Open Access

Vol. 15, No. 3, 2021104, September 2021
doi: https://doi.org/10.5572/ajae.2021.104
ISSN (Online) 2287-1160, ISSN (Print) 1976-6912

Technical Information

Comparison of PM_{total}, PM_{10}, $PM_{2.5}$, NOx, and SO_2 Emission Factors from Coal-fired Power Plants per Load Change

JeongHun Yu, Jihan Song1), DoYoung Lee, MyeongSang Yu, JongHan Jung1), Sung-Nam Chun2), GaYoung Lee2), JongHo Kim3),*

Department of Environmental Engineering, Graduate School of Hanseo University, Seosan, Republic of Korea
1)Environmental Research Center, Hanseo University, Seosan, Republic of Korea
2)Clean Power Generation Laboratory, Korea Electric Power Research Institute, Daejeon, Republic of Korea
3)Department of Infra-System (Environment Engineering), Hanseo University, Seosan, Republic of Korea

***Corresponding author.**
Tel: +82-41-660-1431
E-mail: kimjh@hanseo.ac.kr

Received: 29 August 2021
Revised: 9 September 2021
Accepted: 10 September 2021

ABSTRACT For two bituminous coal-fired power plants with 500 MW and pulverized coal combustion type, the concentration of PM_{total}, $>PM_{10}$, $PM_{2.5-10}$, $PM_{2.5}$, NOx, and SO_2 was measured, and their emission factors were calculated through field measurement. The measurement points started from the boiler downstream and continued to the air pollution control devices (APCDs) that are installed in series, namely, the selected catalytic reduction system (SCR), air preheater (APH), electrostatic precipitator (ESP) and wet flue gas desulfurization system (WFGD). The measurement was performed at one point for more than three times by using the Korean standard method for air pollutants. However, all measurement points, except for the stacks, were not representative of the standard test method. In addition, the PM concentration was too high to reduce the collection time due to isokinetic sampling. There is a limitation of how representative the measurement results can be. During the field measurement period, the power production rate of the two coal-fired power plants was 91.6% and 79.2% in the P-1 and P-2, respectively. Moreover, in the P-2, with a low power production rate, the concentration of PM_{total}, PM_{10}, $PM_{2.5}$, and NOx was found to be low, and the emission factor calculated by dividing the measured concentration value by the fuel usage was also estimated to be low. Such results are due to the coal combustion chamber and various types of APCD being operated at a lower-load condition than the design capacity. In turn, the number of pollutants generated was less, and the removal efficiency of the pollutant became high. However, it was found that the concentration of SO_2 generated and the emission factor are more significantly affected by the sulfur content of the coal than the load factor change. To this end, reducing the operation load of the coal-fired power plant improves the combustion efficiency and APCDs performance and decreases the emission factor, resulting in more reduction of the air pollutants than that based on the simple calculation.

KEY WORDS Coal-fired power plant, Emission factor, Air pollution control devices, Particle size distribution, Upper limit restrictions

1. INTRODUCTION

The concentration of fine particulate matter (PM) is increasing, and in particular, the number of days in which high-concentration fine particulate matter occurred is also increasing (Wu *et al.*, 2020; EEA, 2019). Fine particulate matter has an adverse effect on human health and visibility of the atmosphere and also induces climate change (Watts *et al.*, 2015).

The ambient air quality standards for $PM_{2.5}$ were strengthened in 2018 to 35 $\mu g/m^3$ (daily average) and 15 $\mu g/m^3$ (annual average) in Korea. To satisfy ambient air quality standards, governments, businesses, and the private sector are making air quality changes (Kim *et al.*, 2017). It is important to identify the air pollution sources to effectively manage air quality (Ma and Gang, 2019; Han *et al.*, 2018). Air quality management strategies are forced to focus on high emissions as a priority.

The capacity of the coal-fired power plants in South Korea is 34.7 GW (as of 2019) from 60 power production facilities, and approximately 98% of them use bituminous coal as fuel. The largest number of coal-fired power plants has a 500 MW class capacity (35 units). Recently, the six coal-fired power plants with a capacity of 1000 MW have been constructed. There are two main types of combustion for coal-fired power plants in Korea. One is the use of a pulverized coal combustion (PC) boiler, in which coal of 3 mm or less is mixed with air and injected into a combustion chamber. Another is the circulating fluidized bed combustion (CFBC) boiler, which burns by circulating particles (sand and limestone) and coal in the combustion chamber. Most coal-fired power plants use PC combustion systems in Korea.

The air pollutants emitted from the coal-fired power plants are PM, SOx, and NOx alongside hazardous air pollutants such as Hg and As. These air pollutants are removed by installing various types of air pollution control devices, and the most highly used air pollution prevention system in coal-fired power plants in Korea is the selected catalytic reduction (SCR) - electrostatic precipitator (ESP) - wet flue gas desulfurization (WFGD). The selected catalytic reduction is able to remove NOx. Furthermore, the low-NOx combustion burner is installed for suppressing the generation of NOx from the combustion process. The electrostatic precipitator removes PM and heavy metals. The wet flue gas desulfurization system is able to remove SOx, HCl, HF, and PM (Liang *et al.*, 2020; IPPC, 2017; Saarnio, 2014).

In this study, when two coal-fired power plants with the same capacity and the same APCDs are installed to operate at different power production rates, the concentration of PM (PM_{total}, $>PM_{10}$, $PM_{2.5\text{-}10}$, $PM_{2.5}$), NOx, and SO_2 in the air pollution prevention device installed based on the combustion exhaust gas flow was measured, and their emission factors were calculated and compared.

