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Uncertainty Evaluation of Stack Flowrate Measurement with S-Type Pitot Tube by Monte Carlo Method

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Abstract

In order to attempt to mitigate the climate change, efforts to reduce the quantity of carbon emissions by actively seeking CO_2 trading and carefully control the liability of the emission test monitoring system from the industrial factories are a current issue. Therefore, the quality of greenhouse gas (GHG) emissions measurement with a proper uncertainty needs to be firstly considered. Currently, GHG emissions are estimated by a continuous emission measurement (CEM). The U.S Environmental Protection Agency (EPA), has classified the measurement of GHG emissions by the CEM as the highest quality Tier IV with lowest uncertainty level. Relating to accuracy of the CEM, both knowledge of the uncertainty contributions on GHG concentrations and volumetric flow rates are necessary for achieving a credible result. In order to accurately evaluate the uncertainty of the CEM method, flow rate measurements in the stack as well as GHGs concentration measurements by gas analyzer are crucial due to various uncertainty factors. In this study, we concentrate on finding measurand inputs and their uncertainty estimates that affect volumetric flow rates in a heat and power generation plant. Both the law of propagation method and Monte Carlo method (MCM) are used to evaluate the uncertainty of the flow rate measurement in order to minimize the numerical approximation of the partial derivatives of the complex model with respect to the every input. Consequently, the result of MCM is consistent with the result that by the law of propagation of uncertainty. The relative expanded uncertainties at 95% confidence level with coverage factor k=2 are 528.1 m^3 and 527.2 m^3, respectively.

1. Introduction

The increased GHG emissions such as CO_2, CH_4 and N_2O from the fossil fuel combustion causes the global warming phenomena by increasing average global temperature. The Inter-governmental Panel on Climate Change (IPCC)'s fifth assessment report described a global temperature rise of 0.89°C from 1901-2012 and a total anthropogenic radiation change of 2.29 W/m^2 [1]. Under the United Nations Framework Convention on Climate Change (UNFCCC), all countries are required to reduce greenhouse gas (GHG) emission for mitigating climate change. Korea GHG emission trading scheme has been implemented since January 2015 in accordance with the act on the allocation and trading of GHGs emission permits, which is the first nationwide cap and trade program in operation in Asia. The IPCC has developed practical guidelines for national inventories of GHGs emissions in different sectors such as energy, industrial process, agriculture and waste from economic activities [2]. The energy supply in the energy sector is an important source of GHG emissions as it contributes 25.9% of the global GHG emissions. Therefore, it is essential to properly estimate GHG emissions from the energy supply for mitigating climate change. In order to reduce GHG emission, accurate and reliable GHG emission estimate with proper uncertainties should be carried out. GHGs emission estimate have been based on an activity-based method (i.e., fuel consumption and emission factor) and a continuous emission measurement (CEM). The CEM directly measures GHG emission through monitoring GHG concentrations and volumetric flow rate at a stack. In the U.S Environmental Protection Agency (EPA) [3], GHG emission by the CEM was classified as a highest quality Tier IV with lowest uncertainty level. Even though activity-based method for estimating GHG emission has been adopting in the Korea emission trade scheme, the CEM method should be examined for improving the quality of GHG emission inventories and trading. For evaluating an accurate uncertainty of CEM method, flow rate measurements in the stack as well as GHGs concentration measurements by gas analyzer are crucial due to various uncertainty factors [4]. The main objective of the present study is to evaluate the uncertainties in the stack gas flow rate measurement for the CEM method. To achieve this, continuous flowrate measurement were conducted with a S-type Pitot tube in a heat and power generation plant. The average flowrate were calculated with a flow velocity, a density, water content and a cross-sectional area. Associated uncertainties of accumulated stack flowrate were calculated by propagating the uncertainties of input variables. Besides, Monte Carlo Method was also used to evaluate the uncertainty of flow rate measurement. This method can minimize the numerical approximation of the partial derivatives of the complex model with respect to the every input.

