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# Measurement and Analysis of $PM_{10}$ and $PM_{2.5}$ from Chimneys of Coal-fired Power Plants Using a Light Scattering Method

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## ABSTRACT

Aerial pollutants emitted from the stacks of coal-fired power plants are considered a major source of fine particulate matter released into the atmosphere. To manage fine and coarse particles in the stacks themselves, it is necessary to know the concentration of fine and coarse particles emitted in real time; the current system to do so is tedious. In this study, a system for measuring $PM_{2.5}$ and $PM_{10}$ emitted from the stacks of power plants in real-time was developed, and measurements were performed on six coal-fired power plants. Through these measurements, the mass concentration distribution, according to particle sizes, could be determined. All six stacks showed bimodal distribution, and the count median diameters of each mode were 0.5 µm and 1.1 µm. Additionally, data were compared using the gravimetric measurement method; it was found that the relative accuracies for the measured $PM_{10}$ amounts were within 20% and that the values obtained using the measuring instrument proposed in this study were reliable. Three power plants were continuously measured for one month, and by comparing $PM_{10}$ concentration according to the amount of power generated, it was confirmed that $PM_{10}$ discharged from the stack increased as an exponential function, depending on the amount of power generated.

**Keywords:** Dilutor, Optical particle counter, Coal-fired power plant, Power generation, $PM_{10}$

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## 1 INTRODUCTION

With the rapid development of industrial facilities, public concern continues to rise about particulates in air. Particulates air pollutants are emitted from coal-fired power plants and industrial facilities (Lee *et al.*, 2011; Kim *et al.*, 2016) as well as from the combustion of gases in diesel engines from urban areas (Groves and Cain, 2000; Lewis *et al.*, 1989) and heating systems (Fernandes and Costa, 2012). Research on technologies to reduce the amount of exhaust gas has confirmed that methods such as limiting power generation when $PM_{2.5}$ and $PM_{10}$ are generated at high concentrations (Lee, 2020) and reducing the amount of exhaust gas through repowering technology (Baek *et al.*, 2019) are effective in reducing the concentrations of emitted $PM_{2.5}$ and $PM_{10}$. If information on $PM_{2.5}$ and $PM_{10}$ emitted from the stacks of coal-fired power plants can be obtained in real time, their management can become easy; such information will help monitor the concentrations of $PM_{2.5}$ and $PM_{10}$ emitted in exhaust gas after a treatment device has been used.

Currently, there are two methods for measuring particles in combustion facilities: the gravimetric method and the light transmission method. The gravimetric method involves the EPA Method 201A (U.S. EPA, 1996; Goodarzi and Sanei, 2009), in which $PM_{2.5}$ and $PM_{10}$ are measured using a cyclone method, and the ISO23210 method (ISO-23210, 2009; Wada *et al.*, 2016), which measures $PM_{10}$ and $PM_{2.5}$, using a multi-stage impactor. The gravimetric method is the standard method for measuring aerosol particles, as it directly measures their mass. However, each measurement requires a long time, and information about changes in concentration during that time is lost. It is difficult to measure concentrations continuously, because it takes several days to obtain each set of data.

Park *et al.* (2018) and Kim *et al.* (2017) recommended the use of EPA and ISO methods for measuring $PM_{2.5}$ and $PM_{10}$ concentrations in coal-fired power plants, but neither method reflects changes in the concentrations of $PM_{2.5}$ and $PM_{10}$ according to the power generation output.

The light transmission method measures the concentration of particles by transmitting light from one side of the stack and measuring the degree of change in the intensity of incident light on the other side (Moteki *et al.*, 2019). Continuous measurement is possible using the light transmission method, but it only measures the total mass concentration of particles. Particle sizes cannot be identified in this method, so the concentration of $PM_{10}$ and $PM_{2.5}$ cannot be determined.

In this study, a dilution device (Shin *et al.*, 2019) was developed to measure $PM_{10}$ and $PM_{2.5}$ in a stack of coal-fired power plants in a high-temperature and high-humidity environment. Light scattering equipment was used to measure the emissions discharged from the stacks of six coal-fired power plants. The concentrations of $PM_{2.5}$ and $PM_{10}$, were measured in real time. Using these measurements, the mass concentration distribution was compared according to particle size for each power plant. These measurements were compared with $PM_{2.5}$ and $PM_{10}$ concentrations obtained using the gravimetric method to determine relative accuracy of the proposed method. Finally, by comparing the $PM_{10}$ concentrations to the amount of power generated by each power plant, the relationship between $PM_{10}$ concentration, as measured from the stack using the proposed method, and the amount of power generated was deciphered.

## 2 METHODS

Fig. 1 shows a schematic of the particle concentration measurements obtained from the stack of each coal-fired power plant using the gravimetric equipment and the developed measuring device. In the case of coal-fired power plant stacks, it is not possible to directly use instruments for measuring $PM_{2.5}$ and $PM_{10}$ in the atmosphere because of the high temperatures, high humidity, and high wind speed. When the air inside the stack is released into the atmosphere, particle condensation occurs owing to a rapid drop in temperature, and if the isokinetic sampling is not satisfied owing to the rapid flow velocity changes, the concentrations may be mismeasured for relatively large particles (Dennis *et al.*, 1957). To prevent the aforementioned problems and to accurately measure the concentration of $PM_{2.5}$ and $PM_{10}$, the particles in the stack were sampled through a two-stage dilution device with an ejector. Primary dilution air was supplied through the ejector, and secondary dilution air was supplied through the porous tube. Compressed air was generated by a compressor (NCP052-T50; Air Maker, Korea) and was then supplied to the ejector. During this process, an air dryer (SHD-10, SEHAN Dryer Co., Ltd., Korea) and high-efficiency particulate air (HEPA) filters were installed to supply clean dry air. The secondary dilution air supplied to the porous tube does not require high pressure, hence a ring blower (KJB3-400, Kijeonsa, Korea) with relatively low power consumption and a HEPA filter were used to supply it. A control panel based on a separate programmable logic controller (PLC) was manufactured to control the flow rate and temperature. Particulate concentration was measured in real time using a light scattering particle counter (OPC, 1.109, Grimm, Germany) (Shin *et al.*, 2020).

