

A Study on Real-time Evaluation of Uncertainty of PM-10 Concentration Determined by Tele-measuring Instrument

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Abstract— We developed a real-time particulate matter(PM-10) and its uncertainty monitoring instrument assisted by beta-ray absorption method and continuous tele-measuring system. According to the GUM as an authentic reference, 4 steps of operational procedures for uncertainty evaluation were included to general type of instrument; at first, establishment of a model equation of PM concentration, at second, calculation of each standard uncertainty, at third, calculation of combined standard uncertainty, at fourth, calculation of expanded uncertainty at 95% confidence level.

The developed instrument was tested at Gwanpyeong-dong, Daejeon during Nov. 2023. Through this field application, expanded uncertainties at 720 data points of PM concentration were obtained. At the low level of PM concentration, 22.2 $\mu\text{g}/\text{m}^3$, the expanded uncertainty value was 2.0 $\mu\text{g}/\text{m}^3$ at the 95 % confidence level, while at the high level of PM concentration, 118.6 $\mu\text{g}/\text{m}^3$, it was 9.8 $\mu\text{g}/\text{m}^3$. The expanded uncertainty values versus PM concentration were well fitted with a second-order regression equation, $y = 0.00007 x^2 + 0.073 x + 0.36$ ($\mu\text{g}/\text{m}^3$). In comparison with each uncertainty variance, it was revealed that the most important uncertainty source is the uncertainty of linearity quantified by equivalence evaluation between the PM concentration values obtained by beta-ray absorption method and direct weighing method. And the contribution rate of this uncertainty was 32% of total uncertainty.

It has revealed that the developed instrument has successfully managed to calculate and display real-time measurement uncertainty with various uncertainty source budgeting data.

Keywords—Real-time uncertainty evaluation. Measurement uncertainty, Particulate matter, PM-10, Air quality monitoring instrument, Tele-measuring system

I. INTRODUCTION

In Korea, the beta-ray absorption method is adopted as the fundamental measurement technique[1] for monitoring ambient particulate matter(PM-10). National Ambient air quality Monitoring Information System(NAMIS), as a continuous ambient air quality monitoring system, operates to measure air pollutants including PM-10 and collects measured air quality data across the country. NAMIS also collects data in real-time utilizing the internet network. The collected data are used as foundational information about air quality and

contribute to the national and local air quality improvement policies[2].

Maintaining measurement accuracy requires regular calibration and quality control processes for the monitoring instrument. For this processes, essential tasks include periodic zero/span calibration for PM-10 concentration and the calibration of all sensors measuring sample temperature, pressure and flow rate. During the continuous measurement operations of ambient particulate of PM-10, additional uncertainty factors may arise in comparison to typical single measurement operation[3]. Since the long-term operation leads to changes of reproducibility and linearity of calibration, their quality control process is one of the crucial works for this continuous measurement of PM-10 concentration.

Recently many laboratories adopt “Guide to the Expression of Uncertainty in Measurement(GUM)”[4] for the quality assurance of measurement result[4-13]. Therefore, it is necessary to follow the procedures and show measurement uncertainty in continuous monitoring instrument. In this study, we developed an instrument for simultaneous real-time monitoring of ambient particulate matter(PM) concentration and uncertainty. This instrument was assisted by the beta-ray absorption method and a tele-measuring system. Applying this instrument, PM concentration and its uncertainty values were collected in Gwanpyeong-dong, Daejeon during Nov. 2023. With the measurement results and corresponding uncertainty values, we discussed the measurement quality and the feasibility of the developed instrument.

II. EXPERIMENTS

A. Instrument and modification of software

In this study, the continuous ambient particulate monitoring instrument, K-501A(KOSTEC Inc.) was used and operational software was upgraded to enable onsite evaluation of measurement uncertainty. The basic specifications of K-501A are outlined in Table 1[14].

