Experimental investigation on the optimum geometry of an S-type Pitot tube for GHG emission monitoring

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Abstract. The S-type Pitot tube is a popular device used to conduct periodic volumetric flow rate monitoring performance tests in stacks or ducts. To control the accuracy of the S-type Pitot tube coefficient, all factors resulting in errors must be estimated. However, there are no detailed guidelines in international standards regarding the geometry of the S-type Pitot tube. Thus, in this study, the characteristics of S-type Pitot tubes with various geometries were tested in the Korea Research Institute of Standards and Science (KRISS) standard air speed system to determine an optimal shape for the S-type Pitot tube for measuring the volumetric flow rate in smokestacks. The results revealed that S-type Pitot tubes with a long opening distance are inclined to stability and insensitive to yaw and pitch misalignments. Finally, it was found that an S-type Pitot tube with a bending angle of 30° has a stability coefficient distribution curve.

1. Introduction

In greenhouse gas emission monitoring from industrial smokestacks, the most common device used to measure stack gas velocity is the S-type Pitot tube for estimating volumetric flow rate in the stack by a Continuous Emission Measurement (CEM) [1, 2], as shown Figure 1. The geometric parameters of S-type Pitot tube such as an external diameter, the distance between impact and wake orifices and the bending angle of orifices are described differently in several international documents which are ISO, ASTM and EPA [3-5]. Various geometries of S-type Pitot tube can affect the characteristics of S-type Pitot tube coefficients including the sensitivity to velocity change, the pitch and yaw angle misalignment. However, there is no detailed guidelines of S-type Pitot tube geometry considering the accurate and reliable measuring characteristics in the international standards.

Figure 1. The geometry of S-type Pitot tube
The main objective of the present study is to determine the optimal geometry of an S-type Pitot tube to improve the accuracy of velocity measurements in an actual stack considering velocity changes and yaw and pitch angle misalignments. To this end, S-type Pitot tubes with various geometric parameters, in this case the distance (L) between the impact and wake orifices and the bending angle (α) of the orifices, were manufactured by a 3D printer. Wind tunnel experiments were conducted in the KRISS air speed standard system to determine the effects of the geometric parameters on the S-type Pitot tube coefficients with change in the velocity and yaw and pitch angles. Particle image velocimetry was also utilized to understand the flow phenomena around an S-type Pitot tube.

2. Experimental methods
2.1. Geometrical parameters used in the experiments
To survey the geometrical effects, three combinations of S-type Pitot tube models with the different value of L are designed and manufactured by a 3D printer (ATOMm-4000) as shown in Figure 2. This value was selected based on the limited ranges recommended by international standards, and by considering the actual shape of an S-type Pitot tube. The external diameter D of all models was equal to 9.5 mm. The values of L were 1.05D, 1.6D and 3D. Each combination consisted of three S-type Pitot tube models with bending angles of 15°, 30° and 45°. Here, the bending angle α was defined as the angle formed between the center line of the tube and the straight line crossing the bending point and the center point of the S-type Pitot tube impact plane, as shown in Figure 1.

2.2. Experiments in wind tunnel system
The coefficient distribution, yaw angle calibration and pitch angle calibration curve of all models were implemented in the KRISS standard air speed system. This system included a subsonic open-circuit wind tunnel in which the test section area was 0.9m(width)×0.9m(height)×0.6m(length), the working range was from 2 to 16 m/s, and the maximum turbulent intensity in the test section was 0.5%. Other instruments, i.e., one standard NPL Pitot tube, two MKS differential pressure gauges, one pressure gauge, one temperature sensor, and one humidity sensor were integrated inside the wind tunnel to determine the coefficient of the type S-type Pitot tube [6]. To carry out the yaw angle and pitch angle calibration curves, a rotating device was installed at the top of the test section, which could change the yaw angle and from -180° to +180° at an interval of 1° pitch angles from -45° to +45° at 5° intervals (Figure 3).
3. Results and discussions

3.1. Effect of geometry on the S-type Pitot tube coefficient distribution curves

To estimate the effect of geometry on the coefficient distribution curve, the coefficients of the commercial S-type Pitot tube and those of all 3D print models were calibrated under thirteen different velocities ranging from 2 to 15 m/s and spaced at equal intervals. The results shown in Figure 4 reveal that the coefficient distribution curve of the commercial Pitot tube, and the coefficient distribution curve of the 3D print model exhibited a homologous trend. These results indicated that the 3D print model was designed and implemented properly. Additionally, at the same distance of $L$, the bending angle of the S-type Pitot tube orifices caused the coefficient values to increase slightly when it broadened.