For gravimetric measurements, the EPA 201A method (hereinafter referred to as EPA) and the ISO-23210 method (hereinafter referred to as ISO) were used. Both methods differ only in the method of separating particles; their mass measurement methods through isokinetic sampling, dry air intake flow rate, and particle collection remain the same. The dry air inside the stack was sampled using an air pump, and the particles were separated by size in the particulate matter (PM) sizer, and particles were collected using a filter holder. In the EPA method, the cyclone method is used for particle size separation, and in this study, only the $PM_{10}$ cyclone was installed for measurement owing to the size of the stack sampling aperture. The ISO method uses a multi-stage impactor method to separate particle sizes and can know the concentration of $PM_{2.5}$ and $PM_{10}$ at the same time. The mass of the particles collected in the filter was measured using a weighing scale, and the volume of dry air sucked from the air pump was measured and converted into mass concentration.

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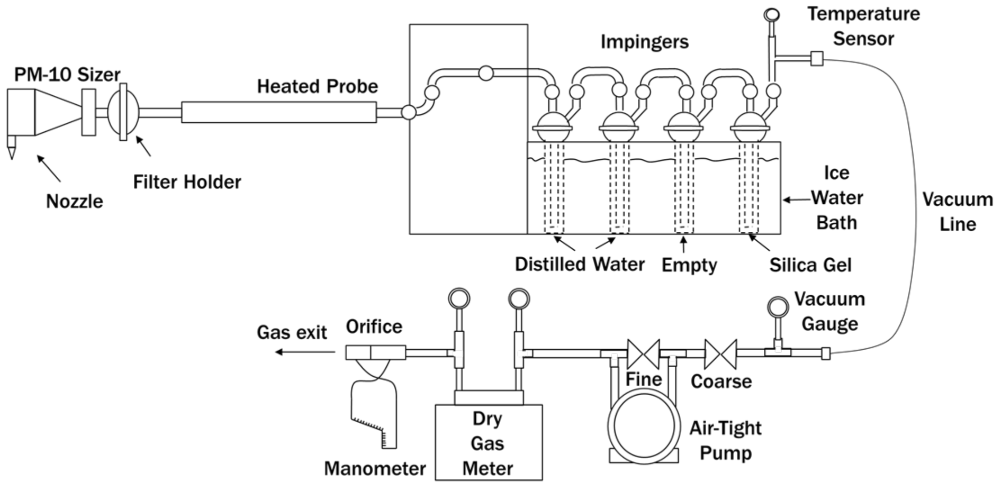
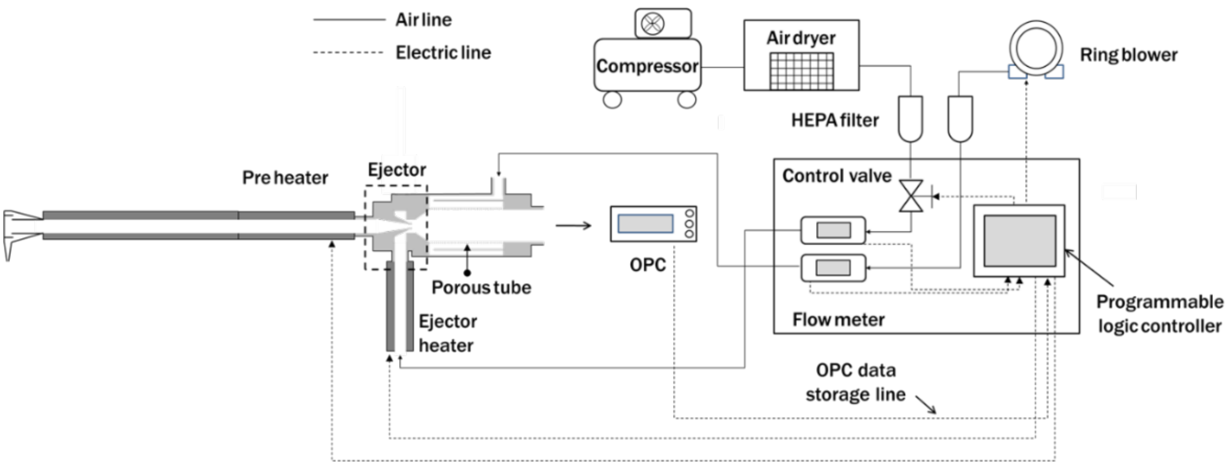
(a)




(b)




In this study, particles were measured from stacks of six coal-fired power plants located in different regions of Korea. Table 1 shows the characteristics of the stacks of coal-fired power plants that were measured. All six power plants used bituminous coal. Power plants D and E had the largest capacity at 1000 MW, power plant B had 870 MW, and power plants A, C, and F had capacities of 500 MW each. The temperature inside the stack was 80–100°C for A, B, C, D, and F and 146°C for E, which was higher than that of the other power plant stacks; this is because in A, B, C, D, and F, the exhaust gas from the boiler passed through the stack through a catalytic reduction device (selective catalyst reactor; SCR) (Stolle *et al.*, 2014), an electrostatic precipitator (electrostatic precipitator, ESP) (Meij and Winkel, 2004), and a wet desulfurization device (wet flue gas desulfurization; wet-FGD) (Córdoba, 2015). The exhaust gas from E was discharged to the atmosphere, and E is not installed with a separate desulfurization and denitrification facility using a circulating fluidized bed boiler. In this power plant, during combustion, a desulfurization agent and a denitrification agent are injected directly into the boiler to treat nitrogen oxides and sulfur oxides simultaneously, and the ESP is only installed at the rear end of the boiler; this is because particles are removed and then discharged into the atmosphere through a stack (Basu, 1999).