2. EXPERIMENTAL

2. 1 Facility

For the measurement targets, two PC type coal-fired power plants with the capacity of 500 MW were selected, which are the type and capacities that are used the most in the domestic coal-fired power plants. Based on the exhaust gas flow, the measurement was conducted at five points, as presented in Fig. 1. Specifically, the measure-

Table 1. Description of coal-fired power plant.

Item		Speciation
Generation facility	Capacity	500 MW
	Type	Pulverized coal combustion boiler, Low-NOx burner
	Fuel	Bituminous, biomass
APCD	SCR	V_2O_5-WO_3/TiO_2 catalyzer, Plate type, NH_3 reagent
	APH	Rotary regenerative heat exchanger
	ESP	5-field Dry ESP
	WFGD	Wet limestone-gypsum absorber

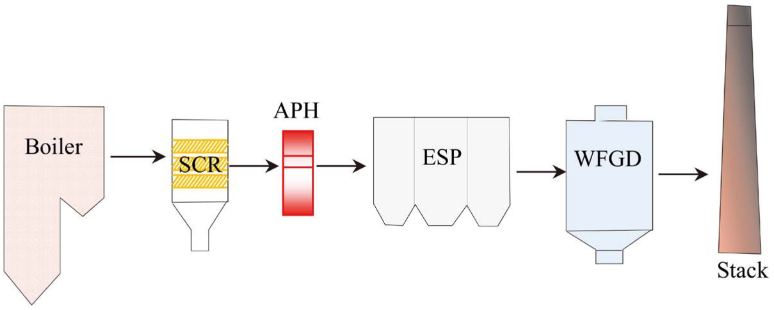


Fig. 1. Measurement points of the coal-fired power plant.

ment was carried out at the SCR for De-NOx, an electrostatic precipitator that removes particulate matter; air preheater (APH) that reduces the temperature of the electrostatic precipitator; and the WFGD. Table 1 and Fig. 1 show a simple summary of the descriptions of the measurement target coal-fired power plants and the measurement points.

2. 2 Test Method

The measurement items are particulate matter, sulfur oxides, and nitrogen oxides. For the particulate matter, the concentration of total particulate matter (PM_{total}) and particulate matter of different sizes ($PM_{2.5}$, $PM_{2.5\text{-}10}$, PM_{10} or more) was measured. The measurement equipment of the ES 01301.1 method (NIER, 2014) was used to measure the concentration of the total particulate matter, while the measurement equipment of the KS ISO 23210 method (KATS, 2012) was utilized to measure the concentration of the particulate matter with different sizes. For the field measurement, the PM sampler and cascade impactor were placed at the same point and conducted the measurement at the same time. The PM_{total} was calculated based on the values measured with the PM sampler, the $PM_{2.5}/PM_{total}$ and PM_{10}/PM_{total} ratios were calculated based on the concentration values obtained using the cascade impactor. The PM_{10} and $PM_{2.5}$ concentrations were estimated by applying these ratios to the total particulate matter concentration. The measurement equipment for each item is tabulated in Table 2. The measurement at each point could not be performed simultaneously for various reasons (multiple PM samplers and manpower required), and hence, it was conducted for the same facility for 1–3 days and repeated more than three times for each point.

The field measurement conducted in this study has limitations. In the boiler, SCR system, and APH points except for the stack, there were some points where the regulation of test methods for sampling of flue gas (ES 01114) could not be followed, i.e., where the fluid flow was unstable, according to the circumstances of the field. However, we measured the fluid velocity and static pressure using the pitot tube, selected the most stable point, and collected the sample in the field. Moreover, because the particulate matter concentration was high in the boiler, SCR system, and APH measurement points, the flow was lowered for the isokinetic sampling, and the sample collection time was shortened. Therefore, there is a possibility of issues regarding the representativeness of the measurement results.

