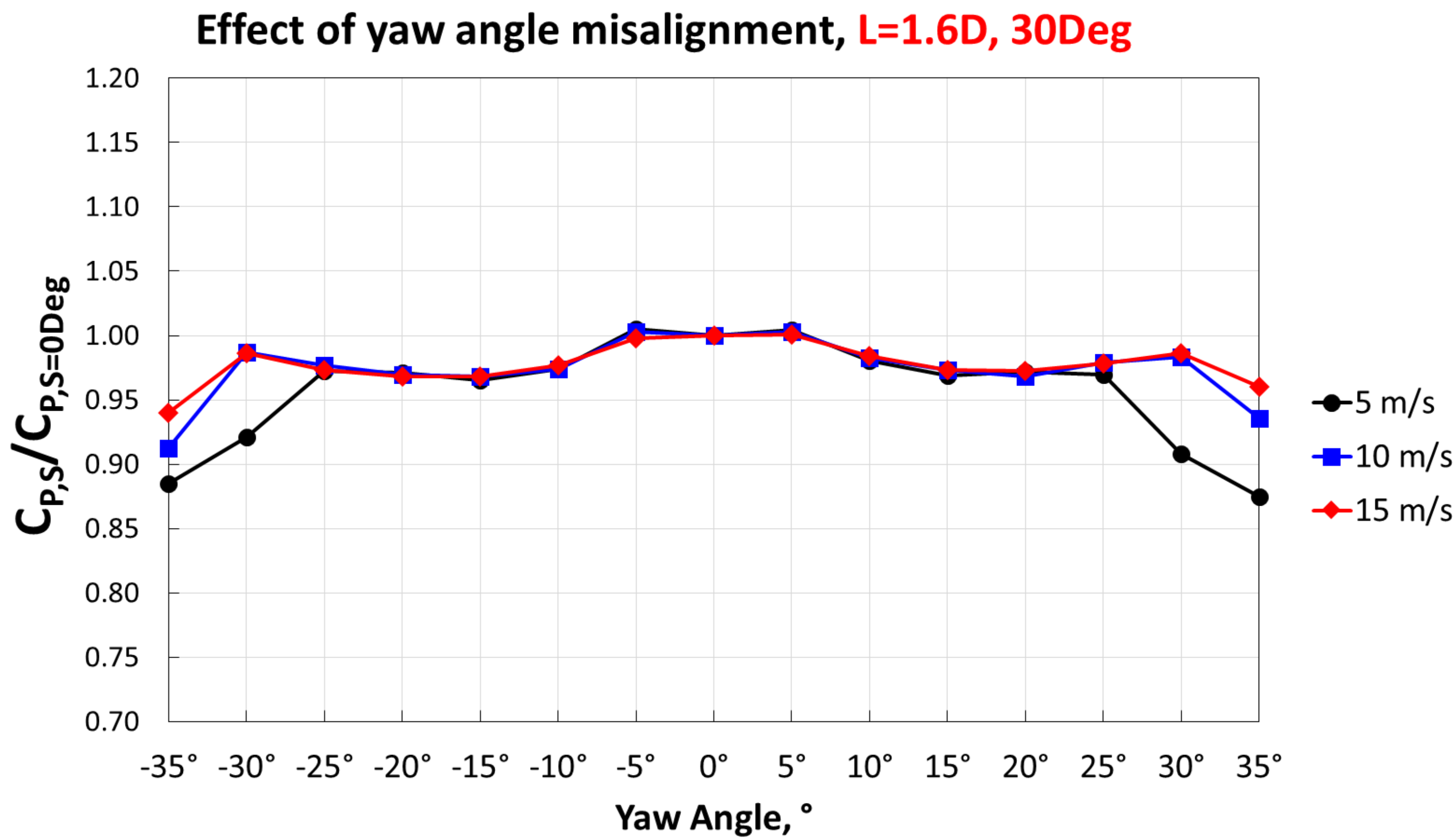




L=1.6D Model (Yaw angle)

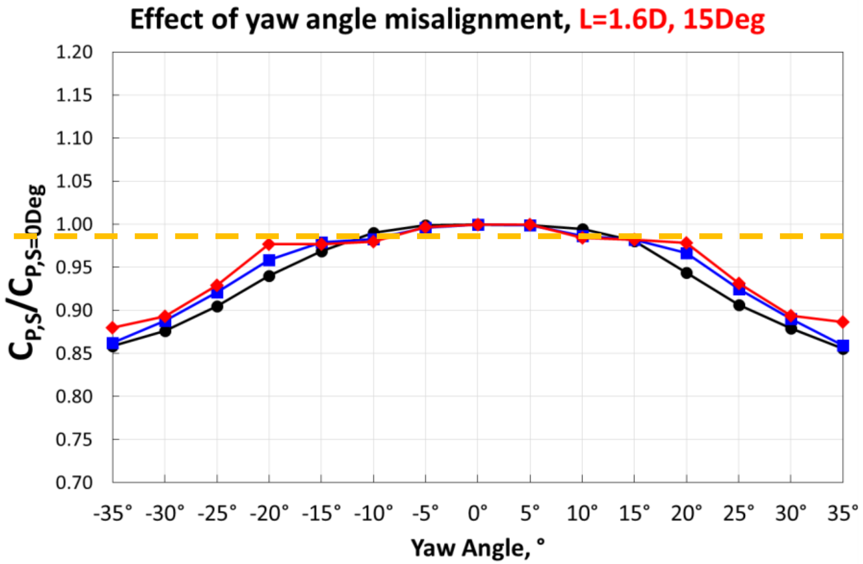
- The normalized S-type Pitot tube coefficients decreased as the yaw angle increases with symmetric tendency

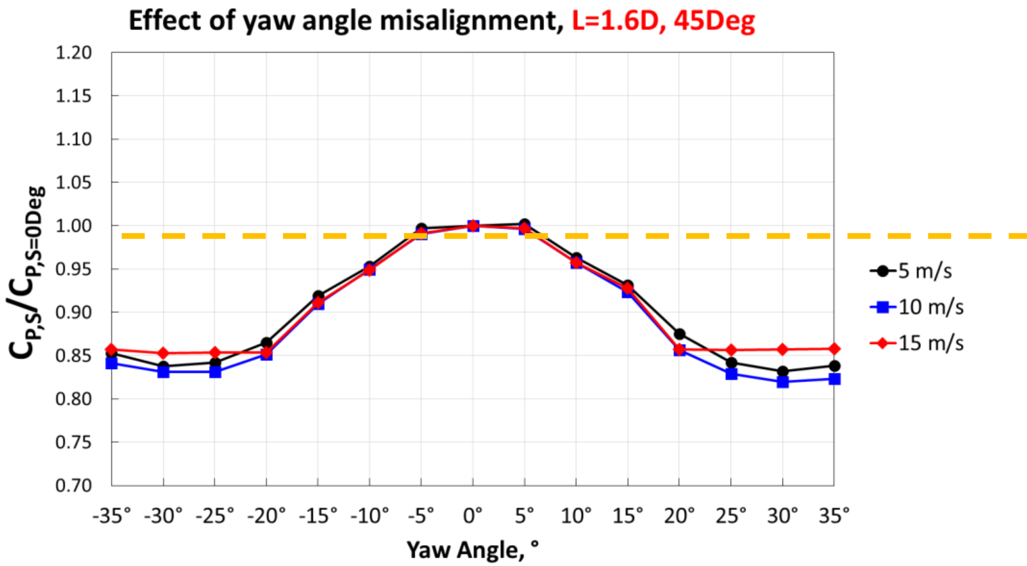


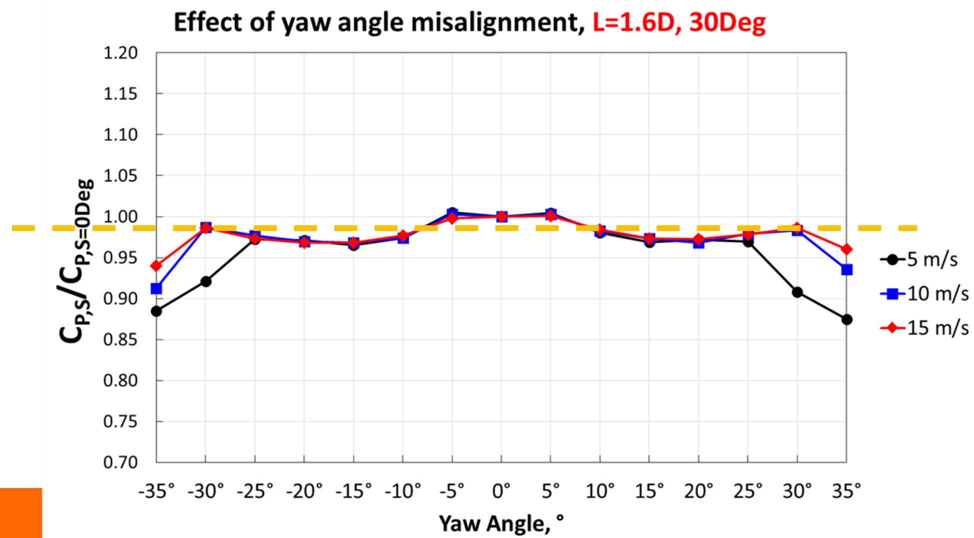


L=1.6D Model (Yaw angle)

- 30 Deg. Model show less sensitive to yaw angle misalignment within wide range of yaw anlges