In this study, the distribution of mass concentration according to particle diameter measured in real time using OPC in each power plant stack was analyzed. The mass median diameter (MMD), geometric standard deviation (GSD), and count median diameter (CMD) were calculated

**Table 1.** Measurement for coal-fired power plant stacks.

| Power Plant | Number of Measurements | Type of coal | Installed capacity (MW) | Temperature (°C) |
|---|---|---|---|---|
| A | 7 | Bituminous | 500 | 95 |
| B | 9 | Bituminous | 870 | 89 |
| C | 7 | Bituminous | 500 | 84 |
| D | 7 | Bituminous | 1000 | 82 |
| E | 6 | Bituminous | 1000 | 146 |
| F | 10 | Bituminous | 500 | 87 |

from the mass concentration distribution and were compared for each power plant. MMD was derived by expressing the mass concentration distribution graph as a lognormal size distribution and mass cumulative distribution graph and then determining the particle size at the point where it becomes 50% of the total sum of masses. GSD was calculated using the following Eq. (1):

$$\sigma_g = \frac{d_{84\%}}{d_{50\%}} \tag{1}$$

where, $\sigma_g$ is the GSD, $d_{84\%}$ is the particle size at 84% of the total mass in the mass cumulative distribution, and $d_{50\%}$ is the particle size at the 50% point.

CMD was calculated using the formula below:

$$\mathrm{MMD} = \mathrm{CMD} \times \exp(3 \times \ln^2\sigma_g) \tag{2}$$

An objective comparison was made by showing the relative accuracies of the concentrations of $PM_{2.5}$ and $PM_{10}$, as measured using the gravimetric method (EPA, ISO) and OPC at each power plant. Relative accuracy was calculated using the continuous automatic measurement method (ES01810.1a; Ministry of Environment, 2011) for the particle-stack exhaust gas, as indicated in the air pollution process test standards. It is calculated using the following formula:

$$\text{Relative accuracy (\%)} = \frac{\overline{|d|} + C.I._{95}}{\overline{X}} \times 100 \tag{3}$$

$$C.I._{95} = \frac{t_{,975}}{n\sqrt{(n-1)}}\sqrt{n\left(\sum di^2\right) - \left(\sum di\right)^2} \tag{4}$$

where $\overline{|d|}$ is the mean of the measurement error, $\bar{X}$ is the average mass concentration of particles obtained by the gravimetric method, $C.I._{95}$ is the 95% confidence interval, $di$ is the error of each measurement value, $n$ is the number of measurements, and $t_{,975}$ are the t-values for the probability that the measured value is within 95% of the true value.

## 3 RESULTS AND DISCUSSION

Fig. 2 shows the mass concentration distribution according to particle size, as measured in the six coal-fired power plants. Based on this, mode diameter, MMD, and GSD were derived, and the CMD was calculated using Eq. (2), as shown in Table 2. All power plants, from A to F in Fig. 2, had a bi-modal distribution. To obtain the MMD and GSD for each mode in the bi-modal distribution graph, two modes in the bi-modal distribution must be calculated separately. In this study, the bi-modal distribution of each graph was calculated as the sum of the equations representing two mono-modal distribution graphs using the curve fitting option of MATLAB; the calculated fitting curve for each graph in Fig. 2 was obtained using this method. In this case, the least-squares method was used, which was expressed in the form of a Gaussian function such as (Higham and Higham, 2016):