3. RESULTS AND DISCUSSION

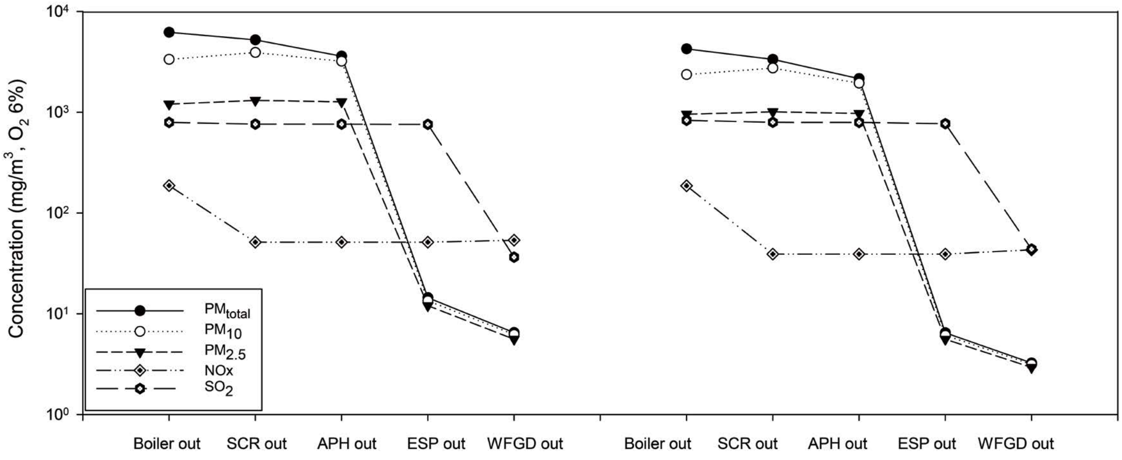
3. 1 Concentration of Air Pollutants

The measurement results of the PM (PM_{total}, PM_{10}, $PM_{2.5}$), NOx, and SO_2 concentrations for each coal-fired power plant and measurement point are presented in Fig. 2. The concentration of PM_{total} generated at the boiler was 6,223.1 ± 147.5 mg/Sm^3 and 4,252.9 ± 403.8 mg/Sm^3 in the P-1 and P-2 facilities, respectively. After passing through the SCR, APH, ESP, and WFGD, it decreased to 5,233.5 ± 63.1 mg/Sm^3, 3,611.1 ± 379.3 mg/Sm^3, 14.4 ± 0.8 mg/Sm^3, and 6.5 ± 0.2 mg/Sm^3 in the P-1 facility and to 3,351.4 ± 401.0 mg/Sm^3, 2,158.3 ± 147.1 mg/Sm^3, 6.5 ± 0.6 mg/Sm^3, and 3.2 ± 0.39 mg/Sm^3 in the P-2 facility, respectively. The nitrogen oxide concentration in the boiler and stack was 187.2 mg/Sm^3 and 53.9 mg/Sm^3 in the P-1 facility and 186.9 mg/Sm^3 and 43.0 mg/Sm^3 in the P-2 facility, respectively. The sulfur dioxide concentration in the boiler and stack was reduced to 794.3 mg/Sm^3 and 36.5 mg/Sm^3 in the P-1 facility and 833.7 mg/Sm^3 and 43.9 mg/Sm^3 in the P-2 facility, respectively. Here, the concentrations were converted to the oxygen concentration 6% condition. Except for the sulfur oxide concentration, the concentration of the PM (PM_{total}, PM_{10}, $PM_{2.5}$) and NOx was found to be lower in the P-2 facility than in the P-1 facility.

The removal efficiency of the air pollution systems is shown in Table 3. The final removal efficiency of the air pollutants, namely PM_{total}, PM_{10}, $PM_{2.5}$, NOx, and SO_2 when they passed through the APCDs and were emitted to the outside of the stack was found to be 99.91%, 99.76%, 99.67%, 74.11%, and 95.47%, respectively, which

Table 2. Measuring equipment.

Item	Method	Instrument
> PM_{10}, $PM_{2.5\text{-}10}$, $PM_{2.5}$	KS I ISO 23210	2-stage cascade impactor (Stage-X MS, X Ear Pro, Italy)
PM_{total}	ES 01301.1	PM sampler (KNJ-5, KNJ, Korea)
SO_2, NOx, O_2	ES 01204	Gas analyzer (Testo 350k, Testo, Germany)



(a) P-1 (b) P-2

Fig. 2. PM, NOx, and SO_2 concentration in APCDs of flue gas stream.

Table 3. Removal efficiencies of air pollutants in APCDs of flue gas stream.

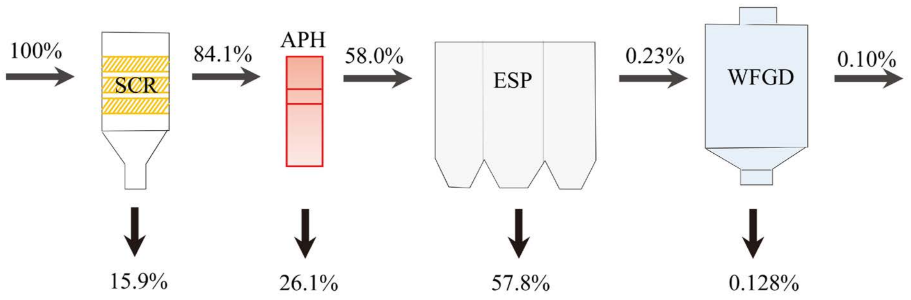
Efficiency (%)		SCR		APH		ESP		WFGD		Stack
		In	Collection	In	Collection	In	Collection	In	Collection	
P-1	$>PM_{10}$	100	28.49	71.51	34.63	36.88	36.85	0.04	0.03	0.01
	$PM_{2.5\text{-}10}$	100	12.97	87.03	27.31	59.71	59.64	0.07	0.04	0.03
	$PM_{2.5}$	100	−8.81	108.81	3.52	105.29	104.30	0.99	0.53	0.46
	NOx	100	72.57	27.43	0.00	27.43	0.00	27.43	−1.35	28.78
	SO_2	100	3.96	96.04	0.00	96.04	0.36	95.68	91.09	4.59
P-2	$>PM_{10}$	100	36.50	63.50	42.77	20.73	20.71	0.02	0.01	0.01
	$PM_{2.5\text{-}10}$	100	19.06	80.94	24.84	56.10	56.06	0.04	0.02	0.01
	$PM_{2.5}$	100	−5.77	105.77	3.82	101.95	101.36	0.58	0.28	0.31
	NOx	100	79.12	20.88	0.00	20.88	0.00	20.88	−2.12	23.00
	SO_2	100	4.39	95.61	0.34	95.27	2.74	92.53	87.27	5.26

were obtained by taking an average of two coal-fired power plants. The removal efficiency of the PM_{total}, PM_{10}, $PM_{2.5}$, and NOx appeared to be higher in the P-2 facility than in the P-1 facility, whereas the SO_2 removal efficiency was higher in the P-1 facility than in the P-2 facility.

