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

Woong KANG

Center for Fluid and Flow
Korea Research Institute of Standards and Science

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
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

\[
E_{CEM} = \sum_{i=1}^{N} E_{5\text{min},i} = \sum_{i=1}^{N} \left( \bar{C}_i \times Q_{5\text{min},i} \times \frac{MW_{\text{gas}}}{22.4L} \right)
\]
Instruments for Stack Flow Velocity in KOREA

- S-type Pitot tubes: 56%
- Thermal flowmeter: 23%
- Ultrasonic flowmeter: 11%
- Averaging Pitot tubes: 10%
**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
- \( \Delta P \): differential pressure between impact and wake orifice (Pa)
- \( \rho \): density of the stack gas (kg/m³)
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

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

- $C_{p,S\cdot type}$: S Pitot tube coefficient
- $C_{p,Std}$: Standard Pitot tube coefficient
- $\Delta P_{S\cdot type}$: differential pressure of S Pitot tube
- $\Delta P_{Std}$: differential pressure of Standard tube

![Calibration Results Diagram](image)

**Calibration Results**

- Avg. = 0.840
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.

<table>
<thead>
<tr>
<th>Stack Diameter</th>
<th>raids</th>
<th>numbers</th>
<th>Distance from center of stack</th>
</tr>
</thead>
<tbody>
<tr>
<td>2R (m)</td>
<td></td>
<td></td>
<td>( r_1 )</td>
</tr>
<tr>
<td>&lt; 1</td>
<td>1</td>
<td>4</td>
<td>0.707 R</td>
</tr>
<tr>
<td>1 ~ 2</td>
<td>2</td>
<td>8</td>
<td>0.500 R</td>
</tr>
<tr>
<td>2 ~ 4</td>
<td>3</td>
<td>12</td>
<td>0.408 R</td>
</tr>
<tr>
<td>4 ~ 4.5</td>
<td>4</td>
<td>16</td>
<td>0.354 R</td>
</tr>
<tr>
<td>&gt; 4.5</td>
<td>5</td>
<td>20</td>
<td>0.316 R</td>
</tr>
</tbody>
</table>
On-site Measurement

Combined Heat and Power Plant

Guhjang Energy, KOREA
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

Average velocity: 15 m/s
Temperature: 400 K
Water content: 8.5 %
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
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.

Yaw angle misalignment → Yaw angle (-10° to 10°)

Change of Velocity Profile → Reynolds number
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.

Misalignment

→ **Pitch angle** (-10° to 10°)

→ **Yaw angle** (-10° to 10°)

Change of Velocity Profile

→ **Reynolds number**
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.
Manufature 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
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

<table>
<thead>
<tr>
<th>KRISS Subsonic Wind Tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind tunnel Type</td>
</tr>
<tr>
<td>Velocity range</td>
</tr>
<tr>
<td>Test section area</td>
</tr>
<tr>
<td>Uncertainty (%)</td>
</tr>
</tbody>
</table>

Resolution = 0.5°
Interval = 2°
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

Impact orifice

Wake orifice

Inflow

Wall B.C

Outflow B.C

30D, 60D, 120D

D : distance of between two orifice surface
**Numerical Simulation**

<table>
<thead>
<tr>
<th>Numerical Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equation</strong></td>
</tr>
<tr>
<td><strong>Meshes</strong></td>
</tr>
<tr>
<td><strong>Boundary Conditions</strong></td>
</tr>
<tr>
<td><strong>Turbulence Model</strong></td>
</tr>
</tbody>
</table>
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.

U = 1.2 % with \( \kappa = 2 \), 95% confidence level.
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

\[ \text{Re}_D = 10,000 \]
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 ($C_{p,0^\circ}$) 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.
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

\[ Re_D = 10,000 \]
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 $+10^\circ$.
- In negative Pitch angles, S-type Pitot coefficients decrease to $-2\%$, which can occur in industry stacks due to deflection 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

![Diagram showing the effects of pitch angle misalignment with different pitch angles: Pitch angle = -10°, Pitch angle = 0°, and Pitch angle = +10°.](image)
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.

\[ C_{P,S} = C_{P,Std} \left( \frac{\Delta P_{Std}}{\Delta P_{S\text{-type}}} \right) \]
• 101 ea of S-type Pitot tubes of 4 major manufacturers in KOREA were calibrated in accredited calibration laboratory (Korea Environment Corporation) in 2011.
• The deviations of the S-type Pitot tube coefficients for the same product of one company vary from 1% to 2%.

![Graphs showing CP, S-Type deviation for different companies with velocity (m/s) range 0 to 30.]

- **Company A (27 ea)**: Deviation < 2.0%
- **Company B (35 ea)**: Deviation < 2.0%
- **Company C (28 ea)**: Deviation < 1.5%
- **Company C (11 ea)**: Deviation < 1.0%
Manufacturing Quality

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

- Company A (27 ea)
  - Deviation < 2.0%

- Company B (35 ea)
  - Deviation < 2.0%

- Company C (28 ea)
  - Deviation < 1.5%

- Company C (11 ea)
  - Deviation < 1.0%
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
- Different deviations of each S-type Pitot tube coefficients within velocity range

![Graph showing deviations of different samples at various velocities](image-url)
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.
Transverse tube axis is perpendicular to the surface of two orifices, longitudinal tube axis is parallel to S-type pitot tube.
- 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
Asymmetric twisted surfaces of the impact and wake orifices with tilted longitudinal tube axes

Manufacturing Quality: Sample #4

Graph showing deviation of Cp with velocity for different samples.
Future work: Numerical simulation

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


\[ Q = V \times A \times \frac{T_{\text{std}}}{T_s} \times \frac{P_s}{P_{\text{std}}} \times (1 - X_w) \times 300 \]
**Uncertainty Evaluation**

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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>unit</th>
<th>Uncertainty component</th>
<th>Sensitivity coefficient</th>
<th>Combined uncertainty contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Type A %</td>
<td>Type B %</td>
<td></td>
</tr>
<tr>
<td>$C_p$</td>
<td>0.826</td>
<td>-</td>
<td>-</td>
<td>0.55</td>
<td>1</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>136.4</td>
<td>Pa</td>
<td>0.80</td>
<td>1.09</td>
<td>0.5</td>
</tr>
<tr>
<td>$\rho$</td>
<td>1.33</td>
<td>kg/m$^3$</td>
<td>0.0054</td>
<td>1.05</td>
<td>0.5</td>
</tr>
<tr>
<td>$D$</td>
<td>2500</td>
<td>mm</td>
<td>-</td>
<td>0.23</td>
<td>2</td>
</tr>
<tr>
<td>$P_s$</td>
<td>756</td>
<td>mmHg</td>
<td>0.0019</td>
<td>0.13</td>
<td>1</td>
</tr>
<tr>
<td>$T_s$</td>
<td>409</td>
<td>K</td>
<td>0.0046</td>
<td>0.24</td>
<td>1</td>
</tr>
<tr>
<td>$1-X_w$</td>
<td>91.5</td>
<td>%</td>
<td>0.0016</td>
<td>0.30</td>
<td>1</td>
</tr>
<tr>
<td>$\Delta V_D$</td>
<td>14.8</td>
<td>m/s</td>
<td>1.54</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>$Q$</td>
<td>12972.5</td>
<td>m$^3$/min (5min)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Combined uncertainty of the flow rate measurement* 1.94 %

95% confidence level, $k=2$

Expanded Uncertainty, $U = 3.88 \%$
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