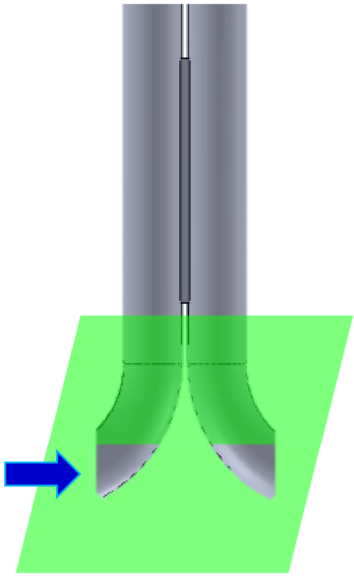


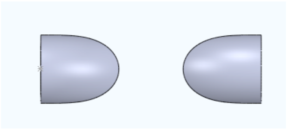


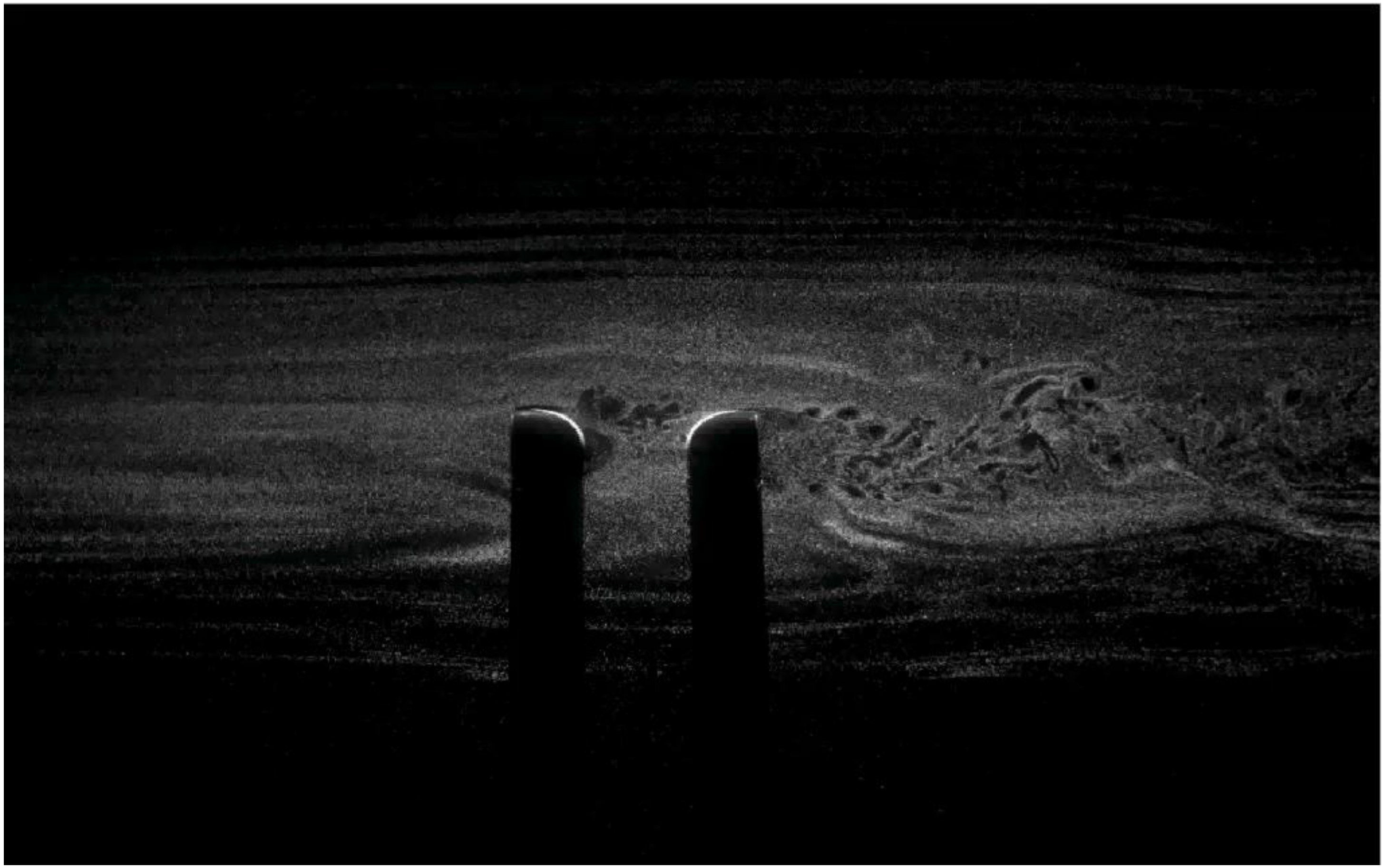


L=1.6D 30 Deg. (Yaw=0°) PIV

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



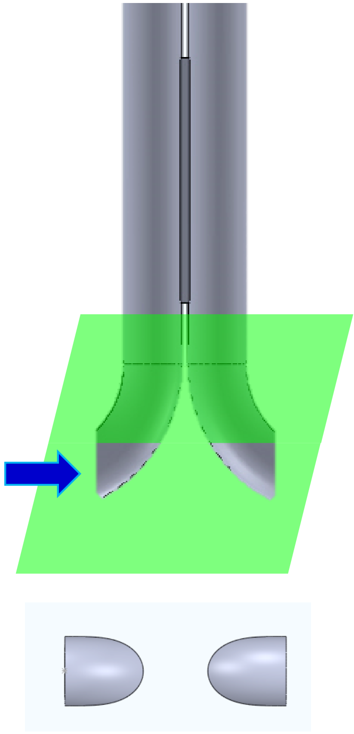


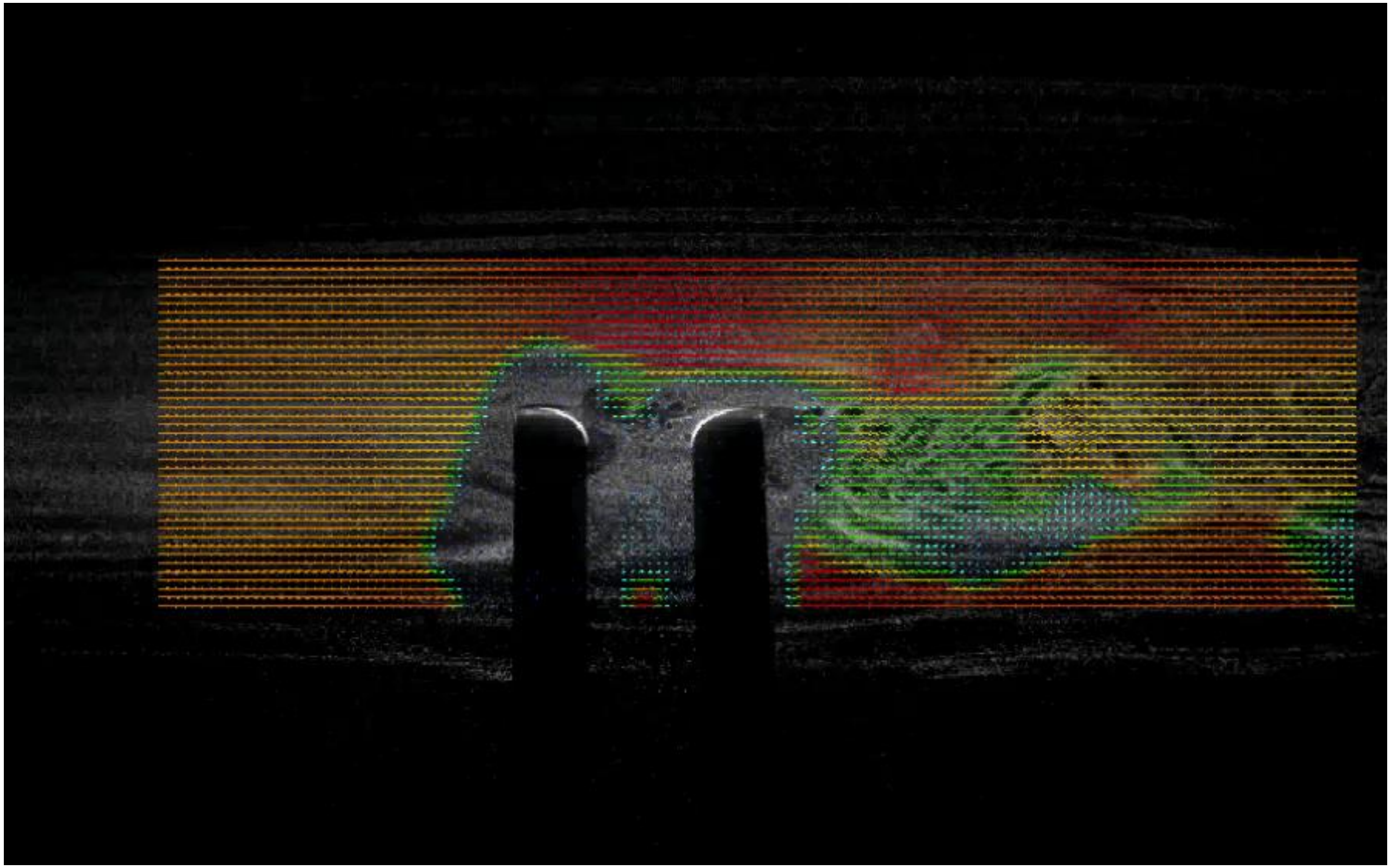


- Each vortical structures from impact and wake orifices are observed

L=1.6D 30 Deg. (Yaw=0°) PIV

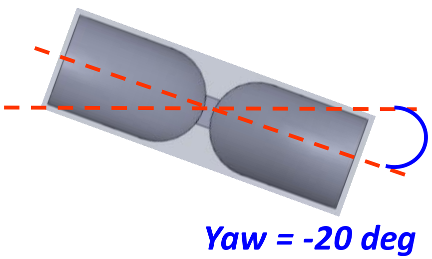
- Velocity vector distribution around S-type Pitot tube

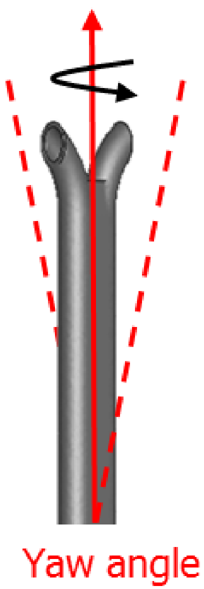


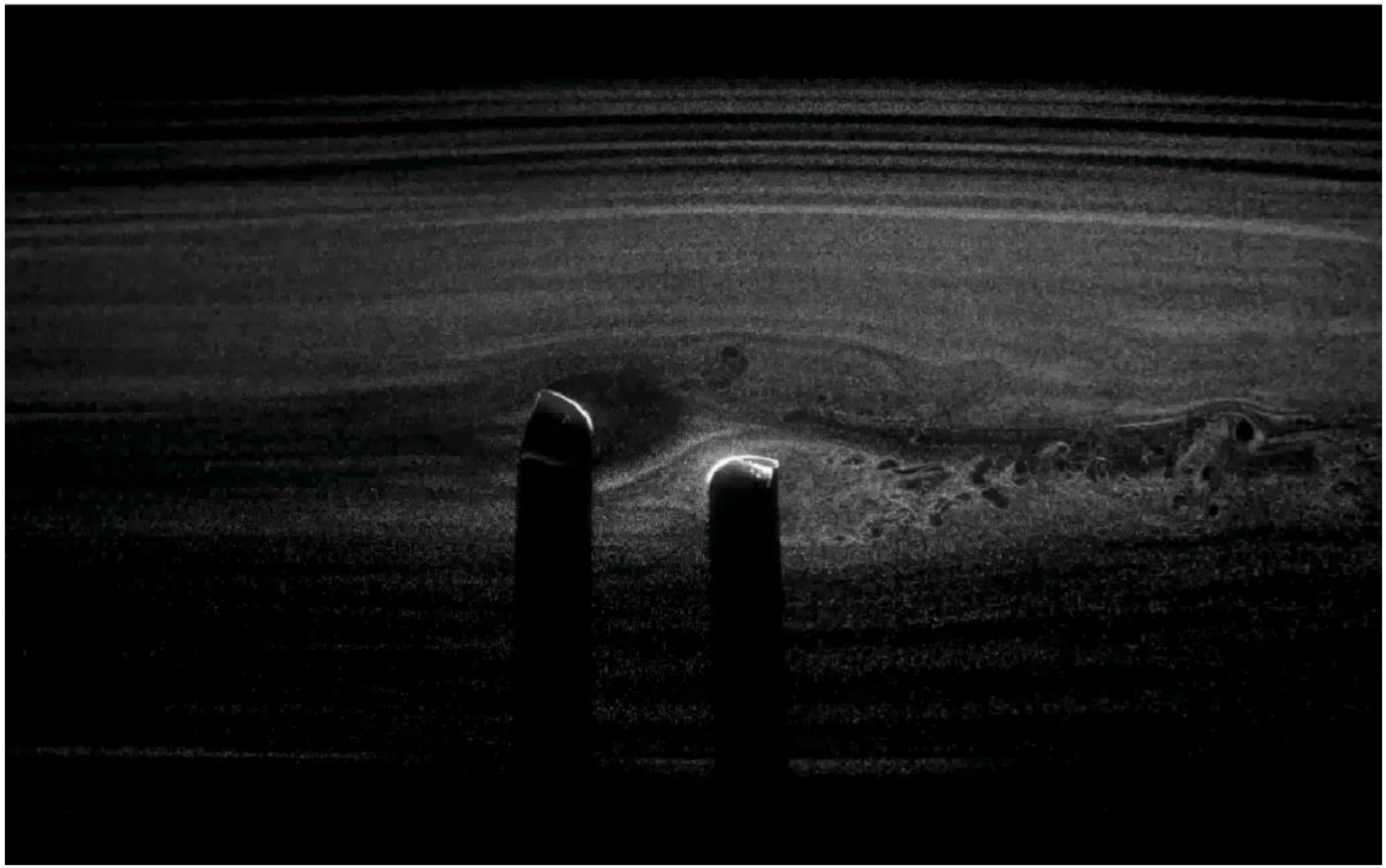


L=1.6D 30 Deg. (Yaw=-20°) PIV

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



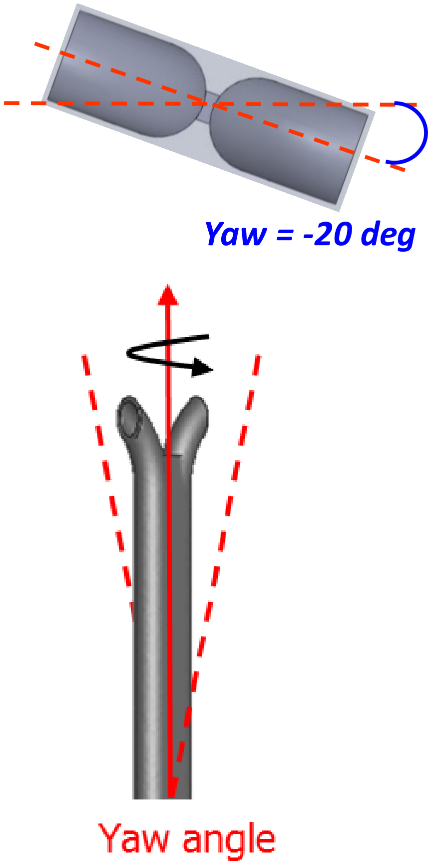


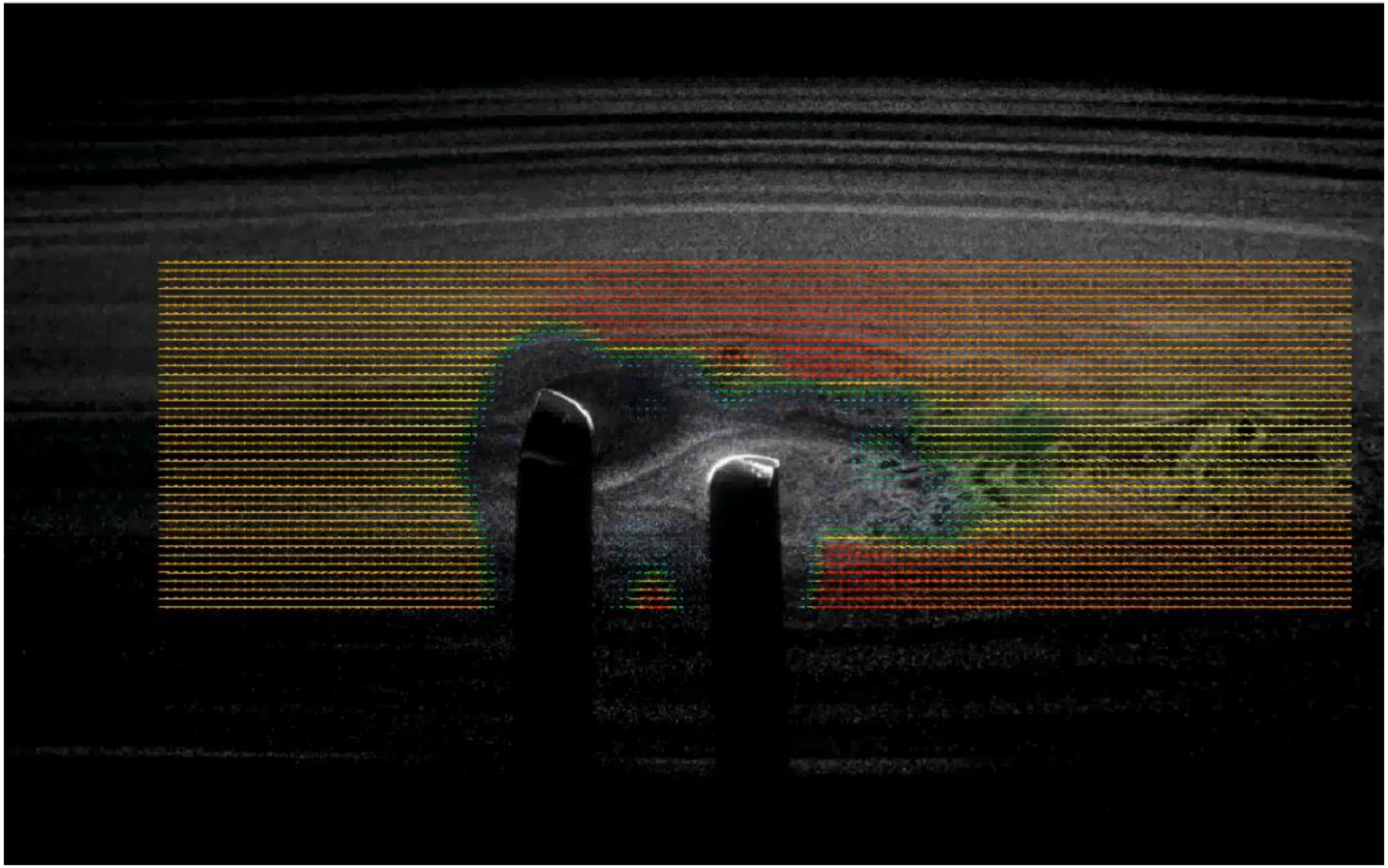


- Due to yaw angle misalignment, separated flows from surface of impact and wake orifice are enhanced