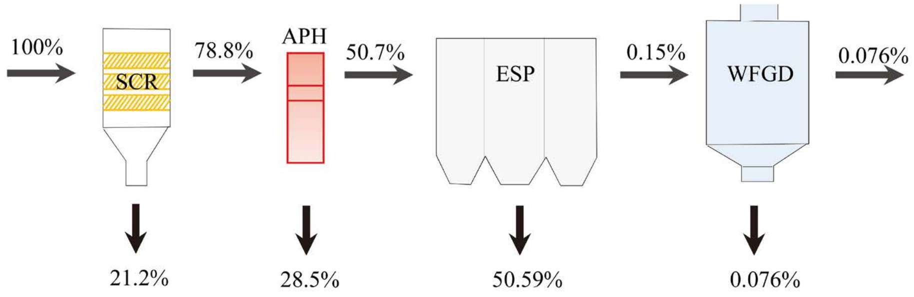
In terms of $PM_{2.5}$, it was found to be generated as it passed through the SCR system, and this suggests that NH_3 sprayed as a reducing agent reacted with SO_2, transformed into either $(NH_4)_2SO_4$ or NH_4HSO_4 particles, and generated fine particulate matter (Ruan *et al.*, 2019; Li, 2017; Shi *et al.*, 2016; Li *et al.*, 2015). The concentration of NOx also increased as it passed through the WFGD system, probably because of the leakage of the exhaust gas since the leakage type Gas-Gas Heater (GGH), i.e., a heat exchanger for adjusting to the adequate operating temperature of the WFGD system for De-SOx, is installed (Seong and Lee, 2017).

Fig. 3 presents the overall particle collection efficiencies for PM_{total} ($>PM_{10}+PM_{2.5\text{-}10}+PM_{2.5}$) at each measurement point. Although there is a slight difference between the P-1 and P-2 facilities, it was identified that the PM_{total} is removed the most in the main collector, ESP. Moreover, it was found that PM_{total} is removed in the SCR system for De-NOx, APH for the heat exchange, and WFGD system for De-SOx, and these results are in good agreement with the results of other studies (Ruan *et al.*, 2019; Sui *et al.*, 2016).

Fig. 4 shows the particle size distribution of the particulate matter at each measurement point. In terms of the size distribution of the particulate matter generated from

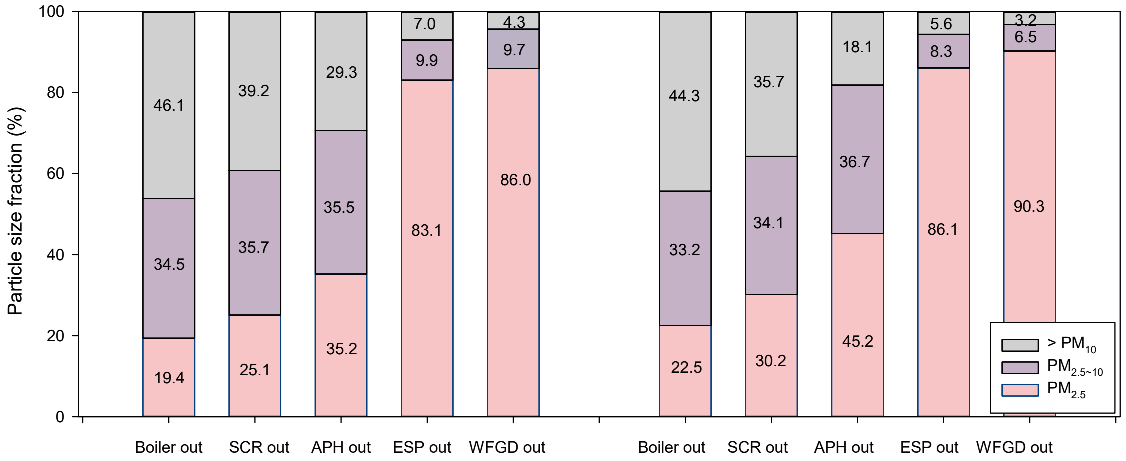


(a) P-1



(b) P-2

Fig. 3. Overall particle collection efficiencies in APCDs of flue gas stream.



(a) P-1 (b) P-2

Fig. 4. Particle size distribution in APCDs of flue gas stream.

the coal combustion, the $PM_{2.5}$, $PM_{2.5\text{-}10}$, and $>PM_{10}$ accounted for 19.4%, 34.5%, and 46.1% in the P-1 facility and 22.5%, 33.2%, and 44.3% in the P-2 facility indicating a similar distribution in two facilities. Although the particulate matter size distribution was similar in the two facilities at the SCR system, APH, ESP, and WFGD system points, $PM_{2.5}$ fraction in the P-1 facility was slightly higher than that in the P-1 facility.

It was identified that the SCR system removes large-sized particulate matter and generates small-sized particulate matter. It was observed that the concentration ratio of $>PM_{10}$ reduces, that of $PM_{2.5\text{-}10}$ does not significantly change, and that of $PM_{2.5}$ increases at the outlet of the SCR system. Such findings suggest that small-sized particulate matter is generated due to the reaction between SO_2 and NH_3, i.e., a reducing agent, and the large-sized particulate matter ($>PM_{10}$) falls into the hopper below the catalyst layer by the soot blower and then is removed (Seo and Chang, 2012).

APH is a heat exchanger for decreasing the temperature of the exhaust gas that passed through the SCR system (340°C) to the adequate operating temperature of the electrostatic precipitator (about 130°C). In general, the specific resistivity of the particulate matter generated from the coal-fired power plant decreases with decreasing temperature of the exhaust gas, and hence, the generation of the back corona is inhibited (Cooper and Alley, 2002). Furthermore, with the decreasing temperature, the volume flowrate decreases, and the residence time within the ESP increases. Therefore, APH plays a role in improving the particle collection efficiency of ESP. However, even in such a heat exchanger, the flow decreases during the process of decreasing the temperature, the effect of gravity increases, and $>PM_{10}$ is removed (Chen *et al.*, 2017). In the measurement results of this study, the removal efficiency of $>PM_{10}$ was found to be 30.7% and 20.1% in the P-1 and P-2 facilities, respectively.