2. On site CEM method

According to the U.S.EPA [3], the amount of GHG emission can be determined by the fuel consumption measurements, the measured carbon dioxide concentration percent by the volume of the fuel and the total amount of exhaust volume flow rate from stack. However, CEMS method is mostly used in the power plants and industrial factories in order to estimate GHG emissions by equation (1):

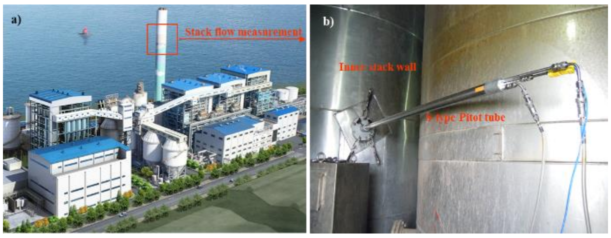
$$E = \sum_{i=1}^{N} E_{5min,i} = \sum_{i=1}^{N} \left(x_{5min,i} \times Q_{5min,i} \times \frac{M_{gas}}{MV} \right) \quad (1)$$

where $E_{5min,i}$ is the emission accumulated every 5 minutes of the ith measurement [% or ppm], $Q_{5min,i}$ is the dried volumetric flow accumulated of the ith measurement [m^3], M_{gas} is the molar mass of an emission gas, MV is the molar volume of ideal gas, and N is the total number of estimated emissions every five minutes. The 5-min accumulated volumetric gas flow rate can be calculated with the following equation:

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

where Q_{5min} is a 5-minute accumulated volumetric dry gas flow [m^3], $\bar{V}$ is an averaged gas flow velocity [m/s], D is the stack diameter [m], P_s is the static pressure [mmHg], T is emission gas temperature [K], $t = 300$ [s], and x_w is the water content [%] in the emission gas.

To measure the gas flow velocity in the stack, the types of flow meter are used as: 3-D Pitot tubes (DAT and sphere), averaging Pitot tubes, ultrasonic flowmeters, S-type Pitot tubes, and thermal flowmeters. But, the S-type Pitot tubes are the most commonly used in Korea, accounting for 56%. So, in this study, an S-type Pitot tube was selected in order to do the flow velocity measurements for CEMS. With a rigid body and two large pressure orifices, the S-type Pitot tube is suitable for measuring the flow velocity in high-dust environments [5,6]. The flow velocity can be obtained by measuring the differential pressure between the impact orifice and the wake orifice based on the Bernoulli equation. The S-type Pitot tube coefficient (C_p) is used to calculate the flow velocity by measuring the differential pressure with the S-type Pitot tube, as in the following equation (3):



a) b

Figure 1: a) combined heat and power generation plant; b) Installation of the S-type Pitot tube in the wall of the stack

$$V_s = C_P \times \sqrt{\frac{2\Delta P}{\rho}} \quad (3)$$

where ΔP is the differential pressure [Pa] between the impact and the wake orifices and ρ is the density of the emission gas [kg/m^3].

All flowrate measurements were conducted in a stack in the combined heat and power plant located in the western region of South Korea, as shown in figure 1. The flow rate measurement system of this company was connected to the national tele-metering system (TMS) for monitoring stack emissions reporting the 5-minute accumulated volumetric flow to the national TMS using equation (2).

3. Uncertainty evaluation of the gas flow measurement in the stack

3.1. Uncertainty evaluation by GUM

The mathematical model equation for the 5-minute accumulated volume flowrate measurement can be expresses as equation (2). Assuming that the input measurements were mutually independent, according to the ISO Guide [7], equation (2) can be expressed as the following uncertainty propagation using the Taylor series approximation.

$$u_c^2(Q_{5min}) = c_{\bar{V}}^2 u^2(\bar{V}) + c_D^2 u^2(D) + c_T^2 u^2(T) + c_{P_s}^2 u^2(P_s) + c_{(1-x_w)}^2 u^2(1 - x_w) \quad (4)$$

where $c_{\bar{V}}$, c_D, c_T, c_{P_s}, and $c_{(1-x_w)}$ are the sensitivity coefficients obtained by the partial differentiation of equation (2) with respect to each variable. $u(\bar{V})$, $u(D)$, $u(T)$, $u(P_s)$, and $u(1 - x_w)$ are the standard uncertainty of each of the variable. $u_c(Q_{5min})$ is the combined uncertainty of Q_{5min}. Type A uncertainty is calculated with a standard deviation from the repeated experiment data of each variable. Type B uncertainty comes from flow calibration certification of instruments, fundamental constant or experience of experts. The sensitivity coefficient of each variable are as follows:

$$c_{\bar{V}} = \frac{\partial Q}{\partial \bar{V}} = \frac{\pi D^2}{4} \times \frac{P_s}{760} \times \frac{273.15}{T} \times (1 - x_w) \times 300$$

$$c_D = \frac{\partial Q}{\partial D} = \bar{V} \times \frac{\pi D}{2} \times \frac{P_s}{760} \times \frac{273.15}{T} \times (1 - x_w) \times 300$$

$$c_{P_s} = \frac{\partial Q}{\partial P_s} = \bar{V} \times \frac{\pi D^2}{4} \times \frac{1}{760} \times \frac{273.15}{T} \times (1 - x_w) \times 300$$

$$c_T = \frac{\partial Q}{\partial T} = -\bar{V} \times \frac{\pi D^2}{4} \times \frac{P_s}{760} \times \frac{273.15}{T^2} \times (1 - x_w) \times 300$$

$$c_{(1-x_w)} = \frac{\partial Q}{\partial (1-x_w)} = \bar{V} \times \frac{\pi D^2}{4} \times \frac{P_s}{760} \times \frac{273.15}{T} \times 300 \quad (5)$$

The combined standard uncertainty of the volumetric flow rate can be expressed as a relative form by dividing the square of flow rate and substituting sensitivity coefficients as following equation (6)

$$\frac{u_c^2(Q)}{Q^2} = \frac{u^2(\bar{V})}{\bar{V}^2} + 4\frac{u^2(D)}{D^2} + \frac{u^2(P_s)}{P_s^2} + \frac{u^2(T)}{T^2} + \frac{u^2(1-x_w)}{(1-x_w)^2} \quad (6)$$

In the on-site energy plant, an S-type Pitot tube installed in the stack is typically fixed in a certain position. The measured velocity in a certain position has difference with the integrated average flow velocity of multi-points in the measuring plane of the cross section. Therefore, when installing an S-type Pitot tube in the stack wall, it is important to determine the best position to obtain a measured velocity that is close to the averaged velocity in the stack.

$$\bar{V} = V_s + \Delta V \quad (7)$$

$\bar{V}$ is the average velocity value calculated with the measured velocity distribution. V_s is the measured velocity value in a certain position fixed in the stack which can be calculated by equation (3) when using S-type Pitot tube. ΔV is difference between averaged velocity and measured velocity of fixed position. The number of traverse points in the cross section of the stack are determined by EPA method [5] and ISO [6].

$$u^2(\bar{V}) = u^2(V_s + \Delta V) = u^2\left(C_P\sqrt{\frac{2\Delta P}{\rho}} + \Delta V\right) \quad (8)$$

$$u^2(\bar{V}) = c_{C_P}^2 u^2(C_P) + c_{\Delta P}^2 u^2(\Delta P) + c_\rho^2 u^2(\rho) + c_{\Delta V}^2 u^2(\Delta V) \quad (9)$$

$$c_{C_P} = \frac{\partial \bar{V}}{\partial C_P} = \sqrt{\frac{2\Delta P}{\rho}}$$

$$c_{\Delta P} = \frac{\partial \bar{V}}{\partial \Delta P} = \frac{1}{2} C_P \sqrt{\frac{2}{\rho \Delta P}}$$

$$c_\rho = \frac{\partial \bar{V}}{\partial \rho} = -\frac{1}{2} C_P \sqrt{\frac{2\Delta P}{\rho^3}}$$

$$c_{\Delta V} = \frac{\partial \bar{V}}{\partial \Delta V} = 1 \quad (10)$$

A typical S-type Pitot tube coefficient is known to be approximately 0.85 according to the ISO [6]. However, for the accurate and reliable velocity measurement, both a specific coefficient and its associated uncertainty, $u(C_P)$, need to be determined for each Pitot tube by a national metrology institute or accredited calibration laboratory. In the present study, the coefficient of the Pitot tube calibrated in the Korea Environment Corporation (KECO) was 0.826. $u(C_p)$ in the KECO calibration was 0.55%. The uncertainty of the different velocity, $u(\Delta V)$ was determined by 1.54%. The uncertainty of the different pressure, $u(\Delta P)$ was 1.91%.