L=1.6D 30 Deg. (Yaw=-20°) PIV

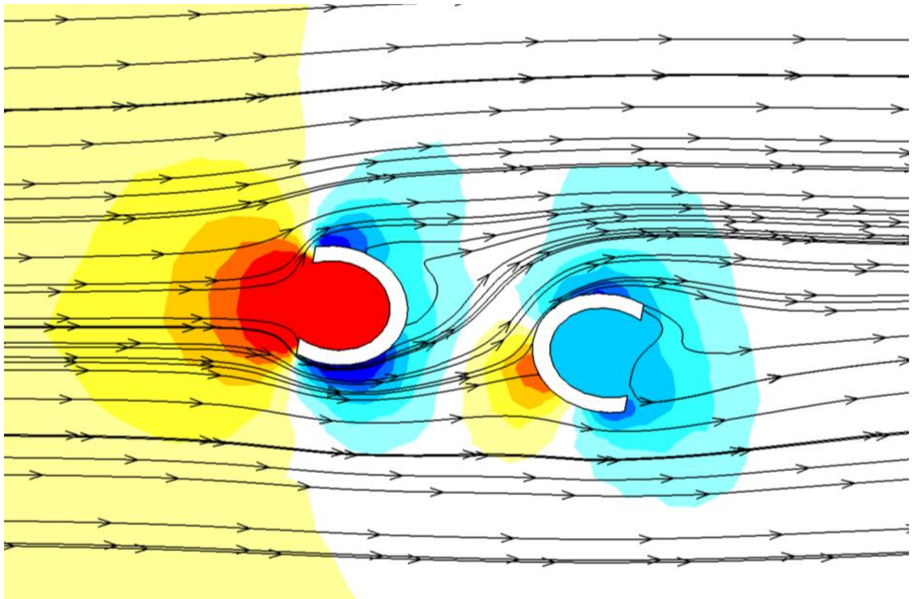
- Velocity vector distribution around S-type Pitot tube

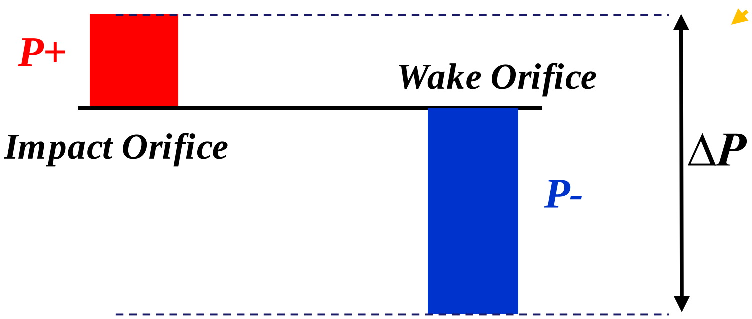


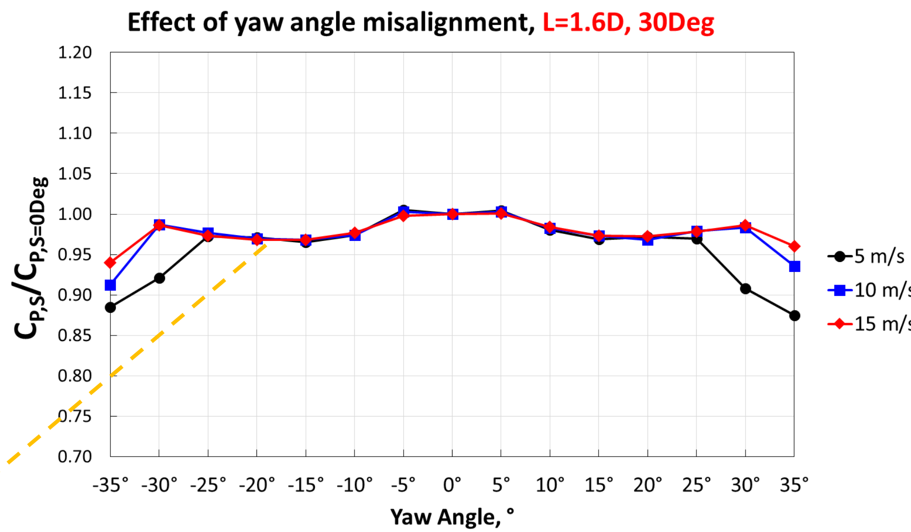


L=1.6D 30 Deg. (Yaw angle) PIV

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





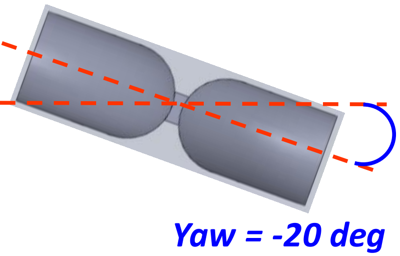


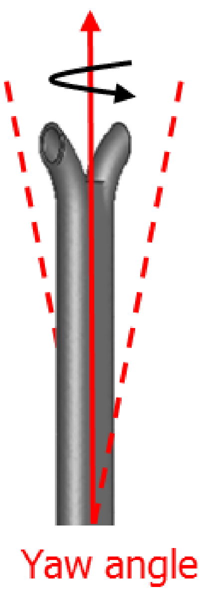
$$C_{P,S} = C_{P,Std}\left(\frac{\Delta P_{Std}}{\Delta P_{S\cdot type}}\right)$$

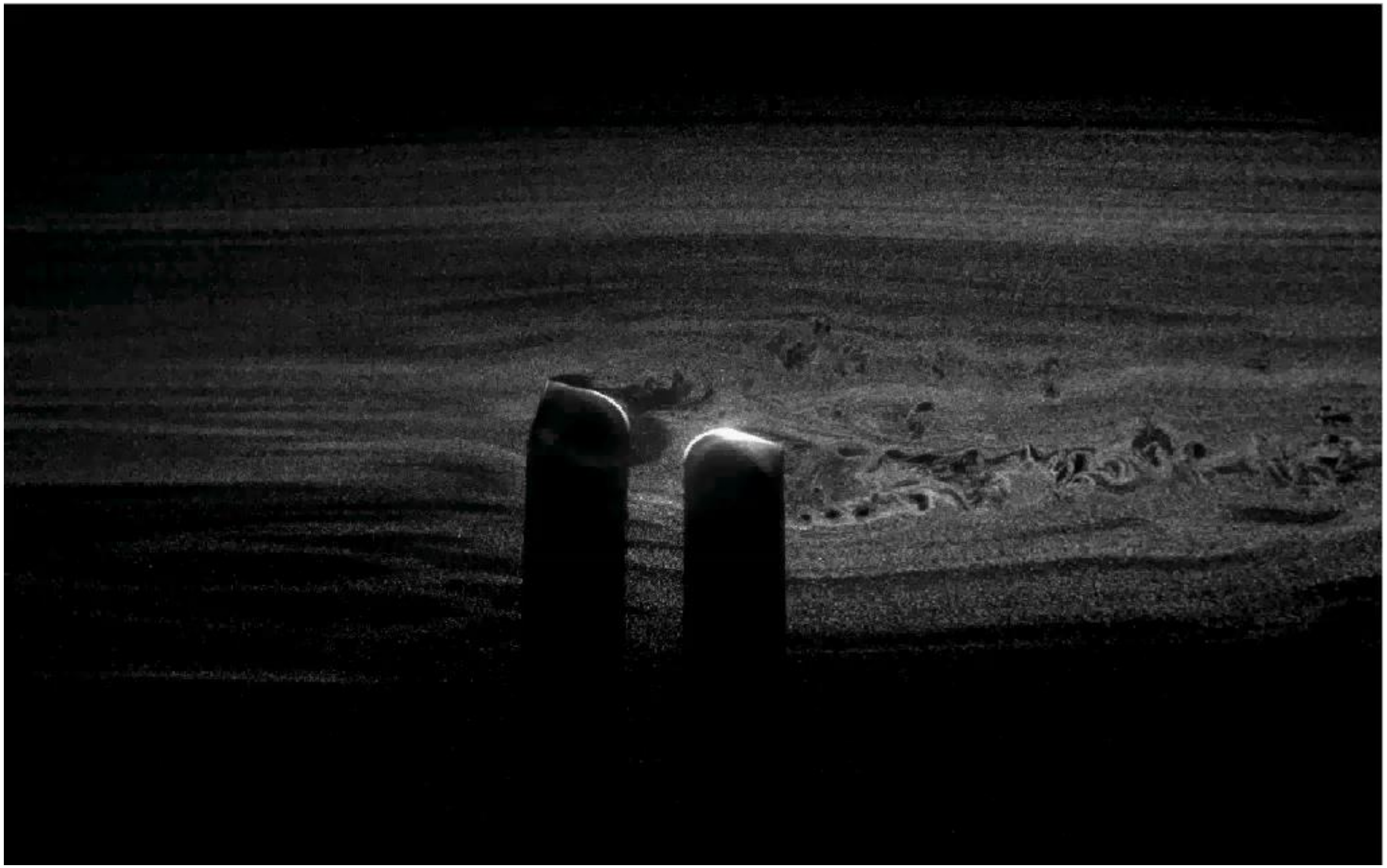
Numerical simulation
FMI, Kang et al. 2015

L=1.6D 45 Deg. (Yaw=-20°) PIV

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



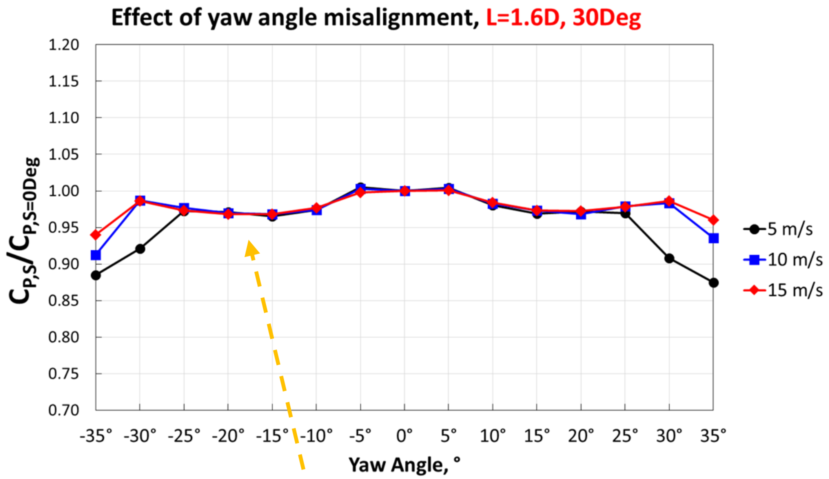


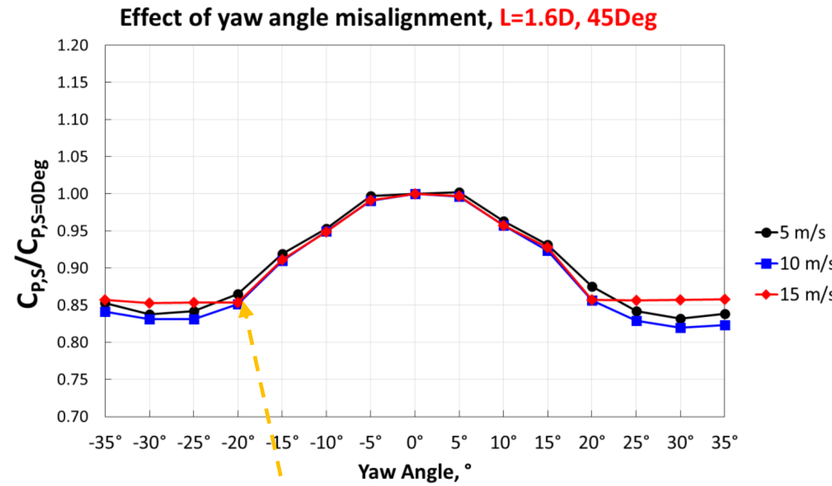


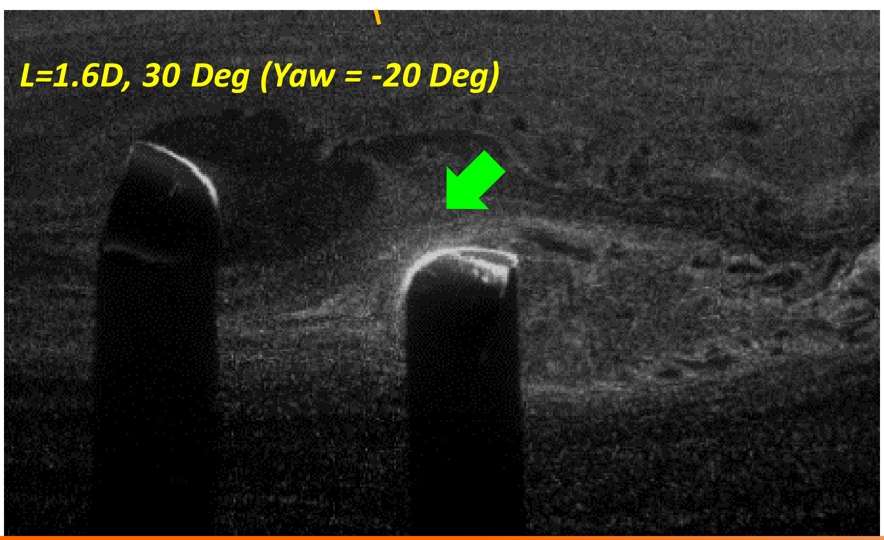
- Separated flow from impact orifice(upstream) interfere with vortical structures of wake orifices(downstream) due to the proximity of two orifices