To explain this result in detail, Figure 4 below show images of the flow field captured by the PIV system around the models with an opening distance of 1.6D and bending angles of 30° and 45°, respectively. For the case of $L = 1.6D$ and $\alpha = 30^\circ$, the separation of flows developed to vortical structures behind the impact and the wake orifices of the model. When the vortices rapidly increased, the dynamic pressure behind the wake orifice dropped considerably. Hence, the coefficients of this model decreased.

Contrary to the case where $L = 1.6D$ and $\alpha = 45^\circ$, photographic evidence indicated that the downstream separated flows were less developed than when $\alpha = 30^\circ$, owing to a gradual change in the curved shape.

![Figure 4](image)

**Figure 4.** Coefficient distribution curves of 3D print models and commercial S-type Pitot tube and flow phenomena around S-type Pitot tube models observed by the PIV system

3.2. The effect of geometry on yaw and pitch angle misalignments

The effects of yaw and pitch angle misalignments were more thoroughly investigated with different 3D print model ranges and geometries. The yaw and pitch angle ranges varied from $-35^\circ$ to $+35^\circ$ within a velocity range of 2-15 m/s. Regarding pitch angle misalignments, the pitch angle calibration curves were mostly insensitive to negative pitch angles regardless of the testing velocity or geometry of the 3D print models. However, at positive pitch angles, they increased by approximately 10% with pitch angles that were narrower than $20^\circ$. Moreover, with pitch angles wider than $20^\circ$, the normalized coefficients could increase over 20% for models with identical bending angles but shorter opening distances.

For the yaw angle misalignments, the trends of the yaw angle calibration curves were closely related to the geometry of the S-type Pitot tubes. In addition to the opening distance, the different bending angle is also a key factor in deteriorating the effect of yaw angle misalignment. To observe the flow phenomena associated to models with different angles, images of the models with $L = 1.6D$, $\alpha = 30^\circ$ and $\alpha = 45^\circ$ were captured with a yaw angle misalignment of $-20^\circ$. Figure 5 shows that the separated flows from the surfaces of both orifices were enhanced. Due to this enhancement, the pressure value near the wake...
orifice decreased. This was similar to the numerical simulation result obtained with a yaw angle misalignment of -10°. Hence, the normalized coefficient curves of the model with $\alpha = 30^\circ$ had a certain degree of stability when the yaw angle misalignment was less than $\pm 20^\circ$. In contrast, the model images with $\alpha = 45^\circ$ indicate that the vortical structures appeared behind the wake orifice. The separated flows from the surface of the impact orifices interfered with these vortical structures and caused the pressure distributions near the wake orifice to drop sharply. Thus, normalized coefficient values of the model with $\alpha = 45^\circ$ tended to decline dramatically with yaw angle misalignments.

![Figure 5. Coefficient distribution curves and flow phenomena around S-type Pitot tube with L = 1.6D, $\alpha = 30^\circ$ and L = 1.6D, $\alpha = 45^\circ$ at yaw angle misalignment of -20°](image)

4. Conclusions

This study investigated the effect of the geometry on type S-type Pitot tubes, which are used to measure the emission gas flow rate in stationary sources. The conclusions drawn from this study are as follows:

1. The distributions of S-type Pitot tube coefficients upon yaw and pitch angle misalignments differed depending on the combination of geometric parameters for the distance (L) and the bending angle ($\alpha$). The actual contact distance of the flow between the two orifices is also an important parameter when determining the effects of yaw angle misalignments, similar to the effects of velocity changes.
2. The results of yaw angle misalignments present that S-type Pitot tube models with long effective lengths are less affected by yaw angle misalignments. On the other hand, the S-type Pitot tube coefficients were mostly insensitive to negative pitch angle misalignment regardless of the velocity and geometry of the various models.
3. Additional research is needed to determine the optimal geometry of S-type Pitot tube for GHG monitoring in a smokestack.

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