Moreover, the density of emission gas (ρ) can be determined by estimating a weighted average density based on the concentration of major gas components (N_2, CO_2, O_2, Ar, H_2O) in the emission gas from the stack as in the following equation 11:

$$\rho = \frac{(x_{CO_2} \times 44 + x_{O_2} \times 32 + x_{Ar} \times 39.94 + x_{N_2} \times 28 + x_{H_2O} \times 18) \times 100}{22.4} \quad 11)$$

The concentration measurements of N_2, CO_2, O_2, Ar and H_2O obtained by ULTRAMAT6 gas analyzers were used to estimate a weighted average density of emission gas at 760 mmHg and 0°C.The uncertainty of the gas emission, $u(\rho)$ including the difference between the weighted average value and the fixed value used in the stack was determined as 1.1%.

The water content can be calculated by condensed moisture in the impinger and volume flow rate in the dry gas meter according to EPA method 4 [8], which can be expressed as equation 12:

$$x_w = \frac{\frac{22.4}{18} m_a}{Q_m \times \frac{273.15}{T_m} \times \frac{P_m}{760} + \frac{22.4}{18} m_a} \quad (12)$$

where m_a is the measured mass of moisture in the impinge (g/min), Q_m is the dry gas volume measured by the dry gas meter (L/min), P_m is absolute pressure at the dry gas meter (mmHg), T_m is absolute temperature (K). In the present study, a continuous weighing method with balance was applied to the uncertainty evaluation of water contents and flow rate. The water mass out of a cold condenser prior gas analyzer and flow meter were measured every 10 seconds, and were found to be about

Table 1: Uncertainty budget of volumetric flow rate measurements at 14.5 m/s

Component	Value	Unit	Standard Uncertainty (%)		Sensitivity coefficient, c_i	Uncertainty contribution, $u_i \times c_i$(%)
			Type A	Type B		
C_P	0.826	-	-	0.55	1	0.55
ΔP	136.4	Pa	0.54	1.78	0.5	0.68
ρ	0.885	kg/m^3	0.0054	1.12	0.5	0.53
D	2500	mm	-	0.23	2	0.46
P_s	756	mmHg	0.0019	0.15	1	0.13
T	409	K	0.0048	0.14	1	0.25
$1-x_w$	91.5	%	0.0016	0.16	1	0.30
$\bar{V}$	14.5	m/s	-	1.54	1	1.54
Q	12972.5	m3/min				
			Combined uncertainty of the flow rate measurement, u_C=			2.03%
			with 95% confidence level, k =			2
			Relative expanded uncertainty, U=			4.1%

0.292 g/min. The dry gas passing through the condenser was measured using a flow meter. The uncertainty of the water content, $u(1-x_w)$ including the difference between the sampling value and the theoretical value of fuel coal used in the energy plant was determined by 0.16%. On the other hand, the uncertainty of the static pressure, $u(P_s)$ was 0.15%. The uncertainty of the temperature, $u(T)$ was 0.14%. And the uncertainty of the stack diameter, $u(D)$ was 0.23%. From all these values, the relative expanded uncertainty of the 5 minutes accumulated volumetric flow rate in Table 1 was estimated about 4.1% (or 527.2 m^3), k=2 with a 95% confident level.

3.2. Uncertainty evaluation by GUM

MCM performs a random draw from prescribed probability distribution for each input parameter and the corresponding value of output parameter will be formed by the known functional relationship. Also, during doing random sampling from the probability density function of the input quantities, MCM provides the probability distribution of the output and the coverage interval [9,10] To do MCM for evaluating uncertainty of the volumetric flow rate, simplifying equation (2) in order to have a general overview regarding the all input variables that will be taken part into the Monte Carlo propagation simulation procedure as follows:

$$Q_{5min} = f(\bar{V}, \mathrm{D}, P_s, T, x_w) \qquad (13)$$

As assuming in 3.1, all input quantities in equation (13) had no relationship with each other. Therefore, no multivariate probability density function was required in this sampling procedure. It means that the 5-minutes accumulated volumetric flowrate and its uncertainty were only estimated by random sampling from the predefined probability distributions associated with each input as Table 2. The values of $\bar{V}$ were randomly drawn from equation (3), (7), (11) and the values of x_w