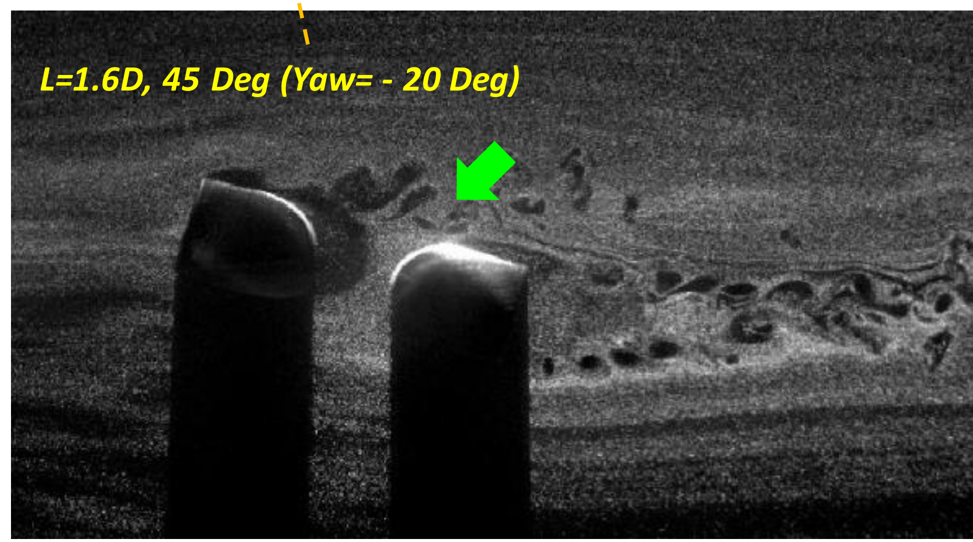
L=1.6D 30 Deg vs 45 Deg (Yaw angle)

- When vortical structure behind the wake orifice were interfered with upstream separated flow, lower pressure near wake orifice
  → Cp,s decereased (45 deg)









Experiments for the effect of S pitot geometry II

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

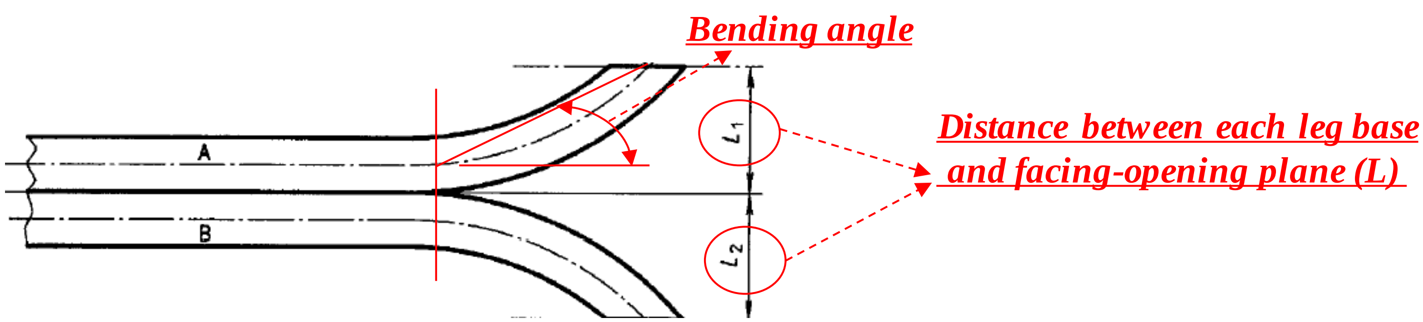
   → **L = 1.05D**, **1.6D, 3D**

2. Bending Angle of opening parts

   → **α = 15°, 30°, 45°**

3. Shape of opening parts

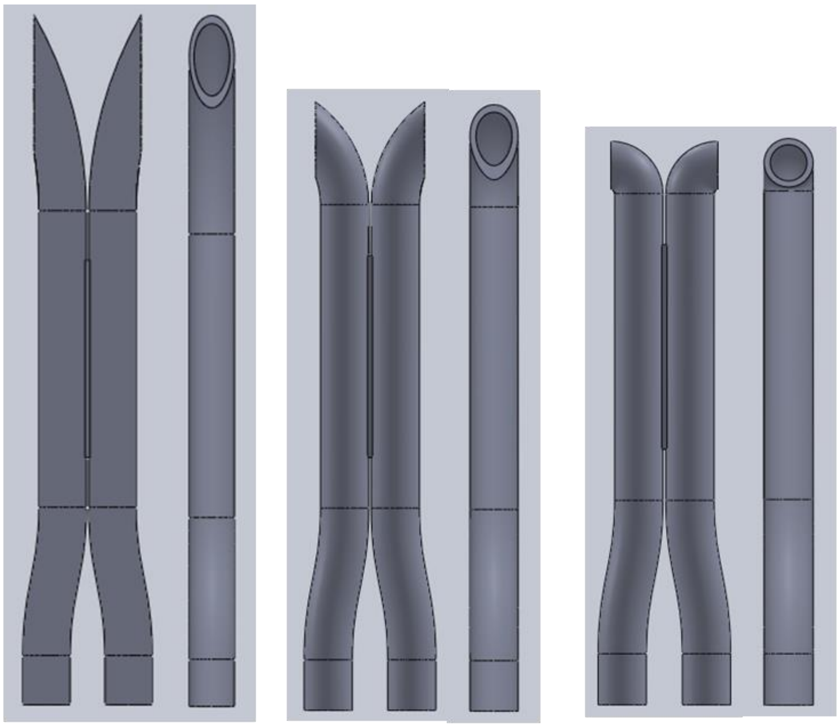
   → **Curved**, **Straight**



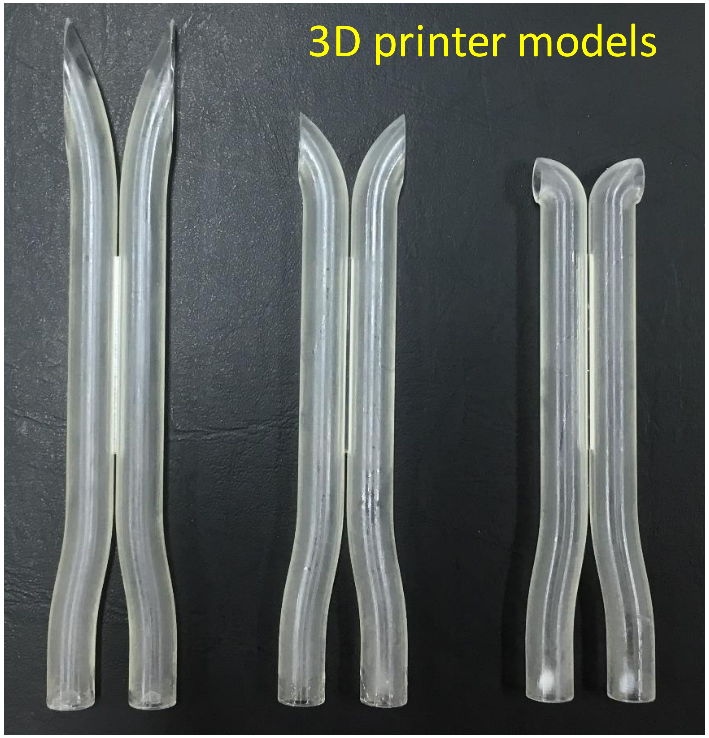
KRISS

L=1.05D Models

- Compare L=1.05D models (α = 15 Deg., 30 Deg. and 45 Deg.)

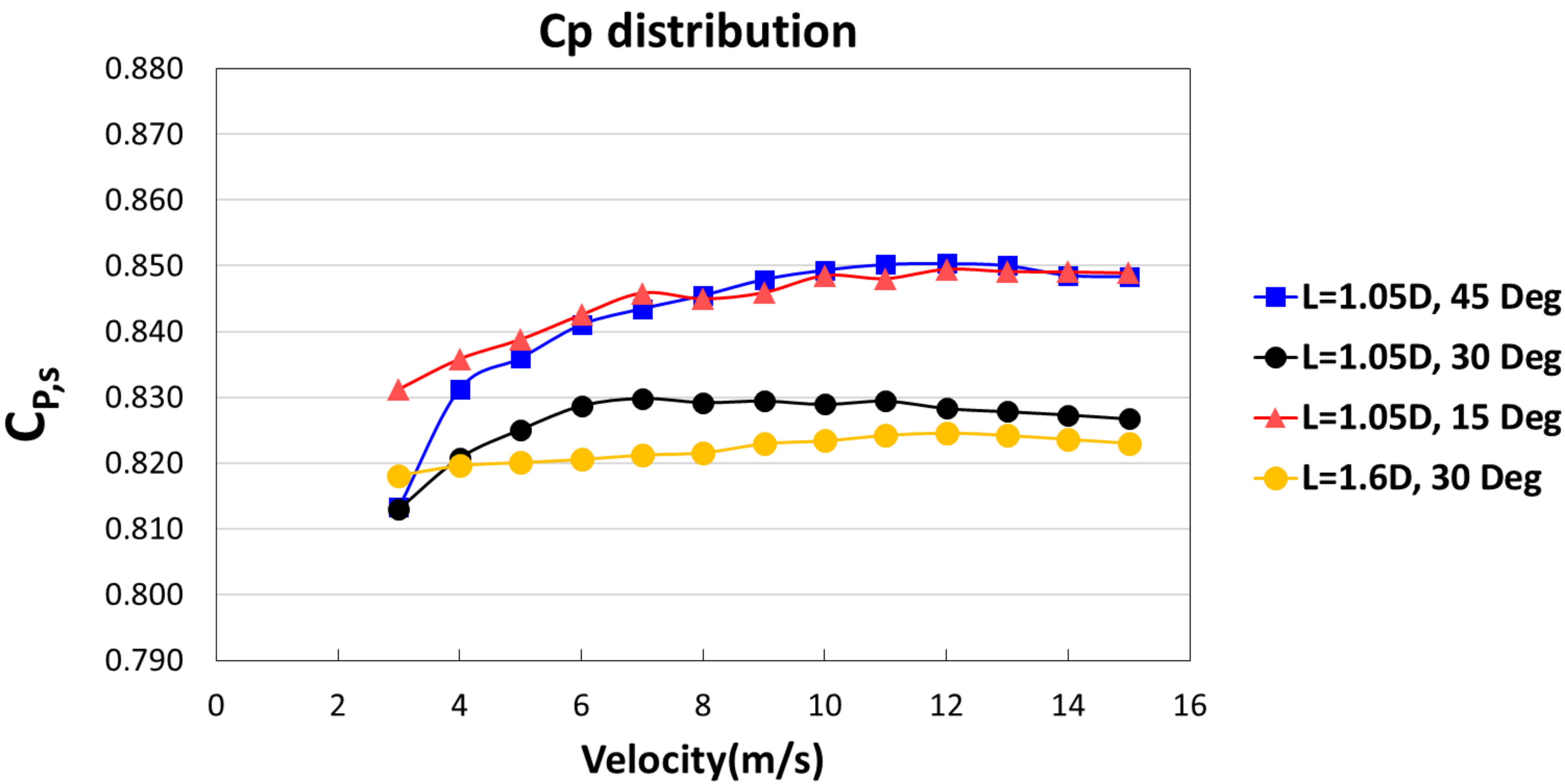


α = 15°, L = 1.05D α = 30°, L = 1.05D α = 45°, L = 1.05D



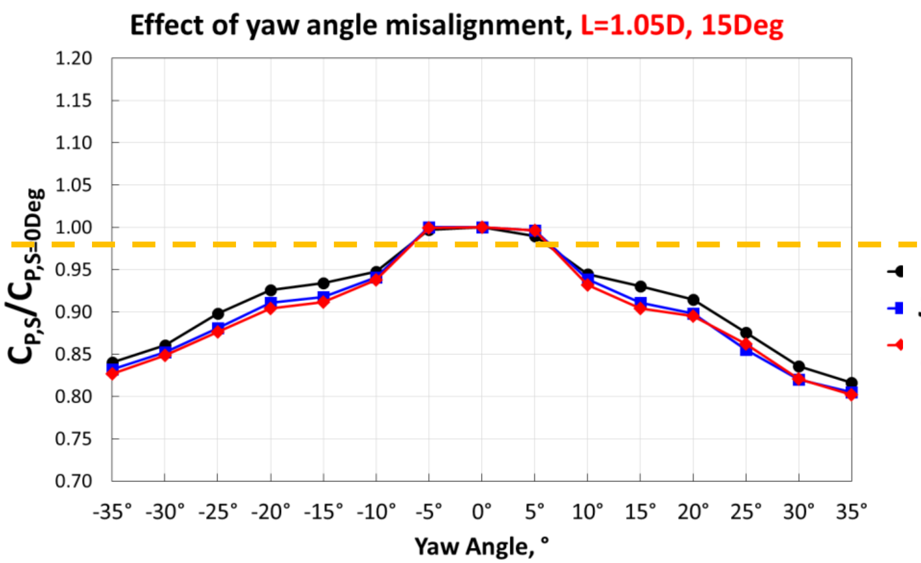
L=1.05D Models(Cp distribution)

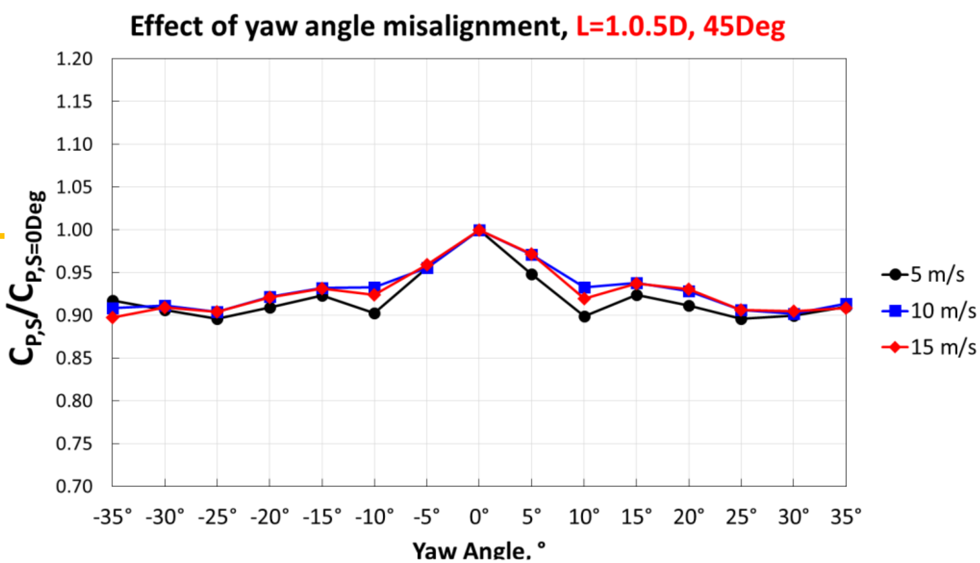
- Three models of L=1.05 S Pitot Cp is increasing as incoming velocity increases