For the modification of conventional type of instrument, 4 steps of operational procedures of uncertainty included; at first, establishment of a model equation of PM concentration, at second, calculation of each standard uncertainty, at third,

calculation of combined standard uncertainty, and at fourth, expanded uncertainty of 95% confidence level[3-12, 15]. Uncertainty factors treated in the processes included repeatability of beta-ray intensity ratio, uncertainty of temperature, pressure and flow measurements, uncertainty of attenuation coefficient, uncertainty of sampling area, linearity and background uncertainty, and drift of standard film.

TABLE 1. K-501A SPECIFICATIONS

Items	Specifications
Measurement method	β -ray attenuation
Measurement range	0-1,000 $\mu\text{g}/\text{m}^3$
Minimum detection limit	<4 $\mu\text{g}/\text{m}^3$ (2 σ)
Measurement cycle	1h
Radiation Source	14C, 60 μCi (<22 $\times$ 106 Bq) source
Filter tape	Glass Fiber Roll Filter
Air flow rate	16.7 L/min
Flow system	Mass flow controller
Operating temperature	0~50 $^{\circ}\text{C}$

B. Approach for the Evaluation of Uncertainty

Generally, basic approach for calculating measurement uncertainty is based on GUM[4-9]. In this study, the operational software in K-501A was designed and included with procedure of GUM. So, the final frame of calculating and displaying measurement uncertainty is such as following Figure 1.

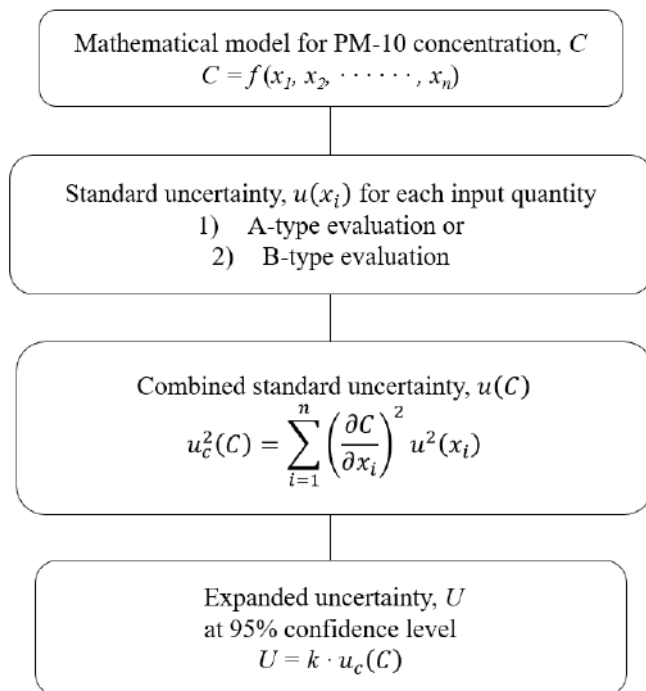


Figure 1. The procedure for accessing real-time measurement uncertainty.

C. Establishing Mathematical Model of Measurand

For the determination of PM-10 concentration, beta-ray

absorption method was incorporated with Beer-Lambert relationship[16, 17]. The equation of measurand with beta ray attenuation before and after sampling particulate from ambient air is such as following Eq. 1.

$$C = \frac{10^6 \cdot A \cdot \ln\left(\frac{I_0}{I}\right)}{\mu \cdot Q \cdot \Delta t \cdot \left(\frac{P}{P_{std}}\right) \cdot \left(\frac{T_{std}}{T}\right)} \quad \text{Eq. 1.}$$

where, C , measured PM-10 concentration($\mu\text{g}/\text{m}^3$), A , area of the sample filter(cm^2), I_0/I , beta-ray intensity ratio before and after sampling, μ , attenuation coefficient(cm^2/mg), Q , sampling flow rate(L/min), Δt , sampling time(min), P_{std} , pressure at standard conditions(mmHg), P , sampling pressure(mmHg), T_{std} , temperature at standard conditions(K), T , sampling temperature(K).