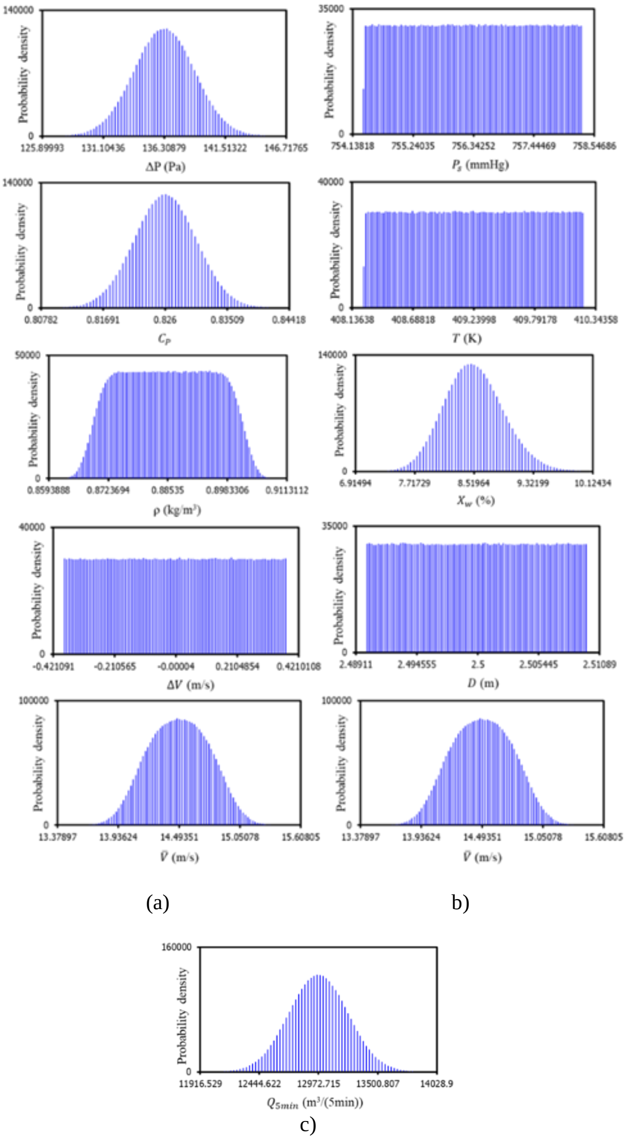


Figure 2: a) Random sequences for $\bar{V}$; b) and c) Random sequences for Q_{5min}

Table 2: The input quantities and the probability density function assigned to them

Input x	Units	$\bar{x}$	Probability density function	Uncertainty $u(x)$
P_S	mmHg	756	Rectangular	1.154
T	K	409	Rectangular	0.577
x_w	%	8.5	Normal	0.40
D	m	2.5	Rectangular	0.0058
$\bar{V}$	m/s	14.5	Normal	0.278

were randomly drawn from equation (12). Random sequences are graphed in figure 2. The number of Monte Carlo trials, M deliver the shape of the probability distribution for the output quantity as well as the coverage probability required and a value of M=10^6 was suggested to give a 95% coverage interval for the output quantity [9]. So, with this choice of M, the result of MCM was Q_{5min} = 12972.7 m^3 and $U_{MCM}(Q_{5min})$ = 528.1 m^3. These value are quite close to the results implemented by GUM (Q_{5min} = 12972.5 m^3) and $U_{GUM}(Q_{5min})$ = 527.2 m^3). The difference of two estimation of uncertainties is 0.17%. The framework of this simulation was based on the Microsoft Excel and Microsoft Visual Basic for Application.

4. Conclusions

The Monte Carlo Method produces the results having no big difference from GUM method, the difference of 0.17%. It also commits to simplify the calculation and show graphically how the effect of input quantities on the distribution shape of output. Hence, MCM is well suited for uncertainty estimation when the functional relationship is complex as this study.

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