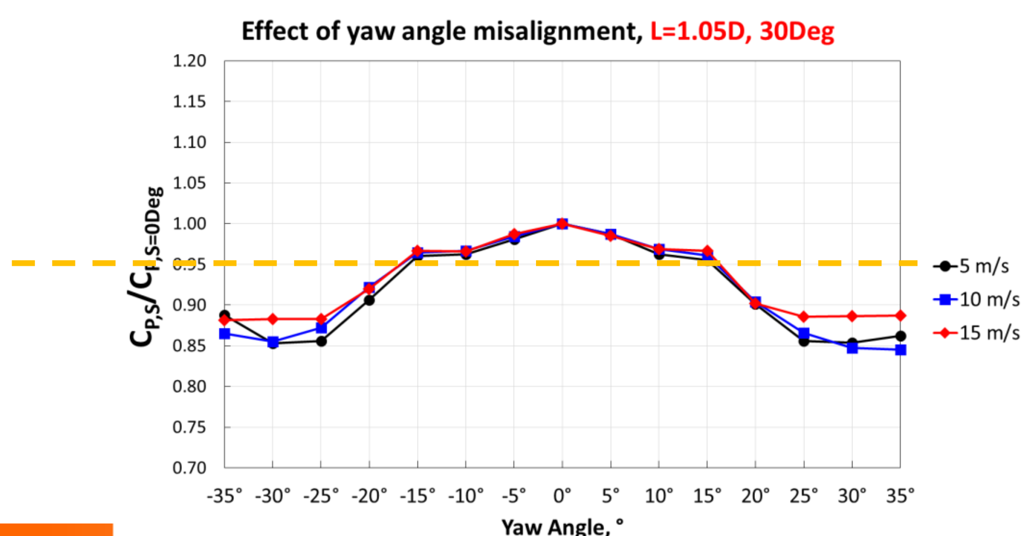


L=1.05D Model (Yaw angle)

- All three models are sensitive to yaw angle misalignments







Experiments for the effect of S pitot geometry III

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

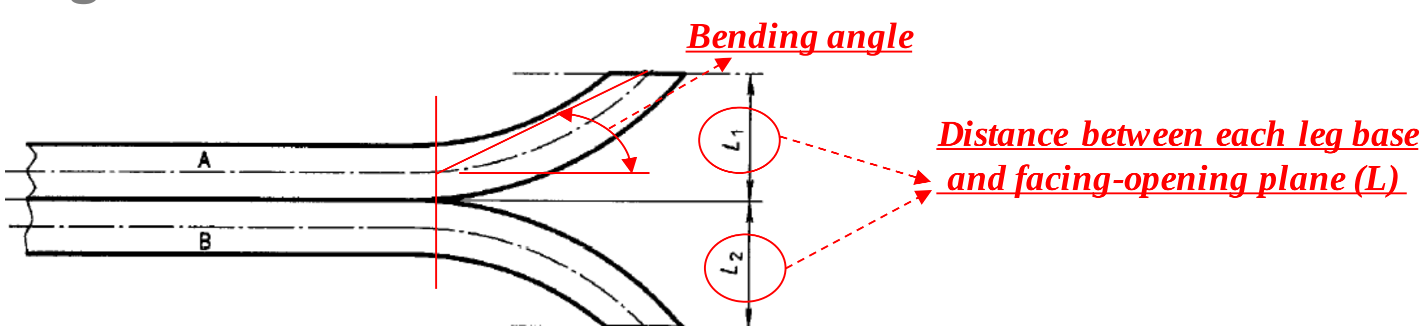
→ **L** = **1.05D, 1.6D, 3D**

2. Bending Angle of opening parts

→ **α = 15°, 30°, 45°**

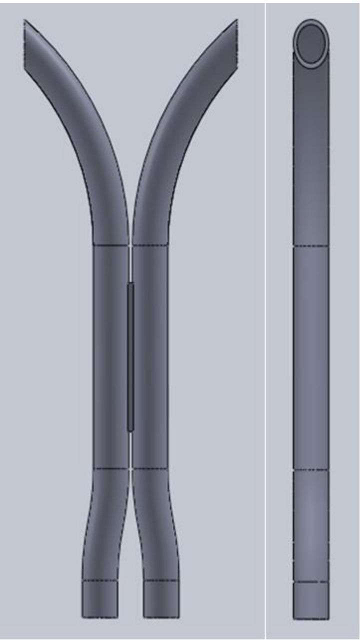
3. Shape of opening parts

→ **Curved**, **Straight**

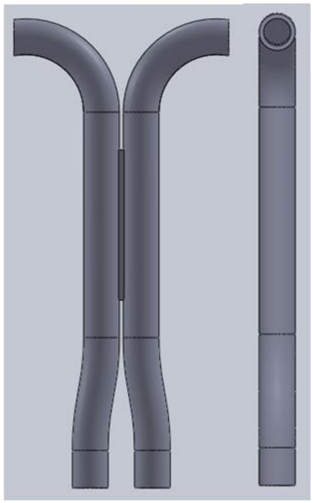


L=3D Models

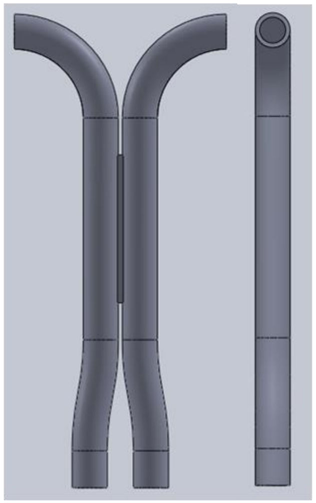
- Compare L=3D models (α = 15 Deg., 30 Deg. and 45 Deg.)



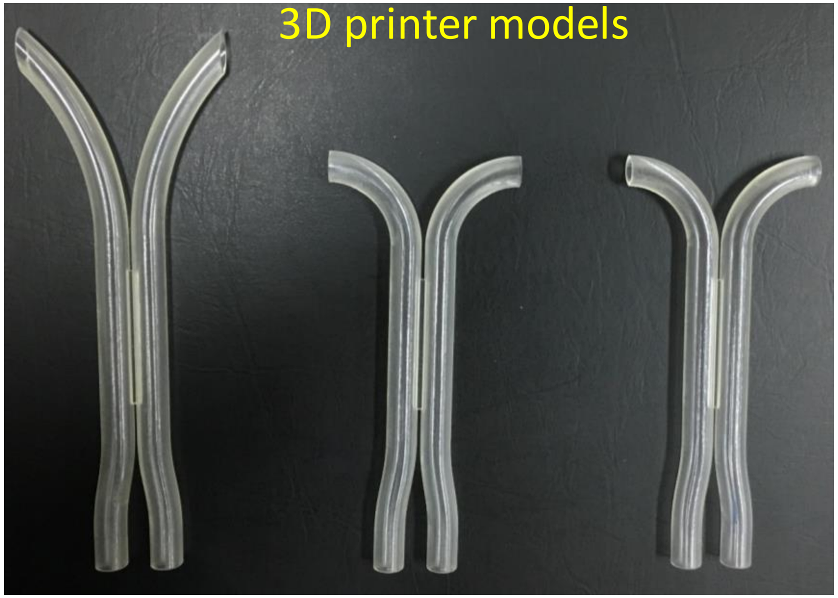
α = 15°, L = 3D



α = 30°, L = 3D

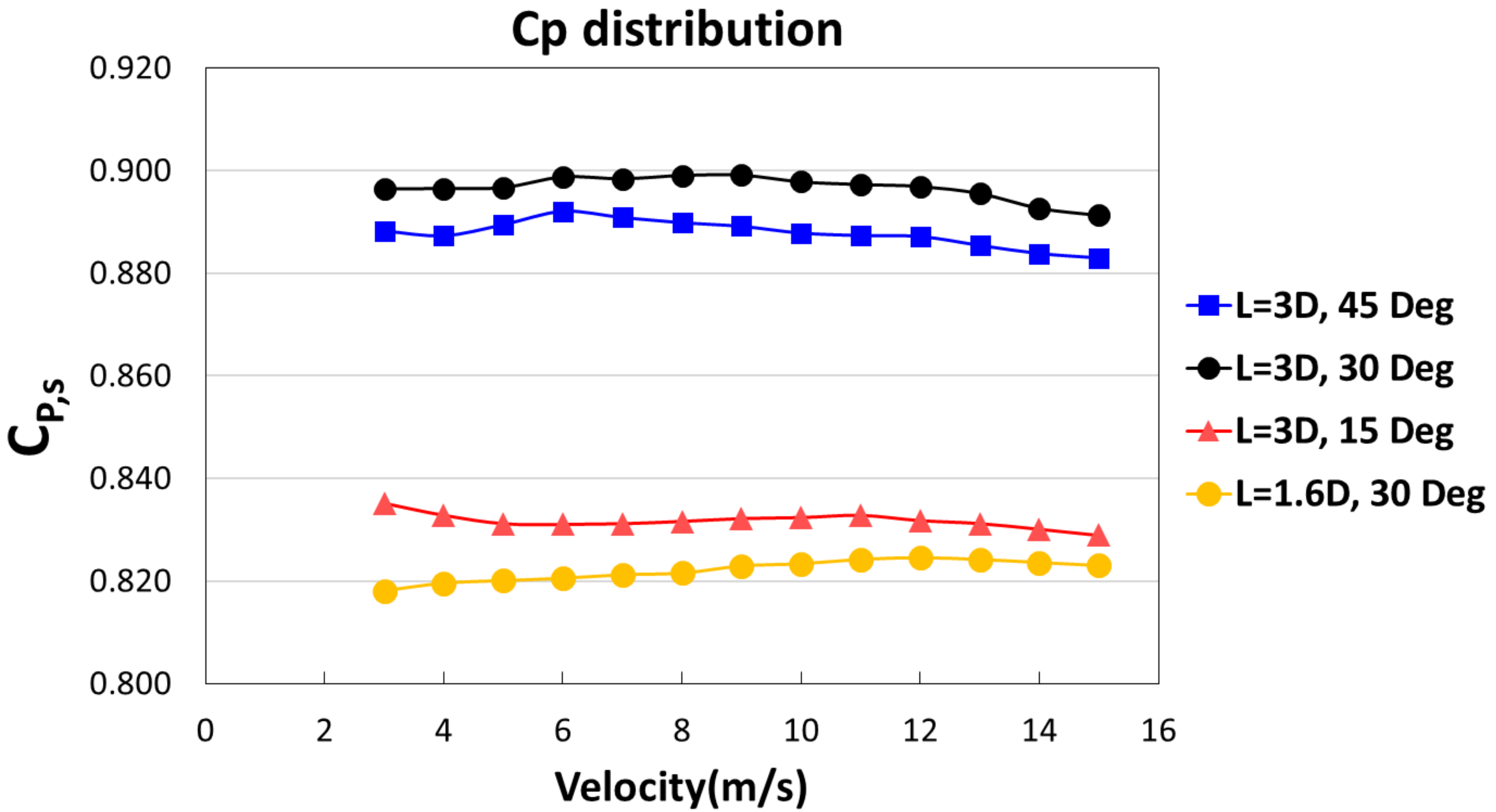


α = 45°, L = 3D



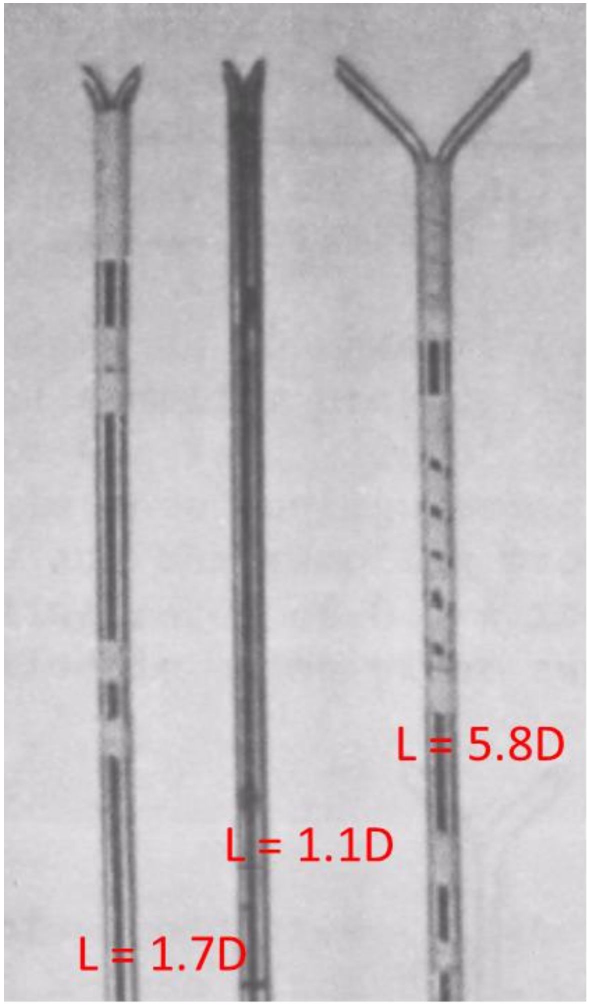
L=3D Models(Cp distribution)