In the continuous operations of ambient particulate of PM-10, additional uncertainty factors may arise. These type of uncertainty factors include the span drift quantified by calibration using standard film and equivalence evaluation[18] results between PM-10 concentration obtained by K-501A analyzer and by direct weighing method. Final mathematical model of measurand, which is suitable to evaluate uncertainty, should be modified as following Eq. 2.

$$C = \frac{10^6 \cdot A \cdot \ln\left(\frac{I_0}{I}\right)}{\mu \cdot Q \cdot \Delta t \cdot \left(\frac{P}{P_{std}}\right) \cdot \left(\frac{T_{std}}{T}\right)} \cdot f_{drift} \cdot f_{lin} + \delta_{bg} \quad \text{Eq. 2,}$$

where f_{drift} is span drift correction factor using standard film, f_{lin} is linearity correction factor of slope and δ_{bg} is intercept correction factor.

D. Standard uncertainty and degrees of freedom

For the input quantities in Eq. 2, the standard uncertainty(SU), and degrees of freedom(DF) should be determined[4] according to the GUM guidelines. Generally, The standard uncertainty can be calculated through Type A or Type B evaluation[4, 12]. In this experiment, all the standard uncertainty values are evaluated by Type B evaluation. For the Type B evaluation, past measurement data, prior quality control experimental results and certificates of various references are essentially needed.

1) SU and DF of sampling area

After determining the diameter of sampling hole using digital micrometer, the area of sampling hole can be quantified by the following Eq. 3.

$$A = \pi \left(\frac{D}{2}\right)^2 \quad \text{Eq. 3.}$$

Assuming that the probability density distribution is rectangular in the determination of diameter, then the standard uncertainty of diameter is calculated as shown in Eq. 4[4, 10, 11].

$$u(D) = \frac{a}{\sqrt{3}} \quad \text{Eq. 4.}$$

where, a , resolution of digital micrometer. By the uncertainty propagation method, the standard uncertainty of area is as

following Eq. 5.

$$u(A) = \frac{\pi D}{2} \cdot u(D) \quad \text{Eq. 5.}$$

The DF in the Type B evaluation of uncertainty can be obtained as shown in Eq. 6[4].

$$v(x_i) = \frac{1}{2} \left(\frac{100}{R} \right)^2 \quad \text{Eq. 6,}$$

where, $R = 100$ - uncertainty of uncertainty evaluation with the unit of percentage.

2) SU and DF of Attenuation Intensity Ratio

In the measurement process of PM-10, the standard deviation with 3 consecutive measurement results were continuously calculated. And a pooled standard deviation was calculated using smaller values than 30 % from bottom of most recent one-week data. The pooled standard deviation as shown in Eq. 7 was used as the standard uncertainty of attenuation intensity ratio.

$$s_p = \sqrt{\frac{\sum_{i=1}^n s_i^2 \cdot v_i}{\sum_{i=1}^n v_i}} \quad \text{Eq. 7.}$$

And degrees of freedom(v) of pooled standard uncertainty of attenuation intensity ratio is as shown in Eq. 8.

$$v = \sum_{i=1}^n v_i \quad \text{Eq. 8.}$$

3) SU and DF of Attenuation Coefficient

To determine the standard uncertainty of μ , it is necessary to measure the weight(W_{film}) and area(A_{film}) of a standard film, and the beta-ray intensity ratio(I_0/I) before and after determining the standard film. With determined data, attenuation coefficient can be derived as following Eq. 9[16].

$$\mu = \frac{\ln\left(\frac{I_0}{I}\right)}{\left(\frac{W_{film}}{A_{film}}\right)} \quad \text{Eq. 9.}$$

To quantify the standard uncertainty of μ , it is prerequisite to evaluate the standard uncertainty of each input quantity. For the uncertainty values of area and beta-ray intensity ratio, same procedures were adopted as described previous sections. And the standard uncertainty of weight of standard film can be calculated using the following Eq. 10 with quality control limit(a) data.

$$u(W_{film}) = \frac{a}{\sqrt{3}} \quad \text{Eq. 10.}$$

Finally, the standard uncertainty of μ was combined using uncertainty propagation rule as shown in Eq. 11.

