Smokestack Gas Velocity Measurements using 3-D Pitot tubes in a Coal-Fired Power Plant

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Abstract

The fossil carbon dioxide (CO_2) emissions from the combustion of fossil fuels and energy generators prevail over total greenhouse gas (GHG) emissions. Therefore, accurately estimating GHG emissions from stationary sources such as coal-fired power plants is also one of the efforts to mitigate the global rise in emissions. The GHG volumetric flow rates in stacks are measured mostly with the S-type Pitot tubes in Korea. But the S-type Pitot tube introduces error when it is operated under the presence of non-axial flows in stacks. In contrast, the three-dimensional (3D) Pitot tubes, which can determine all three-directional velocity components of the flow, are expected to surmount the restriction of the S-type Pitot tube. In this research, the flue gas velocity in the smokestack is measured with the 3D Pitot tubes to investigate the three-dimensional velocity profile and patterns inside the smokestack. The axial and off-axial velocity components of the flue gas in the smokestack are measured with two kinds of 3D Pitot tubes which are prism and spherical 3D Pitot tubes. They are compared with the TMS velocity which is measured with the S-type Pitot tube. The axial velocity components measured by the 3D Pitot tubes are well agreed with the TMS velocities by the S-type Pitot tube, and the velocity distribution and flow patterns inside the smokestack are investigated.

1. Introduction

The fossil carbon dioxide (CO_2) emissions from the combustion of fossil fuels and energy generators prevail over total greenhouse gas (GHG) emissions. Therefore, accurately estimating GHG emissions from stationary sources such as coal-fired power plants is also one of the efforts to mitigate the global rise in emissions. GHG emission quantities can be determined directly from GHG concentration and volumetric flow rate at a stack in the continuous emission measurement (CEM) method. Also, the CEM method has been considered the most reliable method in determining GHG emissions from stationary sources

The GHG volumetric flow rates in stacks are measured mostly with the S-type Pitot tubes in Korea. But the S-type Pitot tube introduces error when it is operated under the presence of non-axial flows in stacks. Because the S-type Pitot tube has a limitation in that it can measure the flow velocity correctly only in a situation where the Pitot tube is well-aligned to the gas flow direction. In contrast, the three-dimensional (3D) Pitot tubes, which can determine all three-directional velocity components of the flow, are expected to surmount the restriction of the S-type Pitot tube.

In contrast, three-dimensional (3D) Pitot tubes, which can determine all three-directional velocity components of the flow, are expected to be able to overcome this restriction of the S-type Pitot tube [1, 2]. Unlike the S-type Pitot tube, 3D Pitot tubes are equipped with five holes in the probe head. The hole directions are all different so that 3D velocity components can be measured.

In addition, to gain a thorough understanding and generalize smokestack velocity measurements with 3D Pitot tubes as S-type Pitot tubes in Korea, it is necessary to conduct more studies under different stack flow conditions in situ. According to current guidelines, including ISO 16911-1 [1] and EPA Method 2F [2], which are mandated as regulations pertaining to stack flow measurements in certain nations, the procedure of velocity measurements using a 3D Pitot tube should follow the nulling method. However, implementing gas velocity measurements with a 3D Pitot tube to survey the velocity distribution of a stack is still a complicated procedure. Therefore, the main purpose of this study is to develop a nulling smokestack flow measurement system that can be utilized practically for velocity measurements on site by 3D Pitot tubes. The developed nulling smokestack flow measurement system is used to measure the gas velocity in a smokestack of a practical combined heat and power plant in Korea. 3D Pitot tubes are installed at the same elevation as the S-type Pitot tube for the TMS, and the data are similar to each other.