ESP is the main equipment that removes the particulate matter, and it removes 57.8% and 50.69% of the PM_{total} generated during the coal combustion in the P-1 and P-2 facilities, respectively. Furthermore, for $PM_{2.5}$, it removes almost all of the $PM_{2.5}$ generated during the coal combustion along with the one generated while passing through the SCR. The particle collection efficiency for $PM_{2.5}$ was 95.9% and 96.4% in the P-1 and P-2 facilities, respectively.

Although the WFGD system is usually used for DeSOx, the wet-scrubbing technology can generally remove the gaseous substance and particulate matter simultaneously and changes the design and operating conditions depending on the substances to be treated. The particulate matter is removed by the inertial impaction, diffusion, electrostatic attraction, and thermophoresis between the sprayed droplet and particulate matter (Kim *et al.*, 2014; Jaworek *et al.*, 2013; Copper *et al.*, 2002). Based on the measurement results of this study, it was identified that particulate matter is removed, and the removal efficiency for $PM_{2.5}$, $PM_{2.5\text{-}10}$, and $>PM_{10}$ was found to be 53.4%, 55.9%, and 72.4%, in the P-1 facility and 47.5%, 60.8%, and 71.4% in the P-2 facility, which is in line with the results of other studies showing higher removal efficiency for larger particulate matter (Chen *et al.*, 2019; Wu *et al.*, 2019; Li *et al.*, 2017; Sui *et al.*, 2016).

The SCR system installed to remove NOx is located downstream of the boiler, which is a good location to adjust the typical reaction temperature of the catalyst (300–400°C) (Li, 2017). The measurement target SCR of this study consists of three plate-type catalyst layers. The catalyst is composed of V_2O_5, and it is designed to use surface velocity of 3000–4,000 hr^{-1}, and NH_3 as a reducing agent. The NOx concentration was 187.2 mg/Sm^3 and 51.3 mg/Sm^3 at the SCR inlet and outlet in the P-1 facility, respectively, and the removal efficiency was measured as 72.6%. The NOx concentration was 186.9 mg/Sm^3 and 39.0 mg/Sm^3 at the SCR inlet and outlet in the P-2 facility, respectively, and the removal efficiency was measured as 79.1%. These NOx removal efficiencies appeared to be slightly lower than those of the typical SCR system (Sorrels *et al.*, 2019; Li., 2017). The emission limit value of the measurement target coal-fired power plant is 102.7 mg/Sm^3 (@ 6% O_2), and the emitted concentration can conform with the emission limit value, suggesting it is not processed at high efficiency. Furthermore, because the low-NOx burner (LNB) is installed at this measurement facility, the concentration of NOx generated in the boiler is low, leading to a low removal efficiency (Zhang *et al.*, 2021; Ti *et al.*, 2014).

The WFGD system that removes SO_2 is the desulfurization technique that is the most widely used in coal-fired power plants. By spraying the limestone slurry ($CaCO_3$), SO_2 is usually converted to gypsum ($CaSO_4$) and then removed. The SO_2 concentration was 794.3 mg/Sm^3 and 36.5 mg/Sm^3 at the WFGD inlet and outlet in the P-1 facility, respectively, and the removal efficiency was measured as 95.4%. In the P-2 facility, the SO_2 concentration was 833.7 mg/Sm^3 and 43.9 mg/Sm^3 at the WFGD inlet and outlet, and the removal efficiency was measured as 94.7%. In this coal-fired power plant, the heat exchanger for the adequate operating temperature of the WFGD system, which is the leakage-type GGH, is installed upstream of the WFGD, and the leakage rate of GGH is between 3% and 5%. Therefore, the theoretical SO_2 removal efficiency of WFGD would be slightly higher considering the leakage rate.

3.2 Emission Factors

The emission factor of air pollutants is calculated using Eq. (1) (Wu *et al.*, 2020; Jang *et al.*, 2011).

$$\begin{aligned}&\text{Emission factor (kg/ton)}\\&\quad = \text{Concentration (mg/Sm}^3) \times \text{amount of flue gas}\\&\qquad (\text{Sm}^3/\text{hr}) \times 10^{-6}/\text{amount of coal feeding (ton/hr)}\end{aligned} \tag{1}$$

Table 4. Coal usage and contents of ash, sulfur in feed coal during sampling periods.

Power plant	P-1 (500 MW)				P-2 (500 MW)			
	Coal usage (ton/hr)	Load (%)	Ash (%)	Sulfur (%)	Coal usage (ton/hr)	Load (%)	Ash (%)	Sulfur (%)
Day 1	182.75	91.5	14.69	0.36	156.17	79.7	13.82	0.41
Day 2	190.50	91.7	12.03	0.44	153.58	78.8	15.05	0.33
Day 3	187.29	91.5	12.46	0.46	157.46	79.1	10.84	0.35

Table 5. PM, NOx, and SO_2 emission factor (kg/ton of coal) in APCDs of flue gas stream.