$$\left(\frac{u(\mu)}{\mu}\right)^2 = \left(\frac{u(I_0/I)}{(I_0/I) \cdot \ln(I_0/I)}\right)^2 + \left(\frac{u(W_{film})}{W_{film}}\right)^2 + \left(\frac{u(A_{film})}{A_{film}}\right)^2 \quad \text{Eq. 11.}$$

4) SU and DF of Sampling Time

In the case of sampling time(Δt), the standard uncertainty is estimated by Eq. 4 with resolution(a) data of the timer used in the software of K-501A. Since the determination of lapsed time involves two times of determination, the standard uncertainty of Δt can be calculated as shown in Eq. 12

$$u(\Delta t) = \frac{\sqrt{2} a}{\sqrt{3}} = a \sqrt{\frac{2}{3}} \quad \text{Eq. 12.}$$

The degrees of freedom can be quantified as the same way as shown in Eq. 6.

5) SU and DF of Temperature, Pressure and Flow Rate

For the evaluation of standard uncertainty of determined values from many sensors in the PM monitor, calibration data with certificates of references are needed. Therefore, the standard uncertainty and degrees of freedom of sample flow rate(Q), temperature(T) and pressure(P) can be extracted from prior calibration data with the certificates provided.

6) SU and DF of Linearity and Background

For the linearity and background control, it is essential to compare measurement results periodically between beta-ray attenuation and direct weighing methods. This equivalence evaluation should be conducted once in every 2 years in Korea as a regulation[2]. To quantify these two standard uncertainty values, most recent equivalence evaluation results were assisted.

We conducted this equivalence evaluation with two different measurement systems for the comparisons of PM-10 concentration. In this study, one measurement system was composed with K-501A in which an air-sampling adaptor was included. And, another system as a reference was composed with the E-SEQ-FRM(Metone Inc.) manual sampler and Microbalance(Satorius Inc.). This evaluation was conducted continuously for more than 2 months on experimental field site[2]. The 24-hour average data measured by two methods were directly compared[18, 19].

In order to quantify standard uncertainty values, at first, a linear regression line($y = b_1 x + b_0$) is calculated with obtained comparison data. And the uncertainty variance matrix(U) of the slope(b_1) and intercept(b_0) of the regression line was derived as shown in Eq. 13[4].

$$U = \begin{pmatrix} u^2(b_0) & u(b_0, b_1) \\ u(b_0, b_1) & u^2(b_1) \end{pmatrix} \quad \text{Eq. 13,}$$

$$= s^2 \begin{pmatrix} n & \sum_{i=1}^n x_i \\ \sum_{i=1}^n x_i & \sum_{i=1}^n x_i^2 \end{pmatrix}^{-1}$$

$$\text{where, } s = \sqrt{\frac{\sum_{i=1}^n (y_i - b_0 - b_1 x_i)^2}{n-2}}$$

Since the standard uncertainty of linearity factor(f_{lin}), includes both the bias of slope and uncertainty of slope, the standard uncertainty of linearity factor can be derived as shown Eq. 14.

$$u^2(f_{lin}) = (u(b_1))^2 + \left(\frac{b_1 - 1}{\sqrt{3}}\right)^2 \quad \text{Eq. 14.}$$

With same idea on the treatment of linearity, the standard uncertainty of δ_{bg} can be derived as shown Eq. 15.

$$u^2(\delta_{bg}) = (u(b_0))^2 + \left(\frac{b_0}{\sqrt{3}}\right)^2 \quad \text{Eq. 15.}$$

7) SU and DF of Drift

For the instrumental drift control, periodic calibration and quality control with standard film are essential. So, the standard uncertainty of drift can be calculated using the $u(m_{film})$ and quality control limit(a) data.