2. 3D Pitot tubes for smokestack measurement

3.1 3D Pitot tubes

3D Pitot tubes are common devices in the turbomachinery field used to measure the components of three-dimensional flows. However, they have recently been considered as a new potential approach for stack flow measurements owing to their capability to measure swirl flows. As described in Figure 1, prism (Figure 1a) and sphere (Figure 1b) Pitot tubes consisting of five sensing holes in the sensing head are numbered from 1 to 5. The central hole is marked as 1, and the other four holes are symmetrically located with respect to the central hole. Holes 2 and 3 are used to measure the yaw-angle velocity component, and holes 4 and 5 are used to measure the pitch-angle velocity component. The five sensing holes of the 3D Pitot tube are connected to a differential pressure sensor with flexible tubes. The pressure differences of ΔP_{12}, ΔP_{23}, and ΔP_{45} are measured with a differential pressure sensor, where ΔP_{ij} represents the pressure difference P_i-P_j. The velocity magnitude of flow V can be calculated by Equation (1),

$$V = F_2 \times \sqrt{\frac{2\Delta P_{12}}{\rho}}, \qquad (1)$$

where the calibration coefficient F_2 is obtained from the calibration procedure. Unlike the S-type Pitot tube, the 3D Pitot tube can measure the orientation of the flow, which is identified with the yaw angle θ_y and the pitch angle θ_p. The three-dimensional velocity components of flow can be determined as shown below:

$$V_x = V \cos\theta_y \cos\theta_p \qquad (2)$$

$$V_y = V \sin\theta_p \qquad (3)$$

$$V_z = V \sin\theta_y \cos\theta_p \qquad (4)$$

Here, V_x is the smokestack axial velocity of the flow, V_y and V_z are the velocity components perpendicular to the axial velocity, as shown in Figure 1c. By combining Equations (1) and (2), the axial velocity of the stack flow measured by the 3D Pitot tube is determined as follows:

$$V_x = F_2 \times \sqrt{\frac{2\Delta P_{12}}{\rho}} \cos\theta_y \cos\theta_p \qquad (5)$$

Two types of 3D Pitot tubes are used to carry out the stack velocity measurements in this research, a prism Pitot tube and a sphere Pitot tube, with corresponding sensing head diameters of 2.45 cm and 5.84 cm. The bodies of these 3D Pitot tubes are extended by 2 m to be compatible with the measuring condition at the smokestack. Calibration of 3D Pitot tubes is mandatory before their use for velocity measurements in smokestacks. Therefore, the 3D Pitot tube's coefficients are calibrated by the airspeed standard system at the Korea Research Institute of Standards and Science (KRISS).

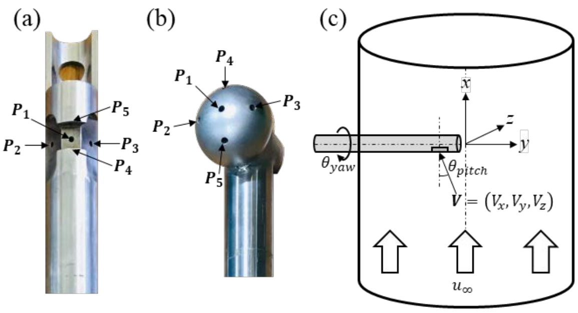

Figure 1: 3D Pitot tubes (a) prism Pitot tube, (b) sphere Pitot tube, and (c) installation scheme of the 3D Pitot tubes in the stack

3.2 3D Pitot tube calibration by the nulling method

The 3D Pitot tubes are calibrated by the wind tunnel facility at KRISS, which is shown in Figure 2. The coefficient curves of Pitot tubes are established by comparison with a reference probe such as a standard Pitot tube, a laser Doppler anemometer, or an ultrasonic anemometer. The calibration system at KRISS includes a subsonic open-circuit wind tunnel, an NPL standard Pitot tube used as the reference, a traversing unit, high-accuracy and bidirectional differential pressure gauges, a controlling system, and a data acquisition system. The dimensions of the test section of the wind tunnel are 900 mm (width) × 900 mm (height) × 6000 mm (length). The operating range of the wind tunnel is from 2 m/s to 16 m/s, and the turbulent intensity in the test section is less than 0.5%. The traverse control unit can control the yaw angle (-35°≤ θ_y ≤35°) and the pitch angle (-35°≤ θ_p≤35°) of the Pitot tube. The probe head is located at the center of the test section at every yaw and pitch angle. All parameters related to the calibration procedure are controlled and acquired by the LabView software.