Emission factor (kg/ton)		APCD	PM_{total}	PM_{10}	$PM_{2.5}$	NOx	SO_2
This study	P-1 (load: 91.6%)	Uncontrolled (LNB*)	3.310A	1.784A	0.642A	1.46*	17.2S
		SCR	2.784A	2.088A	0.699A	0.63	16.6S
		SCR + APH	1.921A	1.710A	0.676A	0.53	16.6S
		SCR + APH + ESP	0.009A	0.009A	0.008A	0.42	13.2S
		SCR + APH + ESP + WFGD	0.004A	0.0038A	0.0035A	0.41	0.61S
	P-2 (load: 79.2%)	Uncontrolled (LNB*)	2.588A	1.441A	0.582A	1.57*	17.1S
		SCR	2.039A	1.672A	0.616A	0.22	16.3S
		SCR + APH	1.313A	1.183A	0.594A	0.31	16.3S
		SCR + APH + ESP	0.0032A	0.003A	0.0028A	0.39	17.7S
		SCR + APH + ESP + WFGD	0.0023A	0.0022A	0.0020A	0.32	0.94S
NAER (2020)		Uncontrolled	50.00	29.10	10.14	7.50	19.0S
U.S. EPA AP-42 (1998)		Uncontrolled	3.18A	1.18A	0.67A	4.99	17.7S
		ESP	0.025A	0.019A	0.010A	–	–
Wu *et al.* (2018)		Uncontrolled	6.9A	1.5A	0.4A	–	–
		ESP	0.094A	0.065A	0.032A	–	–
		ESP + WFGD	0.023A	0.0210A	0.0147A	–	–

*LNB: low-NOx burner
A: ash S: sulfur

Table 4 shows the information on the coal used in two coal-fired power plants during the measurement period. During this period, the P-1 facility generated 91.6% power, and the P-2 facility operated at 79.2%. During the measurement period of the P-2 facility, the power production rate of the power production facility was maintained at <80% due to the upper limit restrictions operated during the seasonal management system for high-concentration fine particulate matter.

During the measurement period, the power production was kept at a constant level (maximum variance of 0.9%) in the two coal-fired power plants, but the coal consumption was found to change (maximum variance of 4%). This change is because of the calorific value change of the coal, and the calorific value of the coal changes depending on its composition, including carbon, moisture, and ash contents. For the stable operation of the power production facility, constant calorific value and quality of the coal are favorable; however, the calorific value is known to vary in the field. During the measurement period, the change in the ash and sulfur contents of the coal was 10.84–14.69% and 0.33–0.46%, respectively.

Using Eq. (1) and information tabulated in Table 4, the emission factors of PM (PM_{total}, PM_{10}, $PM_{2.5}$), NOx, and SO_2 at each spot of the coal-fired power plant were calculated based on the measurement data for each point and the same coal information data, and the results are presented in Table 5. The particulate matter (PM_{total}, PM_{10}, $PM_{2.5}$) emission factors were lower in the P-2 facility with a lower load factor than in the P-1 facility with a higher load factor. The load factor of the P-2 is 84.4% of that of the P-1, but the emission factors of PM_{total}, PM_{10},

$PM_{2.5}$, and NOx were found to be 56.0%, 56.7%, 58.8%, and 78.0%, respectively, suggesting that the reduction of the PM_{total}, PM_{10}, $PM_{2.5}$, and NOx is more significant than the reduction of the coal consumption. However, although the load factor of SO_2 decreased, its emission factor increased by about 1.5 times.

Under the same operating conditions in the facility with the same capacity, if the coal consumption decreases, the exhaust gas flow (Q) becomes lower than the design value, and as a result, the fluid velocity of the combustion chamber and APCDs reduces and the retention time increases. In general, if the passage velocity decreases and, in turn, retention time increases, the removal efficiency of the SCR, ESP, and WFGD system is improved (Chen *et al.*, 2019).

Therefore, the upper limit restrictions operated during the high-concentration fine dust generation period not only reduces the operating load of the power production facility and air pollutant emissions but also improves the efficiency of APCDs and reduces the dust emission factor. However, in the case of SO_2, it is important to use coal with low sulfur content.

The LNB is installed in the two coal-fired power plants. Although the performance of LNB shows 80% efficiency in the two facilities considering NAER's "uncontrolled" emission factor (7.5 kg/ton) (NAER, 2020), the efficiency of the SCR system was 58.2% and 86.0% in the P-1 and P-2 facilities, respectively, indicating lower emission factor in the facility with a lower load factor.

An SO_2 emission factor is determined by the sulfur content of the fuel. Based on the measurement results, it was identified that the difference due to the different sulfur contents of the coal is more significant than the difference in the emission factor due to the load factor. In particular, the emission factor of the WFGD can be affected by the leakage rate of the GGH.

By comparing the "uncontrolled" emission factor of PM_{total}, PM_{10}, and $PM_{2.5}$ with the existing emission factor, the "uncontrolled" emission factor of PM_{total}, PM_{10}, and $PM_{2.5}$ used nationally is 50 kg/ton, 29.1 kg/ton, and 10.14 kg/ton, respectively. In the research of AP-42 (U.S. EPA) and Zhao *et al.*, it is calculated as a function of the ash content included in coal. The emission factor of PM_{total}, PM_{10}, and $PM_{2.5}$ calculated in this study was similar to that of AP-42 but lower than the PM_{total} emission actor of Zhao *et al.* In terms of the emission factor for each prevention device, the emission factor of ESP and ESP + WFGD appeared to be lower than that of the other studies, namely AP-42 and Zhao et al (Wu *et al.*, 2018; Zhao *et al.*, 2010; U.S EPA, 1998).

4. CONCLUSIONS

For the two bituminous coal-fired power plants with 500 MW and PC, the concentration of PM_{total}, $>PM_{10}$, $PM_{2.5\text{-}10}$, $PM_{2.5}$, NOx, and SO_2 was measured through field measurement, and their emission factors were calculated. The measurement was carried out more than three times in the boiler downstream, SCR system, APH, ESP, and WFGD system (stack) by using the Korean standard test method for air pollutants.