E. Combined Standard Uncertainty and DF of Measurand

Basically, the combined standard uncertainty, $u_c(C)$ of PM-10 concentration as a measurand can be calculated by the uncertainty propagation rule shown in Figure 1[4-9]. In this study, at first, equation of combined standard uncertainty can be derived using uncertainty propagation rule and partial derivatives of input quantities. Next, both side of the derived equation can be divided by PM-10 concentration(C) and arranged to appropriate form of equation as shown in following Eq. 16.

$$\left(\frac{u_c(C)}{C}\right)^2 = \left(\frac{u(A)}{A}\right)^2 + \left(\frac{u(Q)}{Q}\right)^2 + \left(\frac{u(\Delta t)}{\Delta t}\right)^2 + \left(\frac{u(\mu)}{\mu}\right)^2 + \left(\frac{u(I_0/I)}{(I_0/I) \cdot \ln(I_0/I)}\right)^2 + \left(\frac{u(T)}{T}\right)^2 + \left(\frac{u(P)}{P}\right)^2 + \left(\frac{u(f_{drift})}{f_{drift}}\right)^2 + \left(\frac{u(f_{lin})}{f_{lin}}\right)^2 + \left(\frac{u(\delta_{bg})}{C}\right)^2 \quad \text{Eq. 16.}$$

The effective degrees of freedom(v_{eff}), which are the degrees of freedom of combined standard uncertainty, can be obtained with the standard uncertainty and DF of each input quantity, and the partial derivatives, as shown in Equation 17.

$$v_{eff} = \frac{u_c^2(C)}{\left(\frac{u_i^4(A)}{\infty} + \frac{u_i^4(Q)}{\infty} + \frac{u_i^4(\Delta t)}{\infty} + \frac{u_i^4(\mu)}{\infty} + \frac{u_i^4(I_0/I)}{v_{I_0/I}} + \frac{u_i^4(T)}{\infty} + \frac{u_i^4(P)}{\infty} + \frac{u_i^4(f_{drift})}{\infty} + \frac{u_i^4(f_{lin})}{\infty} + \frac{u_i^4(\delta_{bg})}{\infty} \right)} \quad \text{Eq. 17,}$$

where, $u_i(x_i) = \frac{\partial f}{\partial x_i} \cdot u(x_i)$,

if the model equation is $y = f(x_1, x_2, \dots, x_n)$.

F. Expanded Uncertainty as Measurand

Basically, the expanded uncertainty(U) is statistical interval of expected measurand value and calculated by multiplying the combined standard uncertainty to coverage factor(k). Since the coverage factor is determined depending on the probability density distribution of measured quantity, t -value from t -distribution with 95 % confidence level can be used in this study. The expanded uncertainty was calculated as shown in Eq. 18[4].

$$U = k \cdot u_c(C) \quad \text{Eq. 18.}$$

As a result of accessing uncertainty, the PM-10 concentration in ambient air can be expressed in a simple form, as shown in Equation 19.

$$C \pm U \quad \text{Eq. 19.}$$

This indicates that the estimated value of PM-10 concentration is located from $C - U$ to $C + U$ at 95 % confidence level.

G. Uncertainty Budget

We calculated how much each uncertainty factor contributes to the uncertainty of the final measurement value. For the comparison with the same unit of variance, contribution rate was derived as shown Eq. 18.

$$\left(\frac{\frac{\partial f}{\partial x_i} u_i(x_i)}{u_c(C)} \right)^2 \times 100(\%) \quad \text{Eq. 20}$$

With the results, we compared the contributions of uncertainty components and verified important sources of uncertainty [4].

H. Installation of the Software of Uncertainty

In this study, particulate monitoring instrument, K-501A was used and operational software was modified by the developed procedure of uncertainty evaluation and expression for PM-10 concentration. The main control menu of K-501A was originally composed of 4 category, such as Setting-up measurement condition, Diagnostics, Calibration and Quality Control. To display real-time calculated uncertainty, we modified and added software of uncertainty as shown in the Figure 2.

With modified operational software, one can periodically exchange all the newly prepared standard uncertainty values and obtain real-time PM-10 concentration and its uncertainty.