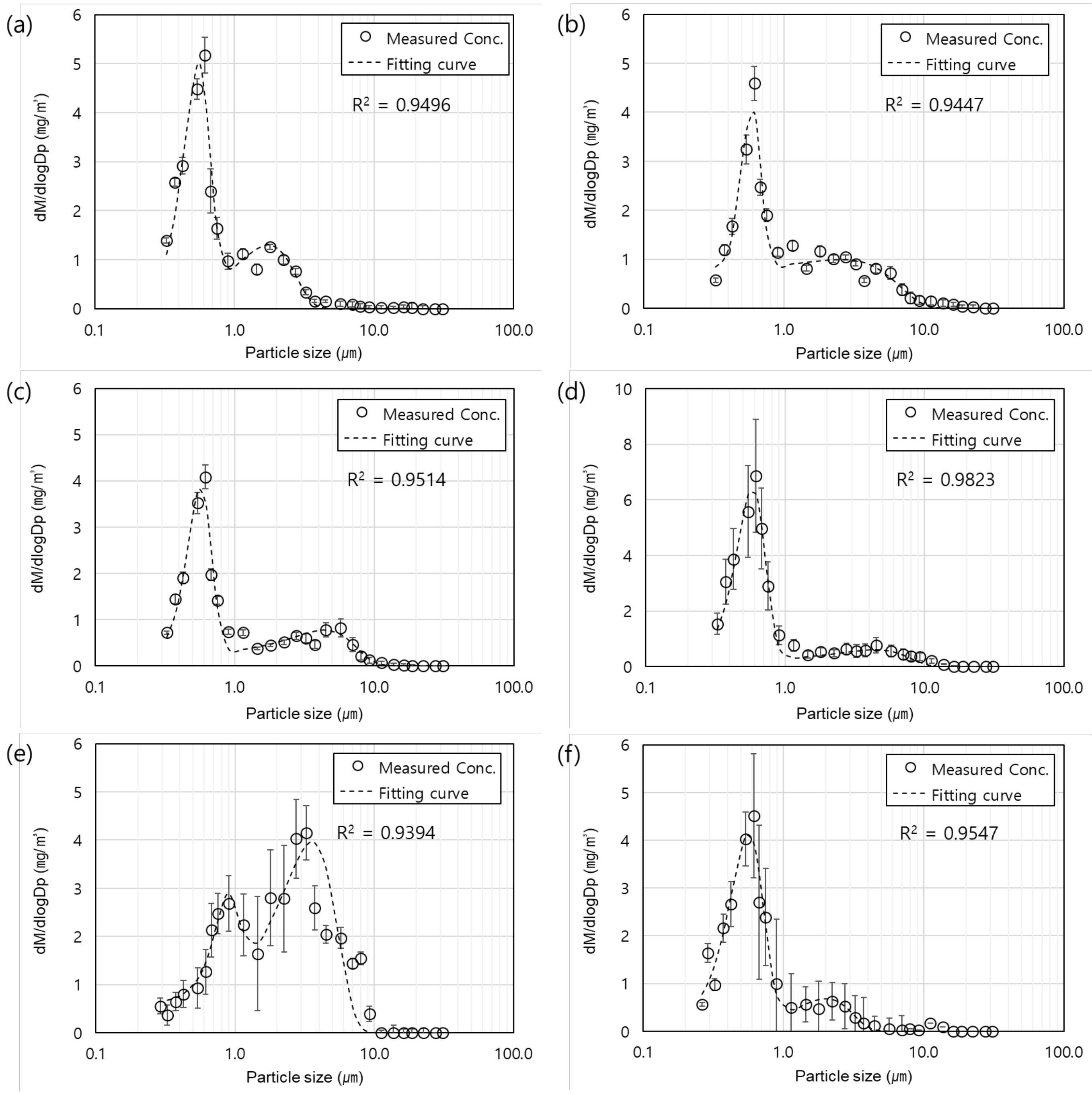



**Fig. 2.** Particle size distributions in mass concentrations for six coal-fired power plant stacks. (a), (b), (c), (d), (e), (f) are from power plant A, B, C, D, E, F, respectively.

$$f(x) = a_1 \exp\left(-\frac{1}{2} \times \frac{(x-b_1)^2}{c_1^2}\right) + a_2 \exp\left(-\frac{1}{2} \times \frac{(x-b_2)^2}{c_2^2}\right) \quad (5)$$

Fig. 2(a) shows the mass concentration distribution according to particle diameters in the stack, obtained using the developed measuring instrument at power plant A. This confirmed that the mass concentration distribution, as shown by the measurement and the fitting curve shown by the calculation, fit well. Power plant A shows a bi-modal distribution with two mode diameters: 0.6 and 1.8 µm. Among them, the total mass concentration of the 0.6 µm mode distribution is 1.8 mg $m^{-3}$, and the total mass concentration of the 1.8 µm mode distribution is 2.1 mg $m^{-3}$

**Table 2.** Mode, MMD, GSD, and CMD for mass concentration distributions from coal-fired power plant stacks.

| | Mode (μm) | MMD (μm) | GSD | CMD (μm) |
|---|---|---|---|---|
| A_1st peak | 0.62 | 0.51 | 1.31 | 0.49 |
| A_2nd peak | 1.80 | 1.15 | 1.60 | 1.01 |
| B_1st peak | 0.62 | 0.48 | 1.22 | 0.47 |
| B_2nd peak | 2.25 | 1.20 | 1.79 | 0.99 |
| C_1st peak | 0.62 | 0.46 | 1.33 | 0.44 |
| C_2nd peak | 4.50 | 1.30 | 1.70 | 1.11 |
| D_1st peak | 0.62 | 0.53 | 1.32 | 0.51 |
| D_2nd peak | 4.50 | 1.61 | 1.80 | 1.32 |
| E_1st peak | 0.90 | 0.55 | 1.25 | 0.53 |
| E_2nd peak | 2.80 | 1.60 | 1.67 | 1.38 |
| F_1st peak | 0.62 | 0.50 | 1.42 | 0.47 |
| F_2nd peak | 2.25 | 1.30 | 1.60 | 1.15 |

generated in the stack of power plant A. Here, the total mass concentration was obtained by summing the mass concentration of particles from 0.25 μm to 10 μm in each modal distribution. The MMD of the 0.6 μm mode is 0.51 μm and its GSD is 1.31. The MMD of the 1.8 μm mode is 1.15 μm and its GSD is 1.6. From this, it can be seen that the CMD is 0.49 and 1.01 μm.

Fig. 2(b) shows the distribution of mass concentration according to the particle size in the stack, as obtained using the developed measuring instrument at power plant B. Similar to power plant A, it shows a bi-modal distribution. Two distributions with mode diameters of 0.6 μm and 2.3 μm, were observed, and the total mass concentrations at each mode diameter distributions were 1.2 and 2.7 mg $m^{-3}$, respectively. The MMD of the 0.6 μm mode is 0.54 μm and the GSD is 1.30; MMD of the 2.3 μm mode is 1.07 μm and the GSD is 1.6. If the MMD of the two modes is converted to CMD, it is 0.52 and 0.95 μm.