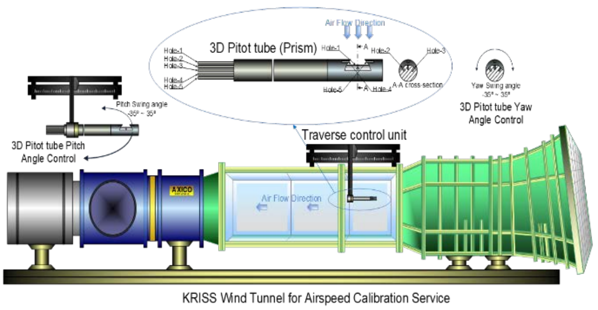

Figure 2: 3D Pitot tubes calibration system for Pitot tubes at KRISS

There are several calibration methods for 3D Pitot tubes specifically equipped with five holes on the probe head. In this research, the yaw-nulling method is adopted according to the EPA and ISO guidelines [1, 2]. In the yaw-nulling method, the 3D Pitot tube should be rotated along the yaw angle direction until the pressure difference between P_2 and P_3 is zero. Subsequently, the pitch angle coefficient of the flow F_1 is determined from the ratio of the pitch pressure ΔP_{45} to the velocity pressure ΔP_{12} via Equation (6). The velocity coefficient F_2 is deduced from the relationship between the velocity pressure of the 3D Pitot tube and the velocity pressure of the airflow measured by the reference Pitot tube using Equation (7). This calibration procedure is performed at a given pitch angle of θ_p, meaning that the calibration coefficients are a function of θ_p. The coefficient of the NPL reference Pitot tube α in Equation (7) is 1.0015.

$$\mathrm{F}_1(\theta_p) = \frac{\Delta P_{45}}{\Delta P_{12}} \qquad (6)$$

$$\mathrm{F}_2(\theta_p) = \alpha\sqrt{\frac{\Delta P_{std}}{\Delta P_{12}}} \qquad (7)$$

In this research, the pitch angle and velocity coefficient curves are calibrated over the testing pitch range of ±35°. The testing velocities are 5 m/s, 10 m/s, and 15 m/s. Figure 3 presents the coefficient curves of the prism and sphere Pitot tubes. These values will be used for the velocity measurements in the smokestack.