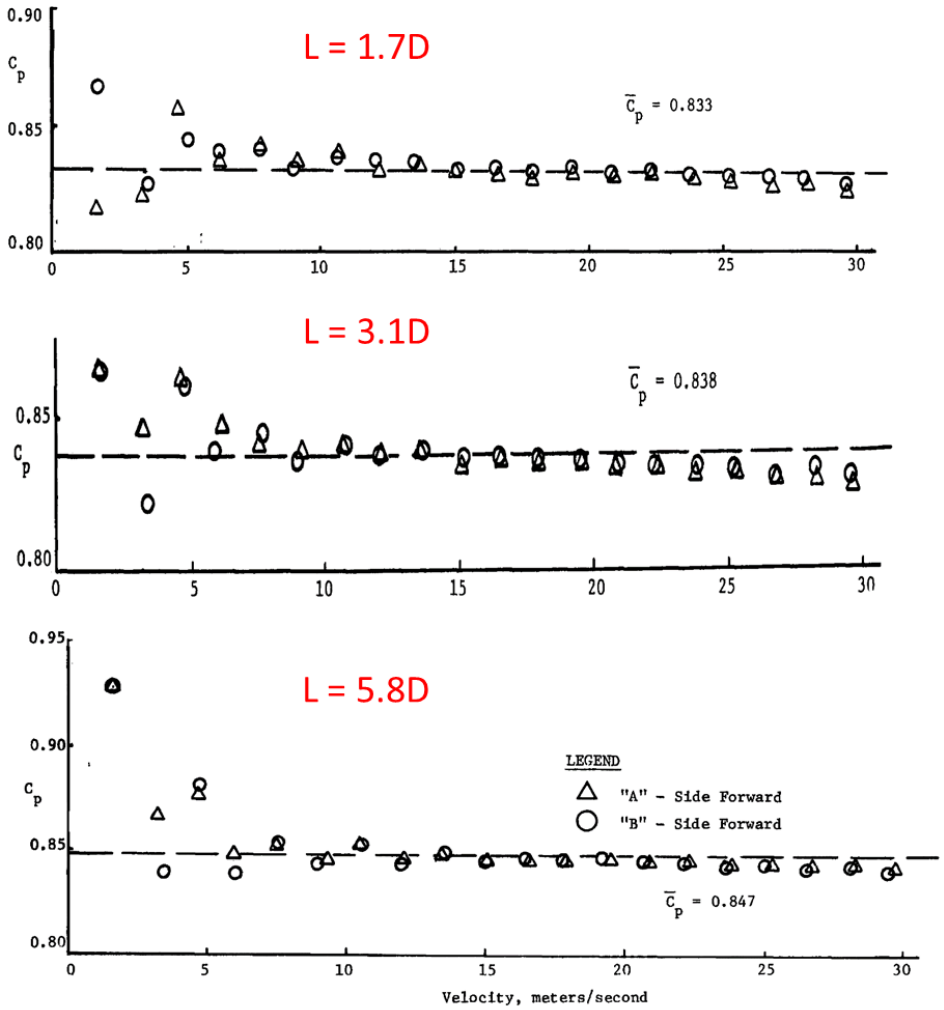
- The α=15 and 45°(L=3D) S Pitot has large Cp compared to short L models
- Cp values were almost constant with velocity change



Previous research

- S Type Pitot Tubes, (William, EPA-600, 1977)

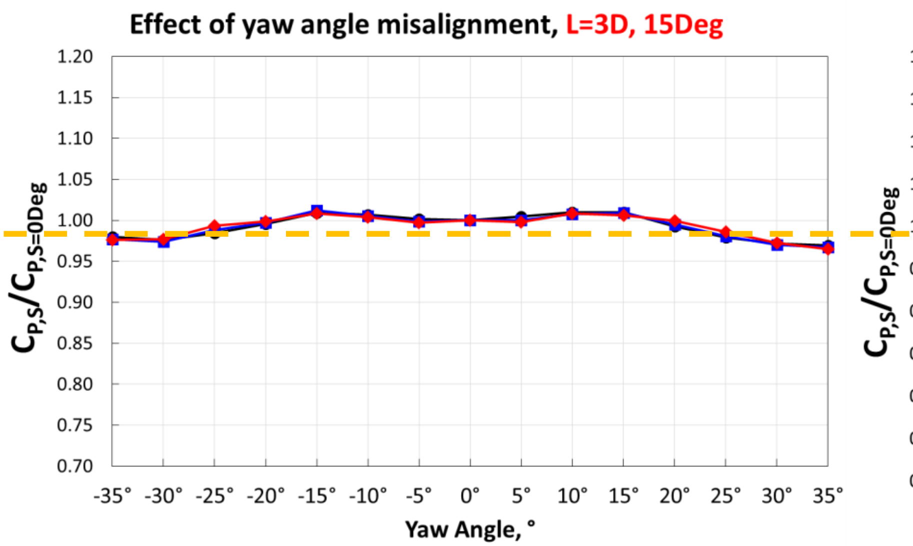


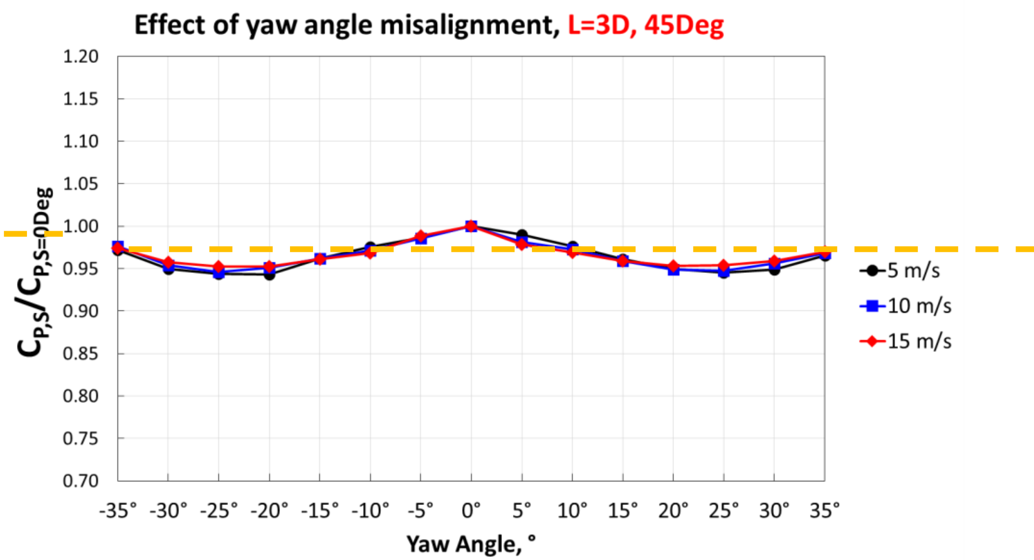


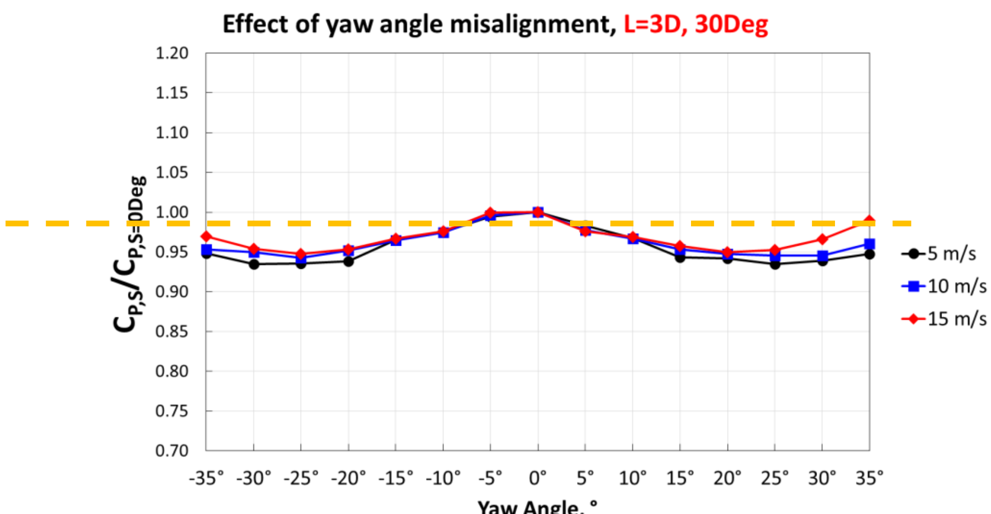
- Cp value increase as Length of S Pitot increase (consistent with present exp

L=3D Model (Yaw angle)

- Three models show non-sensitive to yaw angle misalignment

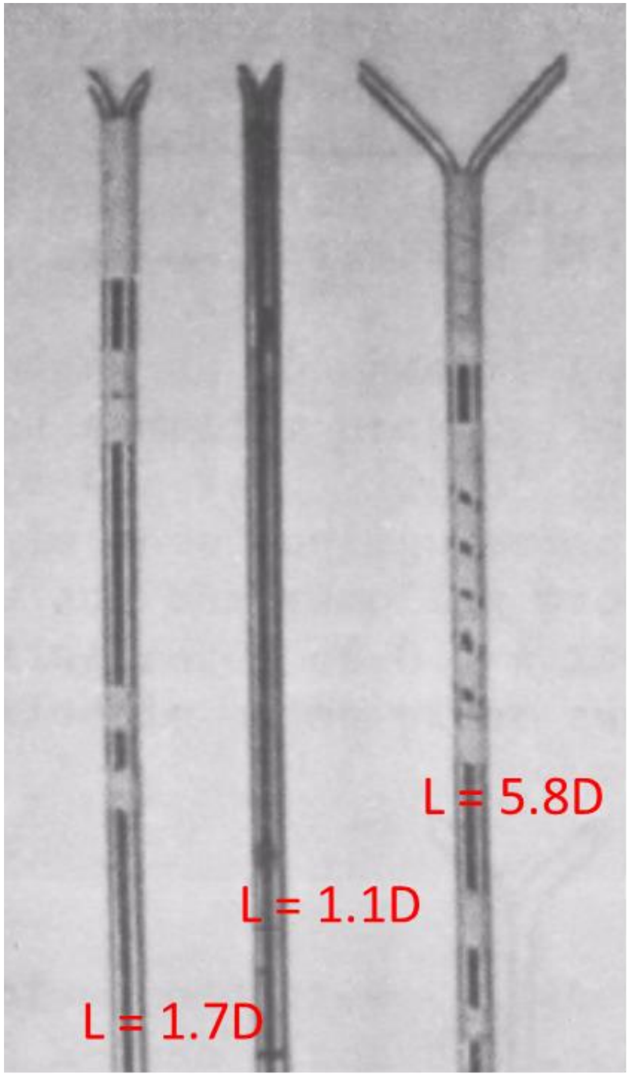


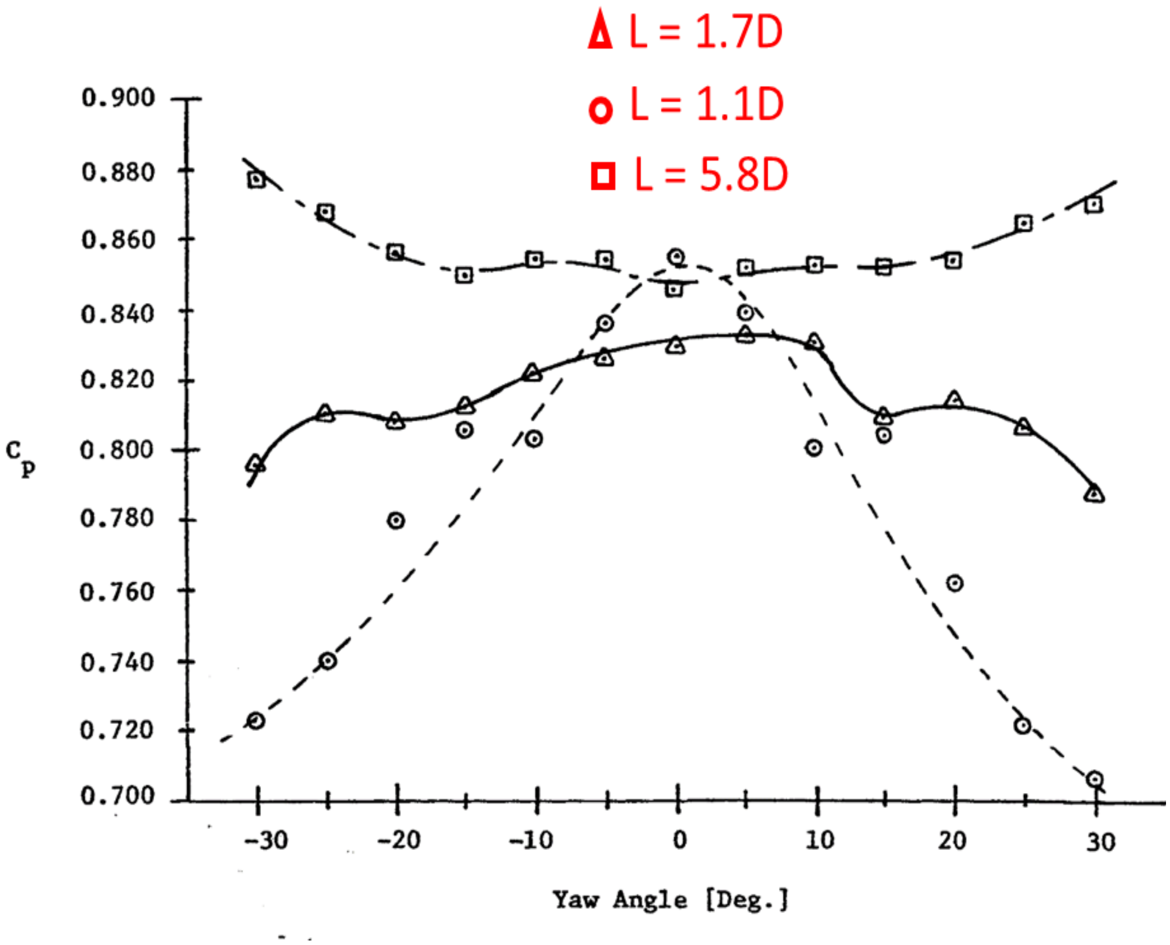




Previous research

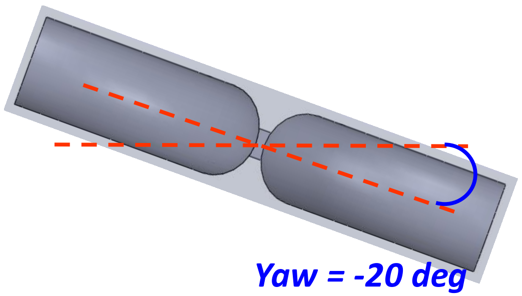
- S Type Pitot Tubes, (William, EPA-600, 1977)