Fig. 2(c) shows the mass concentration distribution according to the particle size in the stack, as obtained using the developed measuring instrument at the C power plant. It had a bi-modal distribution with mode diameters of 0.6 μm and 4.5 μm, and the total mass concentrations at the two modal diameter distributions were 1.5 and 1.6 mg $m^{-3}$, respectively. The MMD of the 0.6 μm mode was 0.46 μm and the GSD was 1.33. The MMD of the 4.5 μm mode was 1.3 μm and the GSD was 1.7. If the MMD of the two modes is converted to CMD, it is 0.44 and 1.11 μm.

Fig. 2(d) shows the distribution of mass concentration according to the particle diameter in the stack, as obtained using the developed measuring instrument at power plant D. It showed a bi-modal distribution. Two distributions with mode diameters of 0.6 μm and 4.5 μm were observed, and the total mass concentrations at the two mode diameters were 1.4 and 0.6 mg $m^{-3}$, respectively. The MMD of the 0.6 μm mode was 0.53 μm and the GSD was 1.32; the MMD of the 4.5 μm mode was 1.61 μm while the GSD was 1.80. If the MMD of both modes is converted to CMD, it is 0.51 and 1.32 μm, respectively. During the measurement period, the $PM_{10}$ concentration of power plant D changed significantly from 1 to 5 mg $m^{-3}$, which was significant compared to other power plants. Therefore, it can be seen that the error bars according to each particle size are larger than that of the preceding power plants A, B, and C, and it can be seen that the mass concentration changes in the mode distribution of 0.6 μm among the two modes is large.

Fig. 2(e) shows the distribution of mass concentration according to the particle diameter in the stack, as obtained using the developed measuring instrument at the E power plant. Bi-modal distribution was observed with two mode diameters: 0.9 μm and 2.8 μm. The total mass concentrations at each mode diameter distribution were 0.4 and 2.6 mg $m^{-3}$, respectively. The MMD of the 0.9 μm mode was 0.55 μm and the GSD was 1.30. The MMD of the 2.8 μm mode was 1.49 μm and the GSD was 1.80. If the MMD of the two modes is converted to CMD, it is 0.53 and 1.22 μm. Power plant E shows a bi-modal distribution similar to the other power plants, but unlike other power plants, E shows a much larger mass concentration of particles larger than 1 μm. Power plant E is different from other power plants because its exhaust gas treatment method after the boiler step is different. Unlike power plants A, B, C, D, and F, where FGD exists in front of the stack, in power plant E, the ESP is located in front of the stack. Depending on the presence or absence of FGD, the concentration of particles over 1 µm discharged from the stack may vary. Similar to power plant D, it can be seen that the change in the mass concentration of particles in power plant E is large through the error bar. During the measurement period, the $PM_{10}$ concentration for power plant E changed significantly from 2.5 to 5 mg $m^{-3}$. However, unlike power plant D, the change in the number of particles larger than 1 µm was larger, and it can be judged that the main particles from the stack of power plant E are particles larger than 1 µm.

Fig. 2(f) shows the distribution of mass concentration according to the particle diameter in the stack, as obtained using the developed measuring instrument at the F power plant. Bi-modal distributions with mode diameters of 0.6 µm and 2.3 µm were observed, and the mass concentrations at each modal diameter distribution were 1.1 and 0.4 mg $m^{-3}$, respectively. The MMD of the 0.6 µm mode was 0.50 µm and the GSD was 1.42; MMD of the 2.3 µm mode was 1.3 µm and the GSD was 1.6. If the MMD of both modes is converted to CMD, it is 0.47 and 1.15 µm, respectively.

In all power plants, a bi-modal distribution graph was observed with two modes around 1 µm. The GSD and CMD were almost similar except for the difference in mass concentration for each particle size. Overall, the average GSD of particles less than 1 µm was 1.33, which was smaller than 1.68, the GSD of particles larger than 1 µm, and the CMD was also similar in all power plants at 0.5 and 1.1 µm. The 0.5 µm particles were likely produced due to evaporation and condensation of inorganic substances during coal combustion, and the particles of the 1.1 µm mode are judged to be generated by the granulation of solid particulate matter in coal.

Fig. 3 shows a graph comparing the $PM_{2.5}$ and $PM_{10}$ concentrations measured using the gravimetric method and the developed measuring device at each coal-fired power plant. For each power plant, an average of eight measurements was taken, and a total of 49 measurements were