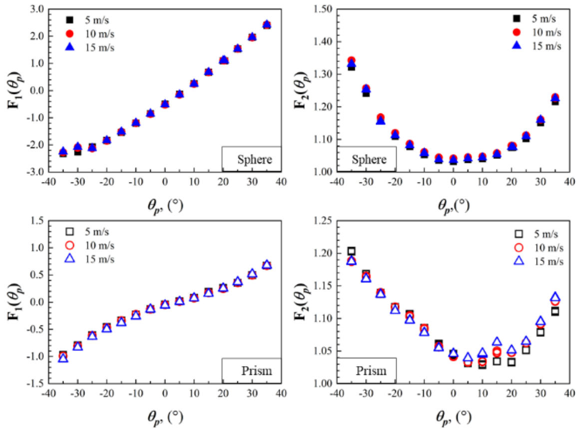

Figure 3: S Calibration results of 3D Pitot tubes

3. Experiment setup

3.1 Nulling smokestack flow measurement instrument

In order to measure the flow velocity in the smokestack using 3D Pitot tubes while complying with EPA Method 2, KRISS developed a portable system that can automatically execute the nulling procedure at each traversing measurement point. The overall configuration of this nulling smokestack flow measurement (NSFM) instrument is described in Figure 4. The instrument consists of 3D Pitot tubes, a control and acquisition part, and auxiliary instruments. After the 3D Pitot tube is installed on the smokestack, the pressuring taps of the Pitot tube are appropriately connected to three differential pressure transmitters to measure the differential pressure between the sensing holes of the Pitot tubes (ΔP_{12}, ΔP_{23} and ΔP_{45}). An inclinometer is attached to the Pitot tube body in order to measure the yaw angle. The differential pressure transmitters and the inclinometer are connected to a four-channel analog input module (NI-9239). A servo motor controller mounted on the rigid fixture rotates the Pitot tube until ΔP_{23}=0 to find the yaw-null angle. When the yaw-nulling angle is found, the differential pressure values between the sensing holes of Pitot tubes, the temperature, the static pressure, and the relative humidity of the stack are acquired by a data acquisition instrument. As shown in Figure 4, all of the controllers and sensors are connected to a laptop through a LAN hub (NI-cDAQ 9181). The entire velocity measurement procedure is controlled and monitored by a LabView program.

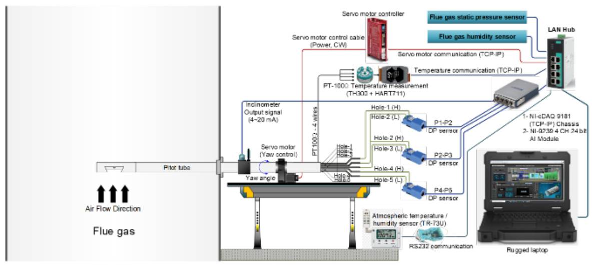

Figure 4: Operating principle of the nulling smokestack flow measurement instrument

3.2 Measurement setup in the on-site smokestack

Figures 5a and 5b show photos of the coal-fired power plant in this study and the in-situ measurement of the gas flow in the smokestack. The power plant is located in the south sea-coast of Korea, and the smokestack has an inner diameter of 2.7 m and a total height of 78.5 m, as shown in Figure 6. The stack inlet (disturbance) is located 6.9 m from the ground, and the measuring section is located 30 m from the disturbance. The power plant is equipped with an S-type Pitot tube for the TMS according to Korean regulations. The sampling port used for installing the 3D Pitot tube lies at the same elevation as the port where the S-type Pitot tube is installed. As shown in Figure 6b, the S-type Pitot tube for the TMS is fixed at a certain point while the traversing points of the 3D Pitot tube vary from position numbers 1 through 9. As shown in Table 1, the sampling points are selected basically according to EPA method 1 and ISO 17080 [3-4], and additional points (#7, #8) are selected to ascertain the velocity profile along the smokestack radial direction. At each traverse point, the differential pressures, stack temperature, humidity, and static pressure are sampled every six seconds after the nulling condition is reached. Generally, a single set of velocity measurements using the 3D Pitot tube takes about 15 minutes for each traverse point, including the adjustment of the measuring position and the yaw-nulling procedures.

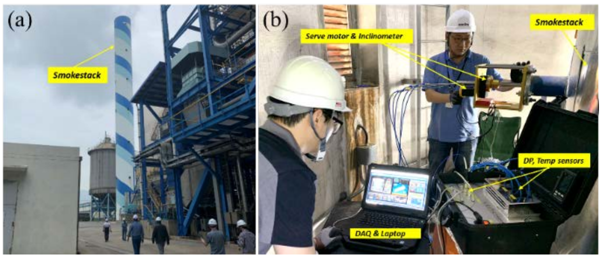

Figure 5: (a) A coal-fired power plant and (b) in-situ measurements of the gas flow in the smokestack

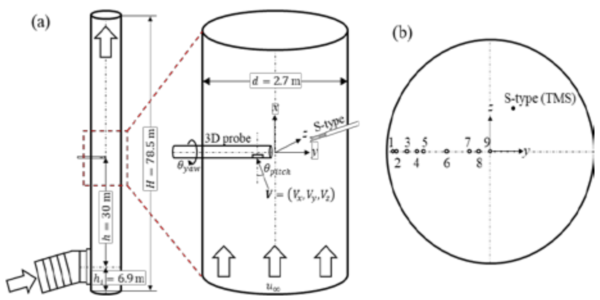

Figure 6: Experimental arrangement in situ: (a) perspective view of the smokestack, (b) y-z plane view of the measurement plane