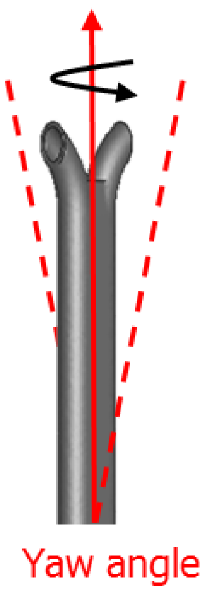


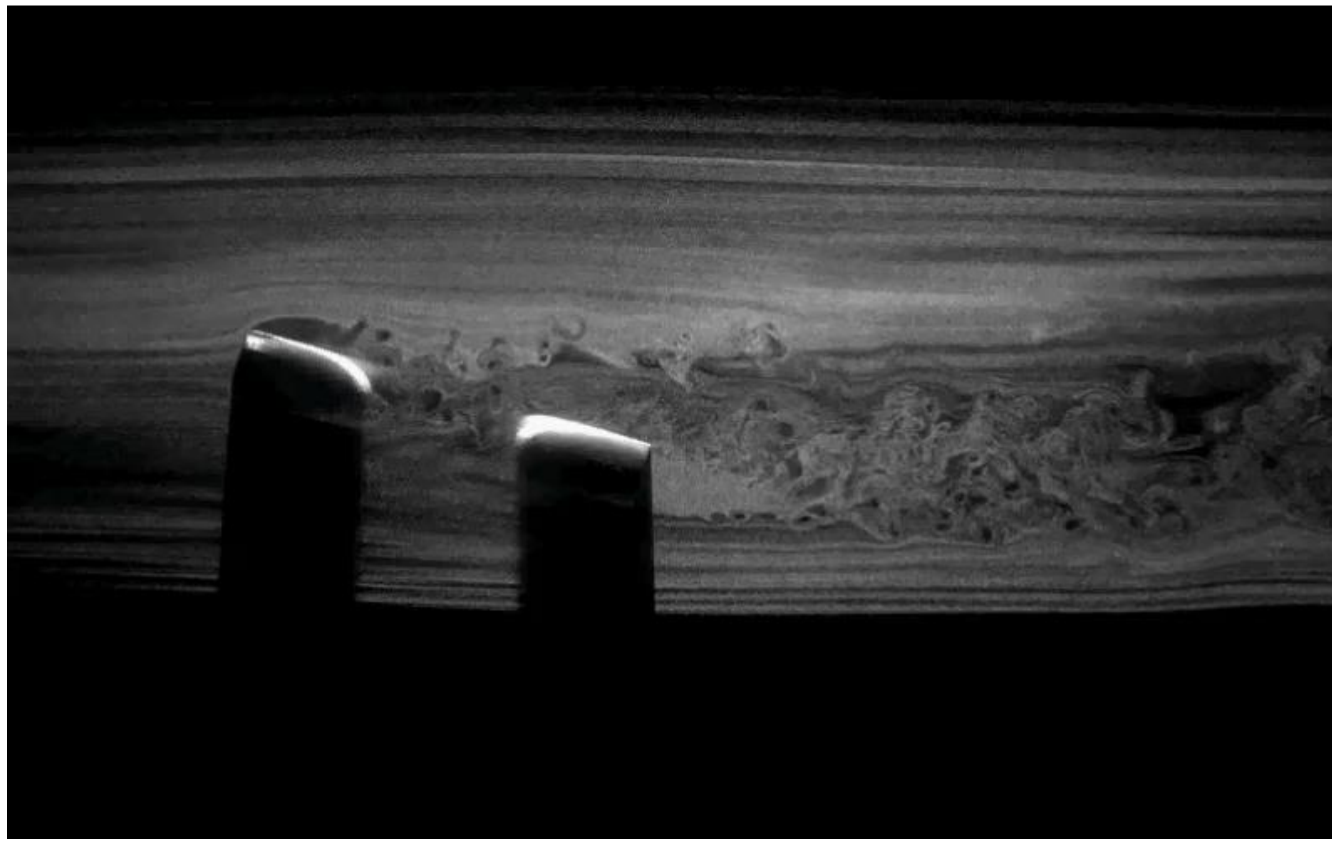


L=3D, 30 Deg. (Yaw=-20°) PIV

- Flow phenomenon around S-type Pitot tube (L=3D, 30 Deg.)







- Due to the distance between two orifice, there is less interference for vortical structures of wake orifices

Practical issue for long L model

- The hole size in the stack for installing S-type Pitot tube

Experiments for the effect of S pitot geometry IV

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

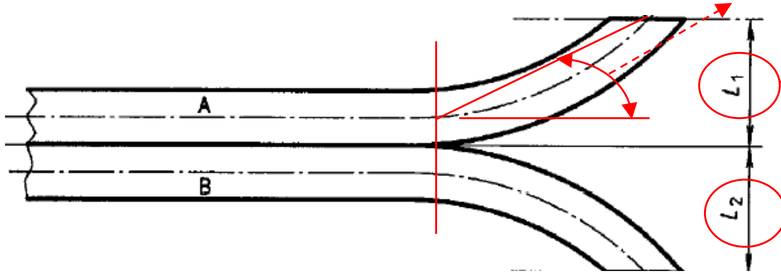
→ **L = 1.05D, 1.6D, 3D**

2. Bending Angle of opening parts

→ **α = 15°, 30°, 45°**

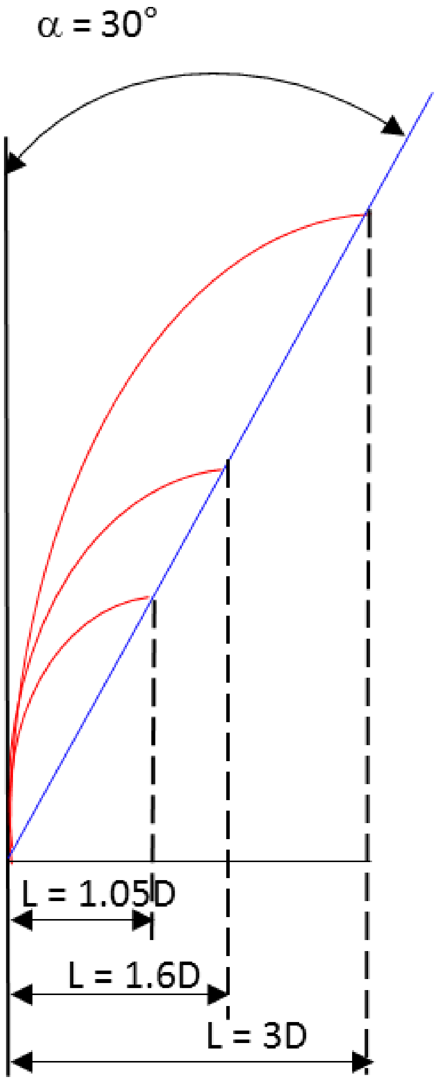
3. Shape of opening parts

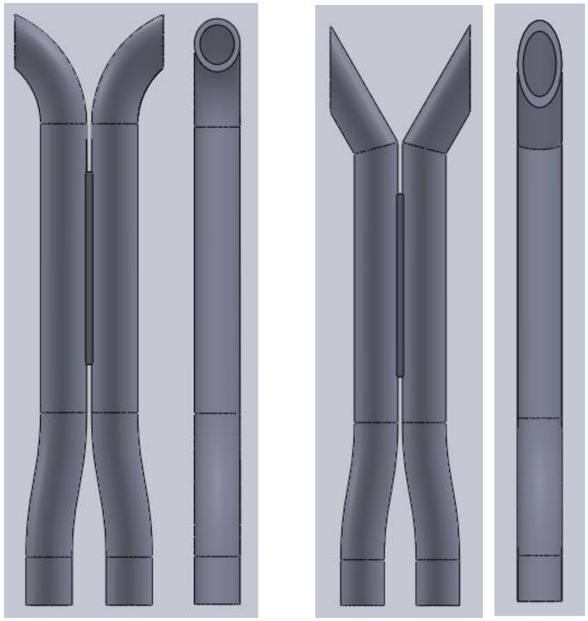
→ **Curved, Straight**



Shape of opening part

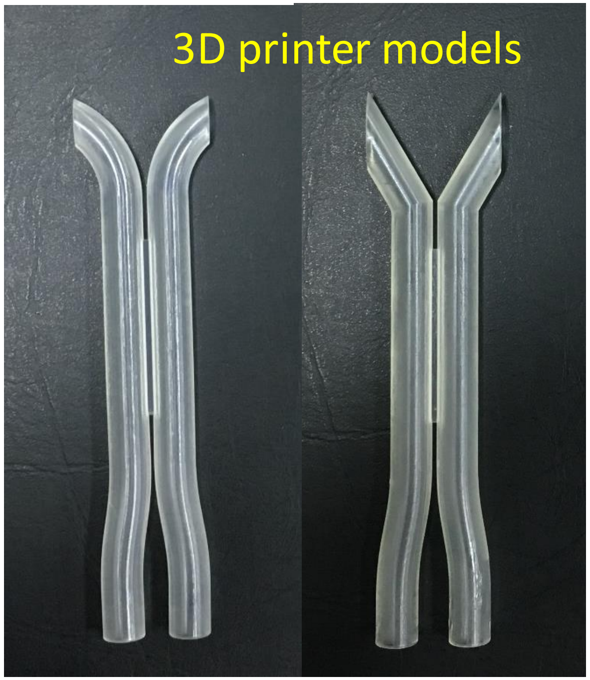
- Curved and Straight models (L=1.6D, 30 Deg)





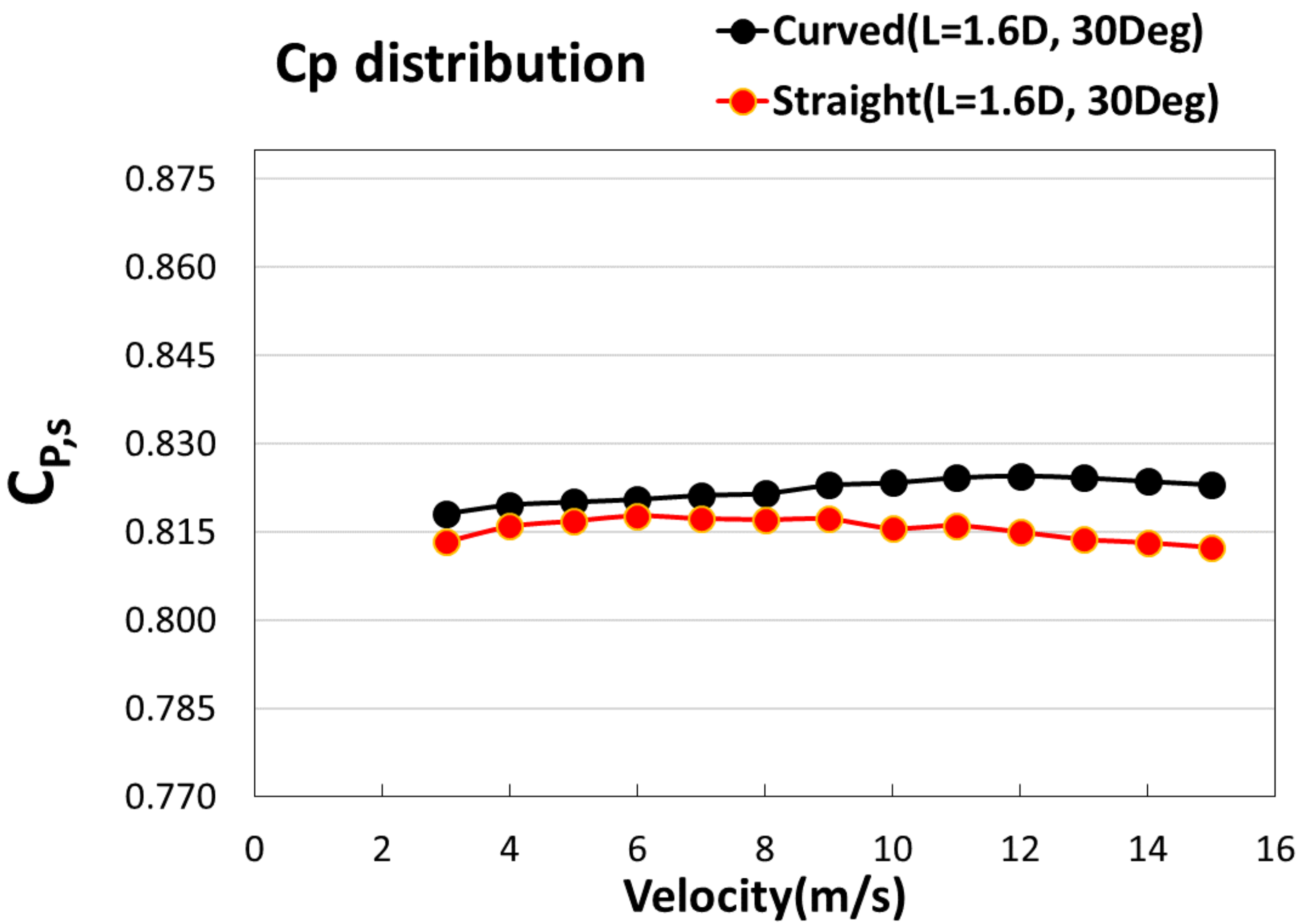
Curved

Straight



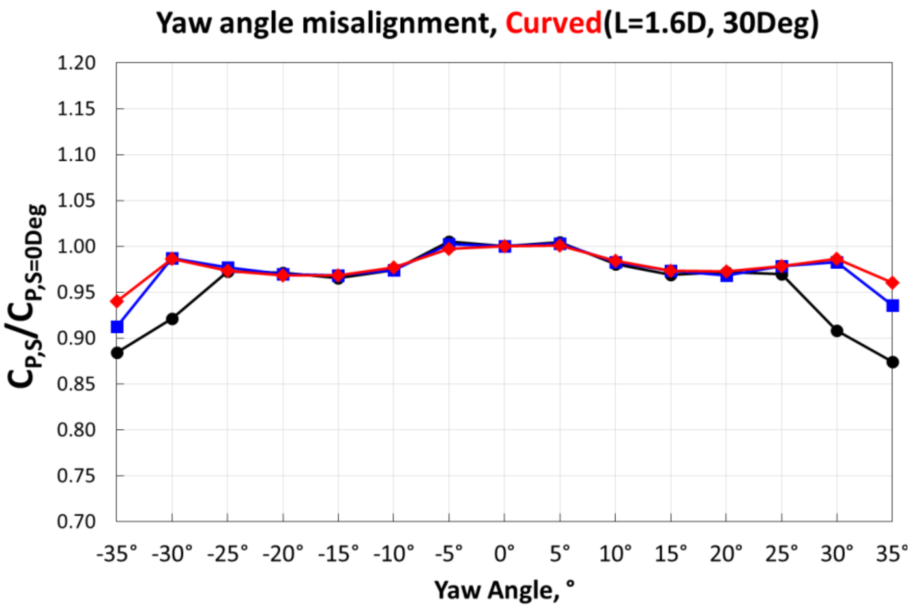
Cp distribution (Curved vs Straight)