During the field measurement period, the load factor was 91.6% and 79.2% in the P-1 and P-2 coal-fired power plants, respectively, and in the P-2 facility with a lower load factor, the measured concentration of PM_{total}, PM_{10}, $PM_{2.5}$, and NOx was low. The emission factor obtained by dividing the measured concentration value by the fuel consumption was also calculated to be low. The load factor of the P-2 facility is only 84.4% of that of the P-1 facility, but the emission factor of PM_{total}, PM_{10}, $PM_{2.5}$, and NOx was 56.0%, 56.7%, 58.8%, and 78.0%, respectively, suggesting the reduction of the PM_{total}, PM_{10}, $PM_{2.5}$, and NOx emissions are more significant than the reduction of the coal consumption. However, although the load factor of SO_2 decreased, its emission factor increased about 1.5 times, indicating no effect of the reduced load factor.

Since the coal combustion chamber and various types of APCDs are operated at lower-load conditions than the design capacity, the number of pollutants generated decreases and the pollutant removal efficiency increases. However, it was identified that the SO_2 concentration and emission factor are more significantly affected by the sulfur content of the coal rather than the difference in the load factor.

To this end, reducing the operating load of the coal-fired power plant improves the combustion efficiency and performance of several APCDs, and reduces the emission factor. It also leads to further decrease of the pollutants rather than the simply calculated reduction which is based on the reduction of power production rate. However, to decrease the SO_2 emission, it is more effective to provide low-sulfur coal.

ACKNOWLEDGEMENT

This study was supported by the Korea Institute of

Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry, & Energy (MOTIE) of the Republic of Korea (grant no. 20161110100140), and Korea Environmental Industry & Technology Institute (KEITI) (grant Graduate School of Fine Particle Management Specialization).

REFERENCES

Chen, H., Pan, P., Shao, H., Wang, Y., Zhao, Q. (2017) Corrosion and viscous ash deposition of a rotary air preheater in a coal-fired power plant. Applied Thermal Engineering, 113, 373-385. https://doi.org/10.1016/j.applthermaleng.2016.10.160

Chen, Z., You, C., Wang, H., Liu, Q. (2019) Experimental study on the synergetic removal of fine particles by wet flue gas desulfurization tower with a flow pattern control device. Powder Technology, 343, 122-128. https://doi.org/10.1016/j.powtec.2018.11.017

Cooper, C.D., Alley, F.C. (2002) Air pollution control; A design approach. (3rd ED.), Waveland Press, Inc., pp. 155-159, 209-217.

EU/EEA (European Environment Agency) (2019) Air quality in Europe-2019 report.

Han, S., Lee, J.Y., Lee, J., Heo, J., Jung, C.H., Kim, E.S., Kim, Y.P. (2018) Estimation of the source contributions for carbonaceous aerosols at a background site in Korea. Asian Journal of Atmospheric Environment, 12, 311-325. https://doi.org/10.5572/ajae.2018.12.4.311

IPPC (Integrated Pollution Prevention and Control) (2017) Best Available Techniques (BAT) Reference Document for Large Combustion Plants, pp. 138-142.

Jang, K.W., Kim, H.C., Song, D.J., Jung, N.E., Hong, J.H., Lee, S.J., Han, J.S. (2011) Estimating PM emission factor from coal-fired power plants in Korea. Journal of Korean Society for Atmospheric Environment, 27(5), 485-493, (in Korean with English abstract).

Jaworek, A., Krupa, A., Sobczyk, A.T., Marchewicz, A., Szudyga, M., Antes, T., Balachandran, W., Natale, F.D., Carotenuto, C. (2013) Submicron particles removal by charged sprays. Fundamentals. Journal of Electrostatics, 71, 345-350. https://doi.org/10.1016/j.elstat.2012.11.028

KATS (Korea Agency for Technology and Standards) (2012) Stationary source emissions-determination of $PM_{10}/PM_{2.5}$ mass concentration in flue gas-measurement at low concentrations by use of impactor.

Kim, H.G., Kim, H.J., Lee, M.H., Kim, J.H. (2014) Experimental Study on the Enhancement of Particle Removal Efficiency in Spray Tower Scrubber Using Electrospray. Asian Journal of Atmospheric Environment, 8, 89-95. https://doi.org/10.5572/ajae.2014.8.2.089

Kim, S., Kim, O., Kim, B.-U., Kim, H.C. (2017) Impact of emissions from major point sources in Chungcheongnam-do on surface fine particulate matter concentration in the surrounding area. Journal of Korean Society for Atmospheric Environment, 33(2), 159-173, (in Korea with English abstract). https://doi.org/10.5572/KOSAE.2017.33.2.159

Li, X. (2017) Optimization and reconstruction technology of SCR flue gas denitrification ultra low emission in coal fired power plant. Materials Science and Engineering, 23, 012111. https://doi.org/10.1088/1757-899X/231/1/012111

Li, Z., Jiang, J., Ma, Z., Wang, S., Duan, L. (2015) Effect of selective catalytic reduction (SCR) on fine particle emission from two coal-fired power plants in China. Atmospheric Environment, 120. https://doi.org/10.1016/j.atmosenv.2015.08.046

Li, Z., Jiang, J., Ma, Z., Fajardo, O.A., Deng, J., Duan, L. (2017) Influence of flue gas desulfurization (FGD) installations on emission characteristics of $PM_{2.5}$ from coal-fired power plants equipped with selective catalytic reduction (SCR). Environmental Pollution, 230, 655e662. https://doi.org/10.1016/j.envpol.2017.06.103

Liang, Y., Li, Q., Ding, X., Wu, D., Wang, F., Otsuki, T., Cheng, Y., Shen, T., Li, S., Chen, J. (2020) Forward ultra-low emission for power plants via wet electrostatic precipitators and newly developed demisters: Filterable and condensable particulate matters. Atmospheric Environment, 225, 117342.