Table 1: Sampling point of the gas velocity in the smokestack

Traverse point number	Distance from the wall		
	Standards	%D	mm
1	ISO	3.0	81
2	EPA	4.4	119
3	ISO	9.8	265
4	EPA	14.6	394
5	ISO	17.8	481
6	ISO	29.0	783
7	N/A	40.0	1080
8	N/A	44.4	1200
9	ISO	50.0	1350

4. Results and Discussion

According to Korean regulations, air pollutant discharge facilities must be equipped with proper measuring instruments. The measurement results are reported online, including the discharged gas volume every five minutes, as measured by an S-type Pitot tube. The volume discharged during five minutes can be converted into the averaged gas velocity as

$$V_{TMS} = \frac{Q}{A \times \Delta t}, \tag{8}$$

where Q is the gas volume discharged during the five minutes, A is the cross-sectional area of the smokestack, and Δt represents the collection time (300 seconds or 5 minutes). The five-minute averaged velocity data during on-site measurement days is recorded every five minutes, as shown in Figure 4. The first rectangle is the TMS velocity data during the sphere Pitot tube measurement, and the second is that during the prism Pitot tube measurement. The measuring duration for the 3D velocity at nine positions is about 15 minutes for each Pitot tube. The mean TMS velocity during the sphere Pitot tube measurement is 20.75 m/s with a standard deviation of 0.62 m/s, while the mean TMS velocity during the prism Pitot tube measurement is 20.31 m/s with a standard deviation of 0.77 m/s.

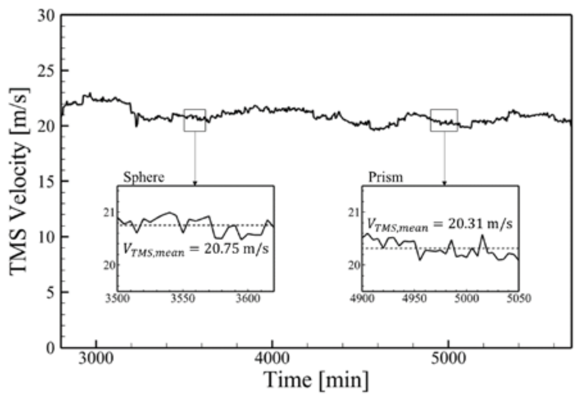

Figure 7: Gas flow velocity as measured by a S-type Pitot tube for the TMS

The flow velocity was measured by the yaw-nulling method with the 3D Pitot tubes at each sampling point listed in Table 1. The velocity magnitude of the flue gas is calculated by equation (2) from the calibrated F_1 and F_2 curves and the measured pressure differences. The 3D components of the velocity (V_x, V_y, V_z) are calculated according to Equations (2) ~ (4), where the yaw angle is obtained from the yaw-nulling procedure and the pitch angle is calculated from Equation (6). The magnitude of the x-directional velocity component (stack axial velocity component) exceeds 98% of the velocity magnitude as V_x >0.98V.