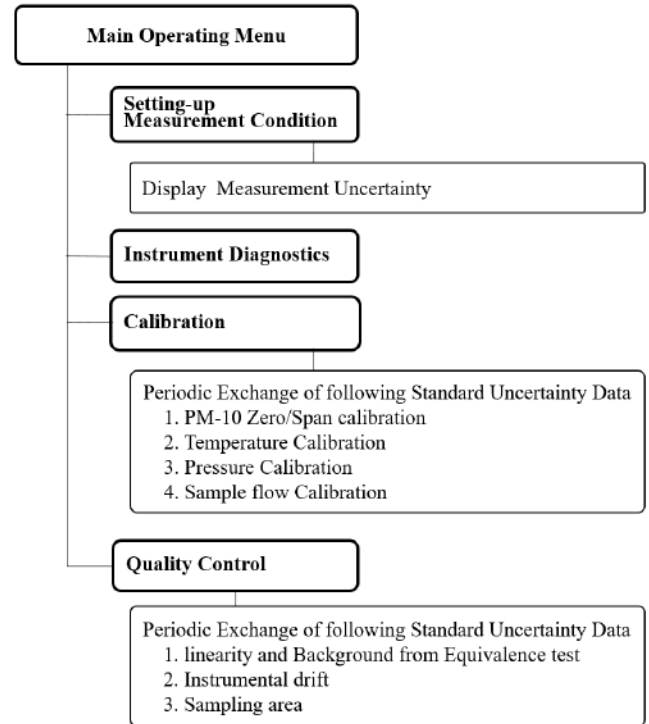


Figure 2. The operating menu for accessing uncertainty.

I. Field Application of Developed Software of Uncertainty

With the modified K-501A, the PM concentration and its uncertainty values were collected for one month at Gwanpyeong-dong, Daejeon during Nov. 2023. Through this field application, PM concentration and their expanded uncertainties of 95% confidence level were obtained and their various characteristics were evaluated.

III. RESULTS

We have obtained many PM-10 concentration and uncertainty values, which are representative results produced by the procedures explained at the previous sections. Here, as an example, we present detailed results only on a PM-10 concentration value, $22.15 \mu\text{g}/\text{m}^3$ obtained once at the field application of measurement and onsite evaluation of uncertainty. For the selected value, all input quantities and associated uncertainty values obtained by the procedures explained at previous sections are such as following Table 1.

TABLE 2. THE STANDARD UNCERTAINTIES and DEGREES of FREEDOM for EACH INPUT QUANTITY and MEASURAND

Input/Output Quantity	Input/Output Quantity Value	Standard uncertainty, $u(x_i)$	Unit	DF
A	1.130	0.000022	cm^2	∞
I_0/I	1.005	0.000091	-	13
μ	0.310	0.0054	cm^2/mg	∞
Δt	50.00	0.000053	min	∞
Q	16.67	0.036	L/min	∞
P	764	0.45	mmHg	∞
T	5.8	0.10	K	∞
f_{drift}	1	0.017	-	∞
f_{lin}	1	0.026	-	∞
δ_{bg}	0	0.30	-	∞
C	22.15	1.00	$\mu\text{g}/\text{m}^3$	∞

The standard uncertainty values of linearity and background shown in Table 2 were evaluated with the results of the most recently performed equivalence evaluation using the K-501A. The scatter plot for the paired comparison data obtained by the equivalence evaluation is shown in Figure 3.

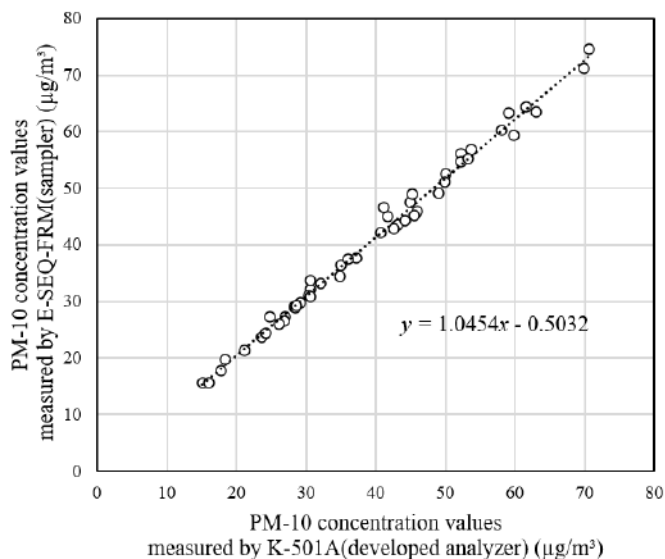


Figure 3. The scatter plot for the equivalence evaluation results.