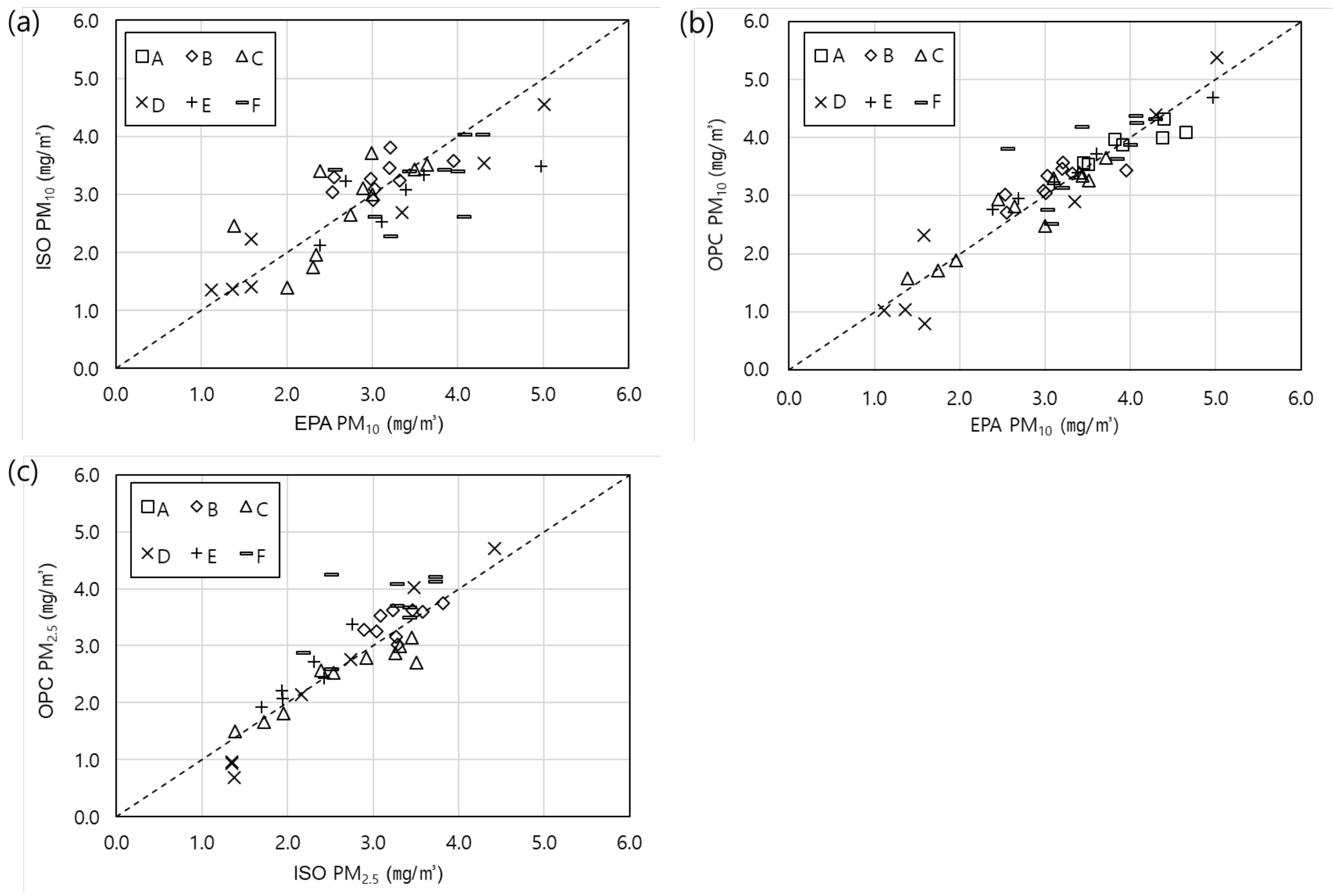



**Fig. 3.** Comparison between OPC PM and gravimetric PM, measured using the EPA and ISO methods, for six coal-fired power plants. (a) is $PM_{10}$ measured using EPA and ISO methods, (b) is $PM_{10}$ measured using EPA and OPC methods, and (c) is $PM_{2.5}$ measured using ISO and OPC methods.

taken. Fig. 3(a) shows a comparison of the $PM_{10}$ concentration using the EPA method 201A method and the concentration measured using the ISO-23210 method. It can be seen that the concentration changes of the EPA and ISO methods are similar for each power plant. By analyzing the relative accuracy of each power plant, power plant B was 16.8%, power plant C 26.8%, power plant D 20.3%, power plant E 24.1%, and power plant F 18.4%. For power plant A, the ISO method cannot be measured. When the relative accuracy is calculated for all power plants, the concentration measured by the EPA method and the concentration measured by the ISO method are similar at 21.3%, so it is judged that the gravimetric measurement results measured in this study are reliable.

Fig. 3(b) shows the comparison results of $PM_{10}$ measured using the EPA method and $PM_{10}$ concentration measured using the developed measuring device. The relative accuracies of power plants A, B, C, D, E, and F were 9.3%, 12.7%, 11.3%, 19.8%, 7.4%, and 17.3%, respectively, and the overall relative accuracy was 13.0%. Overall, the relative accuracy was within 20%, so it can be said that the results measured by the developed measuring device and the results of the gravimetric method are similar. It can be confirmed that the concentration is better than the result of comparing EPA and ISO, because in the case of the gravimetric method, an error is more likely to occur in the process of calculating the concentration after measurement. This is because, for the gravimetric method, particles are directly collected on the filter, which may fall from the filter while going to the scale for measurement after collection. When measuring the scale, measurement errors may occur depending on the surrounding humidity, temperature, and the degree of charge of the filter. If the developed measuring device is used, however, the probability of errors occurring during the measurement process is reduced because it is a method for measuring the concentration directly on site.

Fig. 3(c) shows the result of comparing the $PM_{2.5}$ concentration using the ISO method and the developed measuring device. A wide stack sampling port is required to measure $PM_{2.5}$, using the EPA method. The size of the sampling port of each coal-fired power plant stack measured in this study was 150A (i.e., 165.2 mm), which is impossible to measure; therefore, $PM_{2.5}$, was thus compared with the measurement results of ISO. In Fig. 3(a), it was judged that the $PM_{2.5}$ concentration of ISO was reliable because $PM_{10}$ concentrations of ISO and EPA were similar. For power plants A, B, C, D, E, and F, the relative accuracy of $PM_{2.5}$, compared to ISO, is 15.7%, 15.7%, 18.5%, 17.3%, and 17.8% from power plant B to plant F, respectively, and the overall relative accuracy was 17%. The concentration of $PM_{2.5}$, measured using the developed device, was also judged to be reliable.