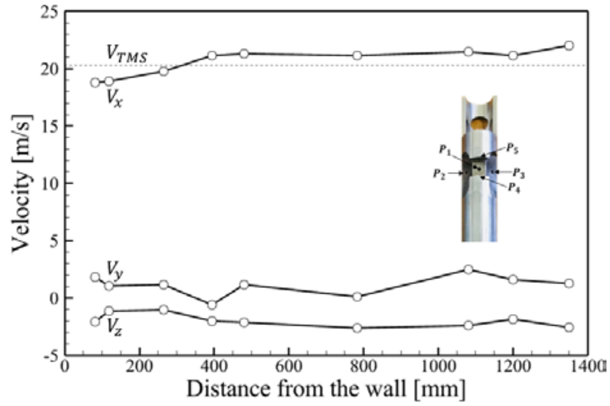

Figure 8: Velocity measured by the prism Pitot tube

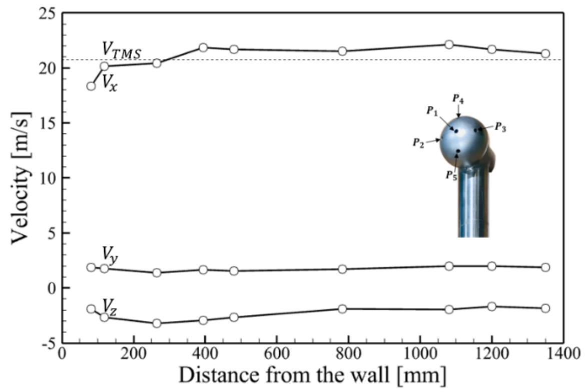

Figure 9: Velocity measured by the sphere Pitot tube

Figures 8 and 9 show the 3D velocity profiles as measured by a prism Pitot tube and a sphere Pitot tube, respectively. The solid lines in the figures represent the directional velocity components of the gas flow, and the dashed line represents the mean velocity measured by the S-type Pitot tube for the TMS during the 3D Pitot tube measurement. As shown in Figures 8 and 9, the x-directional velocity component from the 3D Pitot tubes overlaps the TMS velocity. The y- and z-directional velocity components are measured with the help of the 3D Pitot tubes, as they cannot be measured with S-type Pitot tube.

Figure 10 presents a 3D representation of the velocity vectors in the smokestack. The blue vector represents the TMS velocity measured by the S-type Pitot tube, and the black vectors show the 3D velocity components for each position. The red vectors are the projected vectors onto the y-z plane. The three-dimensional flow patterns inside the smokestack can be explored with the 3D Pitot tubes

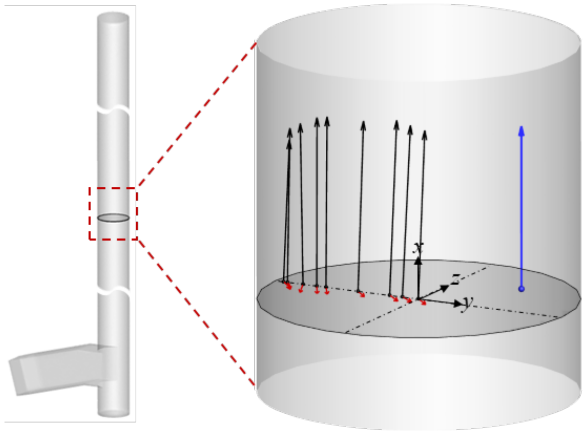

Figure 10: Velocity measured by a sphere Pitot tube

5. Conclusion

The stack flow measurement instrument equipped with 3D Pitot tubes and that operates according to the nulling method noticeably enhances the quality of average axial velocity measurements. The value of the average axial velocity as measured by this instrument is in good agreement with the value determined by the TMS. The results measured by this instrument equipped with 3D Pitot tubes will adhere to Korean regulations to monitor the emissions flows in smokestacks more reliably compared to the use of an S-type Pitot tube. Simultaneously, this study not only develops a portable system equipped with 3D Pitot tubes that can comply with Korea's current legislation on stack flow measurements, but it is also a detailed interpretation of EPA Method 2F with regard to applying 3D Pitot tubes to practical combined heat and power plants in Korea.

References

[1] ISO-16911-1: Stationary source emissions — Manual and automatic determination of velocity and volume flow rate in ducts — Part 1: Manual reference method, ISO/TC 146/SC 1 Station, 2013.

[2] U.S Environ. Prot. Agency 2F Method: Determination of stack gas velocity and volumetric flow rate with three-dimensional probes, 2017.

[3] ISO 10780: Stationary source emissions — Measurement of velocity and volume flowrate of gas streams in ducts, Int. Stand. Organ., 1994.

[4] U.S Environ. Prot. Agency Method 1: Sample and Velocity Traverses for Stationary Sources, 2020.