The slope of regression line was 1.045 and the intercept of that was $-0.503 \mu\text{g}/\text{m}^3$. For the standard uncertainty of linearity and background, both the bias and regression uncertainty were

combined by Eq. 14 and Eq. 15.

The combined standard uncertainty was obtained using Eq. 16 and the value was $1.00 \mu\text{g}/\text{m}^3$. And the effective degrees of freedom were obtained using Eq. 17 and the value was 2×10^{17} (approximately ∞). Since the probability density function was t -distribution with approximately ∞ of degrees of freedom, the probability density function of measurand could be assumed as a Gaussian distribution.

The expanded uncertainty as an expected statistical interval of measurand was calculated by Eq. 18. And its value was $2.0 \mu\text{g}/\text{m}^3$ at the confidence level of 95 %, with $k = 2.0$. By the procedure explained at previous sections, each result was quantified by the software in K-501A and was displayed at the front display panel as shown in Figure 4.

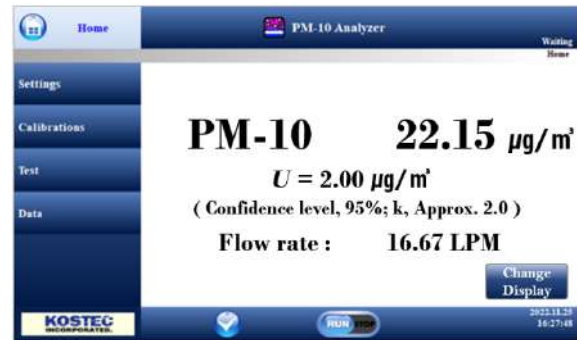


Figure 4. The display of PM-10 concentration measurement results

We compared the contribution rate of each uncertainty source as described with Eq. 20 and found that highest contributed component is uncertainty of linearity (contribution rate, 32 %) found at consistency test. And the contribution rate of the uncertainty of flow rate, temperature and pressure were not so high (contribution rate, below 1.0 %). The uncertainty contributions rate for each input quantity was derived and plotted in Figure 5.

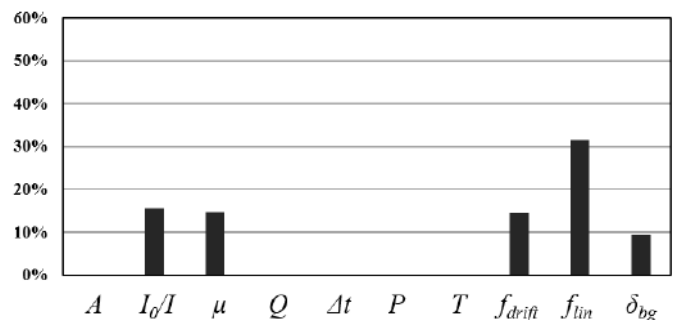


Figure 5. The uncertainty contributions for each input quantity.

During the field application period in November 2023, the measurement uncertainties for hourly average data were collected for PM-10 concentration value, and all the data of uncertainties were depicted versus determined PM-10 concentration as shown in Figure 6. As the PM concentration increased, the expanded uncertainty also increased. For a high concentration level of PM-10, $118.55 \mu\text{g}/\text{m}^3$, the expanded

uncertainty was $9.8 \mu\text{g}/\text{m}^3$ at 95 % confidence level. For a low concentration level of PM-10, $22.15 \mu\text{g}/\text{m}^3$, the expanded uncertainty was $2.0 \mu\text{g}/\text{m}^3$ at 95 % confidence level.