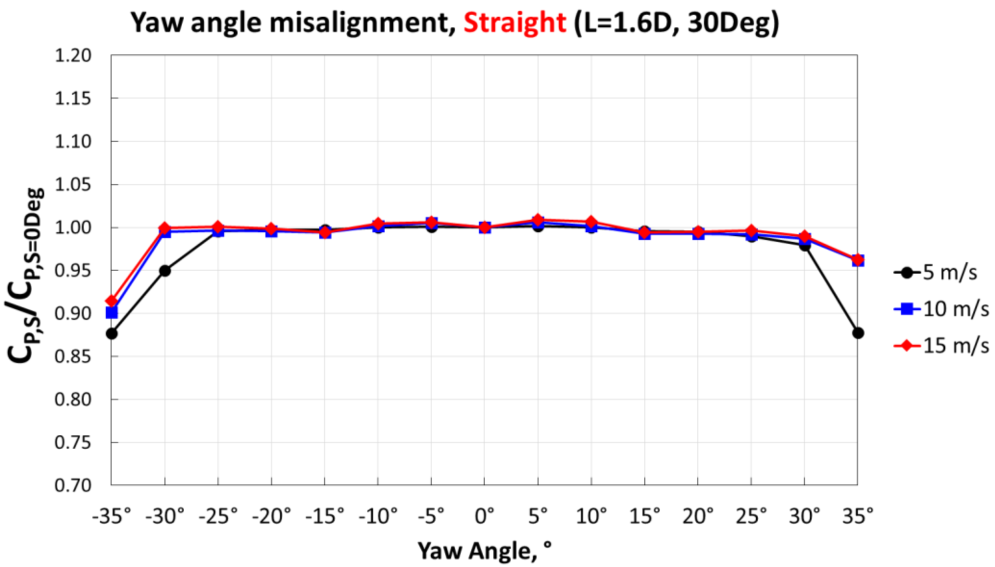
- Cp distribution of Straight model is a little linear compared to Curved model



L=1.6D Curved vs Straight (Yaw angle)

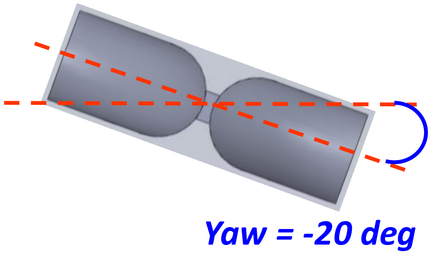
- Straight model is less sensitive to yaw angle misalignment compare to Curved model

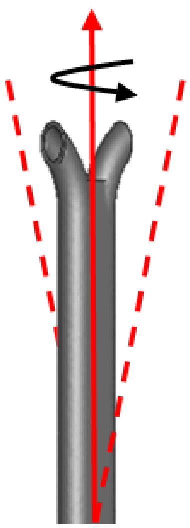


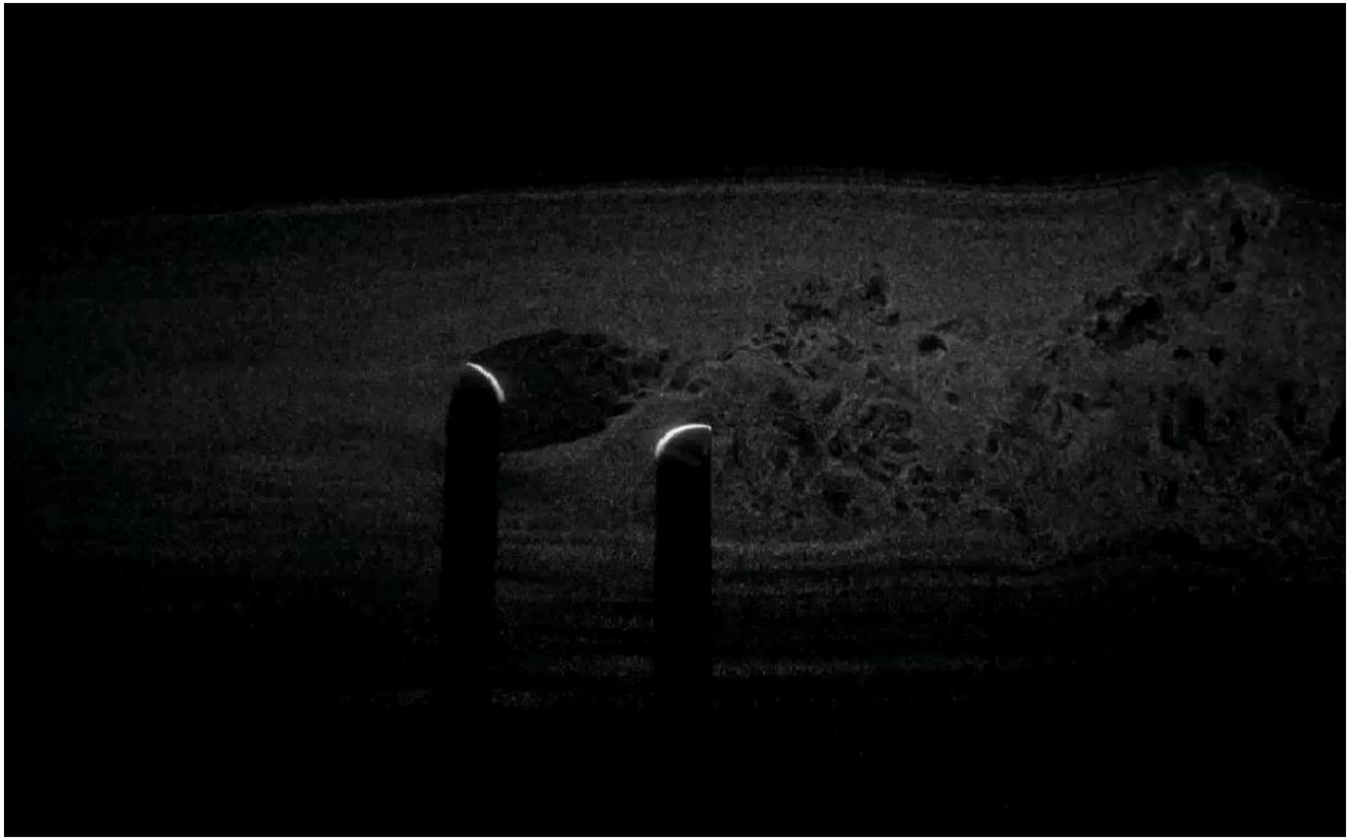


L=1.6D, 30 Deg. Straight (Yaw=-20°) PIV

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



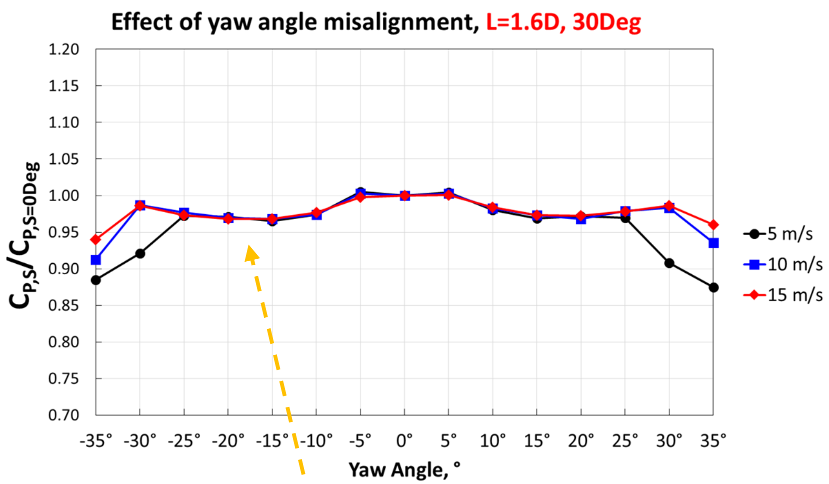


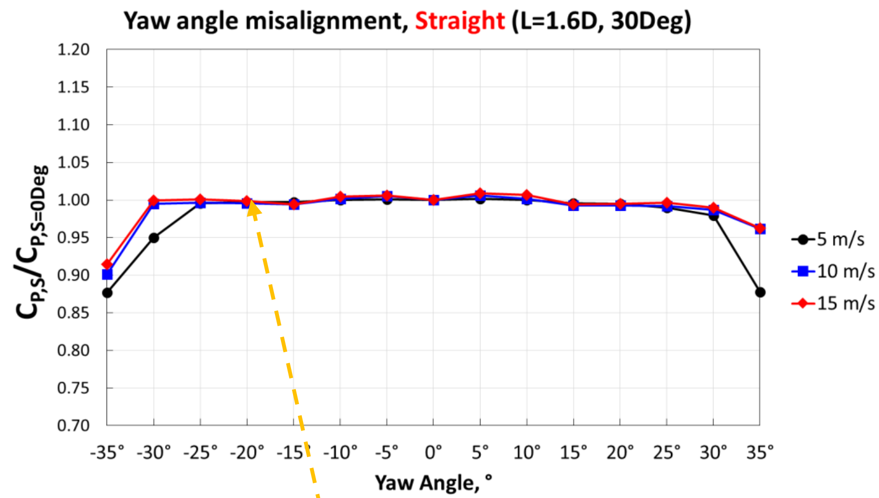


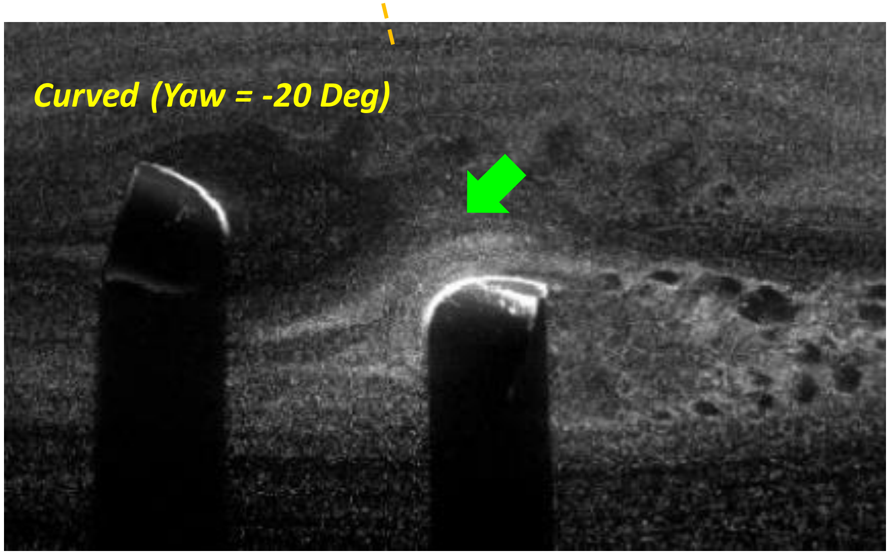
- Vortical structures from impact and wake do not affect each other near orifices

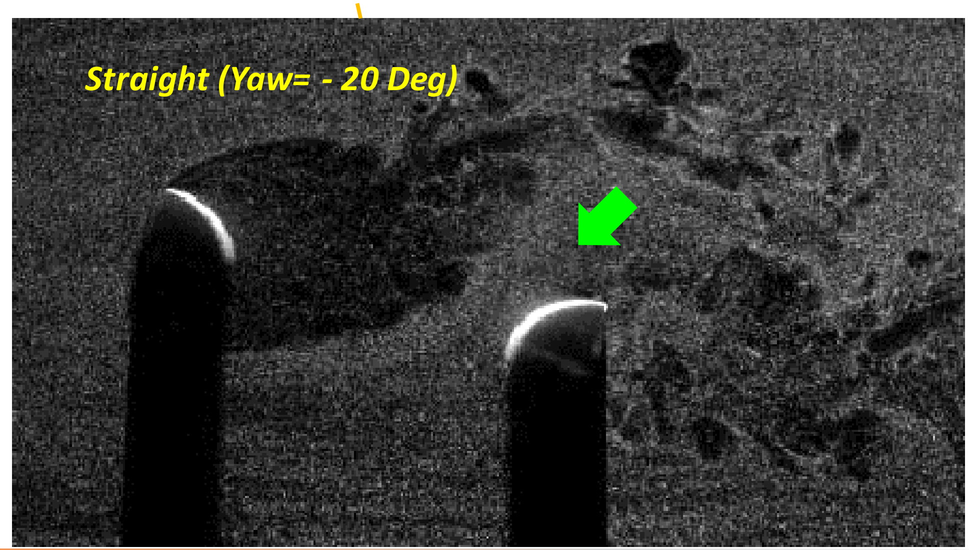
Curved vs Straight (Yaw angle)

- Despite same length(L=1.6D), vortical structures from impact and wake do not affect each other near orifices due to difference of opening shape









Conclusion

- S-type Pitot tube is mainly applied to measurement stack velocity for Smokestack TMS in KOREA
- No detail guideline for manufaturig S-type Pitot tube geometry
- Various geometric parameters on S-type Pitot tube coefficients with yaw and pitch misalignment were investigated by wind tunnel experiments

Conclusion

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

- No detail guideline for manufaturig S-type Pitot tube geometry

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

- L=1.6D, 30 Deg. Model shows the good linearity of Cp distribution and less sensitivity to yaw angle misalignment

- S-type Pitot tube with Long distance(L=3D) shows better characteristics than L=1.6D. But in the real smokestack, it could be non-practical.

- Straight model are least sensitive to yaw angle misalignment. But for the ideal geometry of S-type Pitot tube in the smokestack, more research is need.

Thank you for your kind attention!