Fig. 4 shows the results of comparing the $PM_{10}$ concentration and the amount of power generation measured in real time for one month using the developed meter at power plants D, E, and F. $PM_{10}$ concentration was continuously measured at 1 min intervals, and each data point was averaged over a 30 min period, which was compared to time-dependent power generation data. The power generation of coal-fired power plant D was produced from 780–1100 MWh, and the concentration of $PM_{10}$ emitted from the stack ranged from 1.02–5.93 mg $m^{-3}$. Power plant E

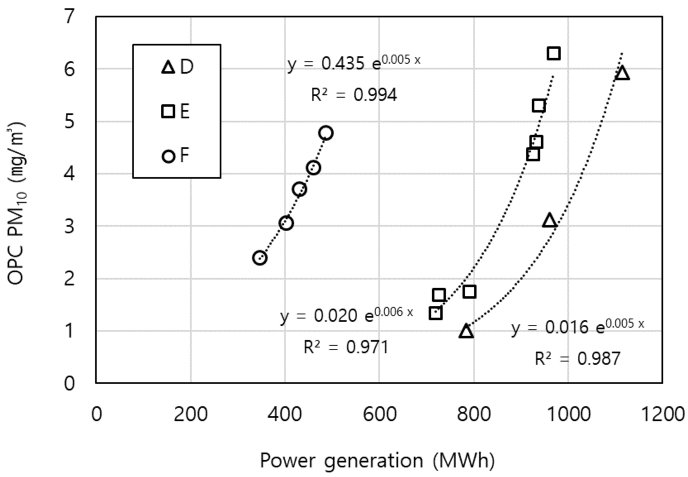



**Fig. 4.** Relation between power generations and OPC $PM_{10}$ continuously measured for 1 month at power plants D, E and F.

produced approximately 720–980 MWh of power, and the concentration of emitted $PM_{10}$ ranged from 1.3–6.3 mg $m^{-3}$. The F power plant produced approximately 340–500 MWh of power, and the concentration of emitted $PM_{10}$ ranged from 2.4–4.8 mg $m^{-3}$. Comparing the generated $PM_{10}$ concentration with respect to the amount of power generation, it can be seen that the $PM_{10}$ generated concentration increases in the order of D, E, and F power plants. The corresponding generator in Power Plant D started operation in 2015, the generator in Power Plant E started operation in 2016, and the generator in Power Plant F started operation in 2009. It is judged that the $PM_{10}$ concentration is higher than the amount of power generation, since the F power plant has the longest operating period. In the case of power plant E, although the year of construction is similar to that of power plant D, the stack is located right behind the electrostatic precipitator, so when the fly ash collected from the electrostatic precipitator falls by periodic rapping, the 2.5–10 µm particles that re-scatter are directly to the stack. Owing to this it is judged that a higher $PM_{10}$ concentration is measured compared to the D power plant, where FGD exists between the electrostatic precipitator and the stack. It can be seen that the $PM_{10}$ relative to the amount of power generation in all three power plants changes according to an exponential function. According to the Air Environment Conservation Act, emission standards have been strengthened since 2020 in Korea. It has an emission limit of 10 mg $m^{-3}$ or less for solid fuel-using power generation facilities of 100 MW or more installed after 2001, and 5 mg $m^{-3}$ or less for facilities installed after 2015. It can be seen that power plant F satisfies the tolerance standards, but power plants D and E do not temporarily satisfy the emission tolerance standards when the load is high.

## 4 CONCLUSIONS

A two-stage dilution device was developed in this study to measure $PM_{2.5}$ and $PM_{10}$ from coal-fired power plant stacks in real time using a light scattering meter. This was used to measure $PM_{2.5}$ and $PM_{10}$ in real time at six coal-fired power plants in Korea. The mass concentration distributions according to the particle size, as obtained by the developed method showed a bimodal distribution. By calculating the CMD, although there was a slight difference, the values obtained from both measuring methods were similar at 0.5 µm and 1.1 µm. Based on the comparison of the developed method with the gravimetric method, the relative accuracies for $PM_{10}$ in the all power plants were within 20%. Finally, continuous long-term measurements were performed; when $PM_{10}$ concentrations were expressed with respect to the change in the amount of power generated, it was confirmed that the concentration of $PM_{10}$ increased exponentially along with the amount of power generated in the D, E, and F power plants.

This study proves that it is possible to continuously measure $PM_{2.5}$ and $PM_{10}$ concentrations in the stack of a thermal power plant using the developed dilution device. It is expected that a large amount of information can be obtained for the operation and management of environmental facilities by checking the characteristics of fine and coarse particles emitted from the stack through real-time measurement.

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## REFERENCES

Baek, S., Jang, J., Kim, Y. (2019). A study on repowering of 500 MW standard coal-fired power plant for performance improvement and emission reduction. J. Korean Soc. Comb. 24, 37–44. https://doi.org/10.15231/jksc.2019.24.4.037

Basu, P. (1999). Combustion of coal in circulating fluidized-bed boilers: A review. Chem. Eng. Sci. 54, 5547–5557. https://doi.org/10.1016/S0009-2509(99)00285-7

Córdoba, P. (2015). Status of flue gas desulphurisation (FGD) systems from coal-fired power plants: Overview of the physic-chemical control processes of wet limestone FGDs. Fuel 144, 274–286. https://doi.org/10.1016/j.fuel.2014.12.065

Fernandes, U., Costa, M. (2012). Particle emissions from a domestic pellets-fired boiler. Fuel Process. Technol. 103, 51–56. https://doi.org/10.1016/j.fuproc.2011.08.020

Goodarzi, F., Sanei, H. (2009). Plerosphere and its role in reduction of emitted fine fly ash particles from pulverized coal-fired power plants. Fuel 88, 382–386. https://doi.org/10.1016/j.fuel.2008.08.015

Groves, J., Cain, J.R. (2000). A survey of exposure to diesel engine exhaust emissions in the workplace. Ann. Occup. Hyg. 44, 435–447. https://doi.org/10.1093/annhyg/44.6.435

Higham, D.J., Higham, N.J. (2016). MATLAB guide (3rd ed.), Society for Industrial and Applied Mathematics, Philadelphia. 177.