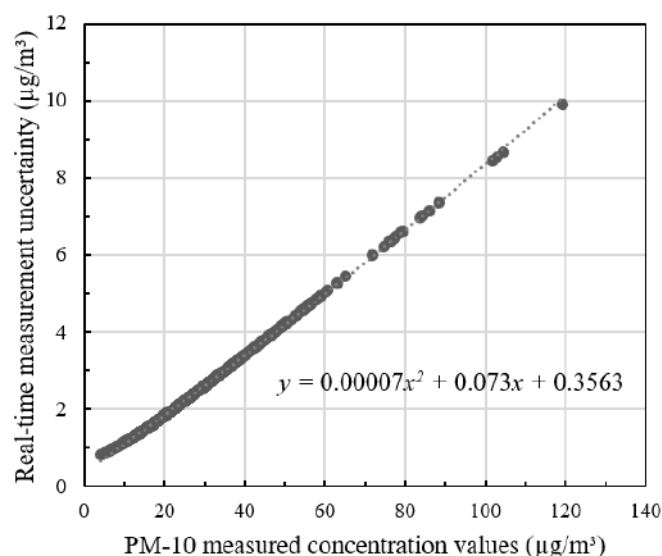


Figure 6. The real-time measurement uncertainty based on PM-10 measured concentration value.

Based on the results, the regression equation of the expanded uncertainty(y) versus PM-10 concentration(x) was formulated as shown in Equation 21. The data was well fitted with a second-order regression line.

$$y = 0.00007x^2 + 0.073x + 0.36 \quad (\mu\text{g}/\text{m}^3) \quad \text{Eq. 21}$$

IV. CONCLUSION

We developed a real-time particulate matter(PM-10) and its uncertainty monitoring instrument assisted by beta-ray absorption method and tele-measuring system. According to the GUM, operational procedure of uncertainty in the instrument included 4 steps; at first, establishment of a model equation of PM concentration, at second, calculation of each standard uncertainty, at third, calculation of combined standard uncertainty, and at fourth, expanded uncertainty of 95% confidence level. Uncertainty factors in the process included repeatability of beta-ray intensity ratio, uncertainty of temperature, pressure and flow measurements, uncertainty of attenuation coefficient, uncertainty of sampling area, equivalence evaluation with direct weighting measurement value after air sampling, and sensitivity drift of standard film.

We tested the developed instrument and the PM concentration and its uncertainty values were collected at Gwanpyeong-dong, Daejeon during Nov. 2023. Through this field application, expanded uncertainties at 720 data points of PM concentration were obtained. At the low level of PM concentration, $22.2 \mu\text{g}/\text{m}^3$, the expanded uncertainty value was $2.0 \mu\text{g}/\text{m}^3$ at the 95 % confidence level, while at the high level of PM concentration, $118.6 \mu\text{g}/\text{m}^3$, it was $9.8 \mu\text{g}/\text{m}^3$. The expanded uncertainty values were also well fitted with a second-order regression equation, y

$= 0.00007 x^2 + 0.073 x + 0.36 \quad (\mu\text{g}/\text{m}^3)$. In comparison with each uncertainty variance, it was revealed that the most important uncertainty source is the uncertainty quantified by equivalence evaluation between the PM concentration values obtained by beta-ray absorption method and direct weighing method. And the contribution rate of this uncertainty was 32% of total uncertainty.

We have studied real-time uncertainty evaluation of PM-10 measurement in ambient air assisted by tele-measuring instrument. As a conclusion, it has revealed that the developed instrument has successfully managed to calculate and display real-time measurement uncertainty with various uncertainty source budgeting data.

ACKNOWLEDGMENT

All authors extend their sincere gratitude to Korea Standard Technology(KOSTEC), Republic of Korea, for their generous support throughout this research. We appreciate CEO Lee Jae-yong's unwavering support, which has been instrumental in bringing this research to its conclusion. Lastly, we would like to express our thanks to all the researchers for their encouragement and support.

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