Ma, C.J., Gang, G.U. (2019) Chemical property of the fly ash collected at an incinerator and its effects on near ambient particles. Asian Journal of Atmospheric Environment, 13, 136-143. https://doi.org/10.5572/ajae.2019.13.2.136

NAER (National Air Emission Inventory and Research Center) (2020) Air Pollutant Emission Calculation Manual IV, https://www.air.go.kr/jbmd/sub90_detail.do?tabPage=2&detailKey=62014P06&inputSchTxt=&typeSchOption=titleNm&menuId=undefined

NIER (National Institute of Environmental Research) (2014) Air pollution standard process test, Measurement method of total particulate matter, ES 01301.1.

Ruan, R., Liu, H., Tan, H., Yang, F., Li, Y., Duan, Y., Zhang, S., Lu, X. (2019) Effects of APCDs on PM emission: A case study of a 660 MW coal-fired unit with ultralow pollutants emission. Applied Thermal Engineering, 155, 418-427.

Saarnio, K. (2014) Chemical composition and size of particles in emissions of a coal-fired power plant with flue gas desulfurization. Journal of Aerosol Science, 74.

Seo, M.H., Chang, H.S. (2012) Computational Study on the Soot Blowing Method for Enhancing the Performance of the SCR System. Particle and Aerosol Research, 8(3), 99-110.

Seong, K.J., Lee, C. (2017) Operation and Improvement Cases of FGD Non-leakage Type Gas-Gas Heater (GGH) for Coal Fired Power Plants. Journal of the Korean Society of Combustion, 22(4), 35-42. https://doi.org/10.15231/jksc.2017.22.4.035

Shi, Y.-J., Shu, H., Zhang, Y.-H., Fan, H.-M., Zhang, Y.-P., Yang, L.-J. (2016) Formation and decomposition of NH_4HSO_4 during selective catalytic reduction of NO with NH_3 over V_2O_5-WO_3/TiO_2 catalysts. Fuel Processing Technology, 150, 141-147. https://doi.org/10.1016/j.fuproc.2016.05.016

Sorrels, J.L., Randall, D.D., Schaffner, K.S., Fry, C.R. (2019) Selective Catalytic Reduction, U.S. Environmental Protection Agency Research Triangle Park, NC 27711.

Sui, Z., Zang, Y., Peng, Y., Norris, P., Cao, Y., Pan, W. (2016)

Fine particulate matter emission and size distribution characteristics in ultra-low emission power plant, Fuel, 185, 863–871.

Ti, S., Chen, Z., Li, Z., Xie, Y., Shao, Y., Zong, Q., Zhang, Q., Zhang, H., Zeng, L., Zhu, Q. (2014) Influence of different swirl vane angles of over fire air on flow and combustion characteristics and NOx emissions in a 600 MWe utility boiler. Energy, 74, 775–787. https://doi.org/10.1016/j.energy.2014.07.049

U.S EPA (United States Environmental Protection Agency) (1998) Compilation of air pollutants emission factors AP-42.

Wang, C., He, B., Sun, S., Wu, Y., Yan, N., Yan, L., Pei, X. (2012) Application of a low pressure economizer for waste heat recovery from the exhaust flue gas in a 600 MW power plant. Energy, 48, 196–202.

Watts, N. *et al.* (2015) Health and climate change: policy responses to protect public health. The Lancet Commissions, 386, 1861–1914. https://doi.org/10.1016/S0140-6736(15)60854-6

Wu, B., Bai, X., Liu, W., Zhu, C., Hao, Y., Lin, S., Liu, S., Luo, L., Liu, X., Zhao, S., Hao, J., Tian, H. (2020) Variation characteristics of final size-segregated PM emissions from ultralow emission coal-fired power plants in China. Environmental Pollution, 113886.

Wu, B., Tian, H., Hao, Y., Liu, S., Liu, X., Liu, W., Bai, X., Liang, W., Lin, S., Wu, Y., Shao, P., Liu, H., Zhu, C. (2018) Effects of wet flue gas desulfurization and wet electrostatic precipitators on emission characteristics of particulate matter and its ionic compositions from four 300 MW level ultralow coal-fired power plants. Environmental Science & Technology, 52(23), 14015–14026. https://doi.org/10.1021/acs.est.8b03656

Wu, B., Tian, H., Hao, Y., Liu, S., Sun, Y., Bai, X., Liu, W., Lin, S., Zhu, C., Hao, J., Luo, L., Zhao, S., Guo, Z. (2020) Refined assessment of size-fractioned particulate matter ($PM_{2.5}$/PM_{10}/PM_{total}) emissions from coal-fired power plants in China. Science of The Total Environment, 706, 135735. https://doi.org/10.1016/j.scitotenv.2019.135735

Wu, Q., Gu, M., Du, Y., Zeng, H. (2019) Synergistic removal of dust using the wet flue gas desulfurization systems. Royal Society Open Science, 6: 181696. https://doi.org/10.1098/rsos.181696

Yao, S., Cheng, S., Li, J., Zhang, H., Jia, J., Sun, X. (2019) Effect of wet flue gas desulfurization (WFGD) on fine particle ($PM_{2.5}$) emission from coal-fired boilers. Journal of Environmental Science, 77, 32–42.

Zhang, X., Chen, Z., Zhang, M., Zeng, L., Li, Z. (2021) Combustion stability, burnout and NOx emissions of the 300-MW down-fired boiler with bituminous coal: Load variation and low-load comparison with anthracite. Fuel, 295. https://doi.org/10.1016/j.fuel.2021.120641

Zhao, Y., Wang, S., Nielsen, C.P., Lo, X., Hao, J. (2010) Establishment of a database of emission factors for atmospheric pollutants from Chinese coal-fired power plants. Atmospheric Environment, 44(12), 1515–1523. https://doi.org/10.1016/j.atmosenv.2010.01.017