ISO 23210 (2009). Stationary source emissions determination of $PM_{10}$/$PM_{2.5}$ mass concentration in flue gas measurement at low concentrations by use of impactors. https://www.iso.org/standard/53379.html

Kim, H.B., Kim, D.S., Youn, J.S., Han, S., Jeon, Y.W., Jeon, K.J. (2017). Comparison of measurement methods and size fraction of fine particles ($PM_{10}$, $PM_{2.5}$) from stationary emission source using Korean standard and ISO: Coal power plant and refinery. J. Korean Soc. Atmos. Environ. 33, 342–350. https://doi.org/10.5572/KOSAE.2017.33.4.342

Kim, H.C., Kim, S., Son, S.W., Lee, P., Jin, C.S., Kim, E., Kim, B.U., Ngan, F., Bae, C., Song, C.K., Stein, A. (2016). Synoptic perspectives on pollutant transport patterns observed by satellites over East Asia: Case studies with a conceptual model. Atmos. Chem. Phys. Discuss. 1–30. https://doi.org/10.5194/acp-2016-673

Lee, H. (2020). 5 Power Generation Companies, "We will reduce fine dust with the best possible": Suspension of coal-fired power plants and promotion of upper limit restrictions… Reduction of 2,108 tons of fine dust emissions compared to the previous year 5 power generation companies, investment in eco-friendly facilities and promotion of indoor storage of outdoor storage facilities. J. Electr. World. 5, 38–40.

Lee, S., Ho, C.H., Choi, Y.S. (2011). High-$PM_{10}$ concentration episodes in Seoul, Korea: Background sources and related meteorological conditions. Atmos. Environ. 45, 7240–7247. https://doi.org/10.1016/j.atmosenv.2011.08.071

Lewis, T.R., Green, F.H., Moorman, W.J., Burg, J.A., Lynch, D.W. (1989). A chronic inhalation toxicity study of diesel engine emissions and coal dust, alone and combined. J. Am. Coll. Toxicol. 8, 345–75. https://doi.org/10.3109/10915818909019560

Meij, R., Winkel, B. (2004). The emissions and environmental impact of $PM_{10}$ and trace elements from a modern coal-fired power plant equipped with ESP and wet FGD. Fuel Process. Technol. 85, 641–656. https://doi.org/10.1016/j.fuproc.2003.11.012

Ministry of Environment (2011). Particulate matter-automated measuring method in flue gas, Air Pollution Process Test Standard, ES01810.1a.

Nobuhiro, M., Yutaka, K., Tomoki, N., Kazuyuki, K., Lokesh, K.S., Takuya, I., Takeshi, K., Yutaka M. (2010). Radiative transfer modeling of filter-based measurements of light absorption by particles: Importance of particle size dependent penetration depth. J. Aerosol. Sci. 41, 401–412. https://doi.org/10.1016/j.jaerosci.2010.02.002

Park, H.S., Lee, D.A., Yang, J.G., Jang, S.G. (2018). Emission characteristics of $PM_{10}$ and $PM_{2.5}$ in thermal power plants using different fuel types. J. Korean Soc. Atmos. Environ. 34, 534–541. https://doi.org/10.5572/KOSAE.2018.34.4.534

Richard, D., William, R.S., David, M.A., Leslie S. (1957). Isokientic sampling probes. Ind. Eng. Chem. 49, 294–302.

Shin, D., Woo, C.G., Hong, K.J., Kim, H.J., Kim, Y.J., Lee, G.Y., Chun, S.N., Hwang, J., Han, B. (2019). Development of a new dilution system for continuous measurement of particle concentration in the exhaust from a coal-fired power plant. Fuel 257, 116045. https://doi.org/10.1016/j.fuel.2019.116045

Shin, D., Woo, C.G., Hong, K.J., Kim, H.J., Kim, Y.J., Han, B., Hwang, J., Lee, G.Y., Chun, S.N. (2020). Continuous measurement of $PM_{10}$ and $PM_{2.5}$ concentration in coal-fired power plant stacks using a newly developed diluter and optical particle counter. Fuel 269, 117445. https://doi.org/10.1016/j.fuel.2020.117445

Stolle, R., Koeser, H., Gutberlet, H. (2014). Oxidation and reduction of mercury by SCR $DeNO_x$

catalysts under flue gas conditions in coal fired power plants. Appl. Catal. B. 144, 486–497. https://doi.org/10.1016/j.apcatb.2013.07.040

U.S. Environmental Protection Agency (U.S. EPA) (1996). Air quality for particulate matter, National Center for Environmental Assessment, Office of Research and Development, Research Triangle Park. NC, Report No: EPA/600/p-95/001CF.

Wada, M., Tsukada, M., Namiki, N., Szymanski, W.W., Noda, N., Makino, H., Kanaoka, C., Kamiya, H. (2016). A two-stage virtual impactor for in-stack sampling of $PM_{2.5}$ and $PM_{10}$ in flue gas of stationary sources. Aerosol Air Qual. Res. 16, 36–45. https://doi.org/10.4209/aaqr.2015.06.0383