



PM_{2.5} Emission Reduction by Technical Improvement in a Typical Coal-Fired Power Plant in China

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ABSTRACT

To investigate PM_{2.5} reduction by technical improvement in typical Chinese coal-fired power plants, two units built in different time with different particulate matter (PM) control technologies but with the same coal-fired boiler type were selected to characterize the concentrations of PM_{2.5} generated and emitted from coal-fired power plants. We found that significant benefit of PM_{2.5} emission reduction was achieved by technological improvement. Due to the increase in the installed capacity and the application of low NO_x burner alone, PM_{2.5} emission factor without adopting other air pollution control devices decreased from 0.153 kg t⁻¹ (the 100 MW unit) to 0.123 kg t⁻¹ (the 300 MW unit). With the help of an improved electrostatic precipitator (ESP) of which removal efficiency increased from 76.4% to 97.5%, PM_{2.5} emission factor further decreased from 0.014 kg t⁻¹ (the unit with a normal ESP) to 0.003 kg t⁻¹ (the unit with a cold-side ESP and a wet flue gas desulphurization (WFGD)). However, the application of flue gas denitrification and desulfurization devices may alter PM_{2.5} compositions and their emissions. For instance, the installation of a WFGD was found to largely increase the emissions of water-soluble ions in PM_{2.5} (e.g., SO₄²⁻, Ca²⁺, and NH₄⁺).

Keywords: PM_{2.5}; Emission factor; Coal-fired power plant; Water-soluble inorganic ion; Wet flue gas desulphurization (WFGD).

INTRODUCTION

Currently, many cities in the world, especially in developing countries such as China and India, have confronted with severe fine particulate matter (PM_{2.5}) problems that attracts worldwide public attention (Krzyzanowski and Schwela, 1999; Zhang and Day, 2015). Coal combustion in coal-fired power plants is one of the major anthropogenic sources of PM_{2.5} (Lu *et al.*, 2010; Lei *et al.*, 2011).

At present, China has the strictest standard for pollutant emission from coal-fired power plants in the world because of the largest amount of coal consumption and very severe air pollution. Many environmental regulations have been enacted to reduce pollutant emission per electricity generated since the early 1990s in China. Coal-fired power plants

have been exploring and improving technologies, including increasing generating capacity, adapting low NO_x burner, enhancing the performance of current air pollution controlling devices (APCDs) and employing advanced APCDs, to increase coal combustion efficiency and decrease pollutant emission. One example is that the power generating units in capacity of less than 200 MW have been gradually abolished from 2003 (The State Council, 1999, 2007), and newly-built units are required to be no less than 300 MW. Common pulverized coal-fired power plants installed the similar APCDs, including selective catalytic reduction (SCR) system, electrostatic precipitators (ESP) and flue gas desulfurization (FGD) system. According to the 11th five-year plan and the 12th five-year plan, FGD system (especially wet flue gas desulfurization (WFGD)) and SCR system were widely installed in coal-fired power plants to guarantee low SO₂ emission and low NO_x emission, respectively (The State Council, 2006, 2011). ESP, widely used in Chinese thermal power plants, has higher collection efficiency with better design and flue gas preconditioning technology, such as wet ESP, electrostatic-bag precipitator and cold-side ESP (Kulmala *et al.*, 2008; Yao *et al.*, 2009; Li *et al.*, 2013; Xiong *et al.*, 2015). Cold-side ESP alters particles characteristics, such as reducing specific resistance and molecular thermal

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motion and hence improved collection efficiency. This technology has been applied in many coal-fired power plants successfully (Kulmala *et al.*, 2013; Wang *et al.*, 2015; Xiong *et al.*, 2015; Hu *et al.*, 2016). According to statistics, ESP and flue gas desulfurization (FGD) had been installed for nearly all coal-fired power plants by 2012 and selective catalytic reduction (SCR) had been installed for most coal-fired power plants (more than 80%) by 2014 (Xu *et al.*, 2009; Wang *et al.*, 2010; Wang and Hao, 2012; Zhao *et al.*, 2013; Wang *et al.*, 2014). Ongoing discussions about super low emission aim at further reducing pollutants emission, especially PM, NO_x and SO₂ emissions (Zhao *et al.*, 2015). PM emission characteristics, such as mass concentration and size distribution, might alter as these technical improvements for conserving energy and reducing emission were carried out.

In this study, PM_{2.5} emissions from two coal-fired power generating units with the same boiler type but different APCDs were characterized as a case study on the benefit of technical improvements on PM_{2.5} emission reduction from power industries in China. Such information could support policy-making on cleaner power generation from coal-fired power plants, which is irreplaceable in the foreseeable future in many countries, including China, India, USA, Canada, and Japan.

METHODOLOGY

Unit Description

Two typical pulverized coal-fired units, of installed capacity of 100 MW and 300 MW, respectively, in the same coal-fired power plant (in Shanxi province) but with different APCDs, were selected for this study (Table 1). Unit 1, with an installed capacity of 100 MW, taking service in 1994 and shut down in 2013, was equipped with an ESP with three electric fields. The measurement for Unit 1 was carried out in 2003. Unit 2, with an installed capacity of 300 MW and

operating from 2004, was equipped with a low-NO_x burner (LNB), a SCR unit, an cold-side ESP (with a gas-gas heater (GGH) ahead, a pre-one-field-ESP and a four-field ESP), and a WFGD. The measurement for unit 2 was carried out in 2014. Similar APCDs of Unit 2 have been installed in most pulverized coal-fired power plants in China (Liu and Wen, 2012). Both units burned bituminous coal whose relative parameters and testing conditions are shown in Tables 1 and 2.

PM Sampling

An electrical low pressure impactor (ELPI, Dekati Ltd., Finland) (Keskinen *et al.*, 1992) with 13-stage cascade samplers (cut-off diameter is 0.03–10 μm) was applied to measure particle size distributions and to collect PM samples. A set of greased membranes were put on the stages from one to ten to collect PM (0.03–2.5 μm) in different size ranges to determine their mass and a set of Teflon membranes were applied to collect PM (0.03–2.5 μm) samples for water-soluble ion analysis.

The dilution sampling system was selected in this study considering high concentrations of particles at ESP inlet and high humidity at WFGD outlet. The sampling system, as it is shown in Fig. 1, consists of the ELPI, an isokinetic sampler probe, precut cyclone (cutoff diameter is 10 μm) and two Dekati diluters (Yi *et al.*, 2006; Li *et al.*, 2015). The sample flue extracted from the stack was initially mixed with the clean and dry air in the first diluter at the same temperature with flue gas in the stack, and then the sample flue mixture was blended with the clean and dry air again at the atmospheric temperature in the second diluter. The total dilution ratio was 1:64. Then the diluted sample flue was pumped into the ELPI. The sampling positions were located at both inlets and outlets of every APCDs of two units. For unit 1, the sampling locations were at the ESP inlet and at the ESP outlet. For unit 2, the locations

Table 1. Description of two units tested.

Unit	1#	2#
Installed capacity (MW)	100	300
Commissioning Date	1994	2004
Boiler Type	Pulverized coal-fired boiler (Tangential)	Pulverized coal-fired boiler (Tangential)
Testing load	100%	100%
APCDs	ESP	LNB, SCR, ESP (with a GGH), and WFGD
Testing year	2003	2014
Coal type	bituminous	bituminous
Ash content ^a (%)	30.6	36.0
Sulfur content ^a (%)	2.01	1.79

^a as received basis.

Table 2. Test conditions of two units

Sampling location	1#		2#			
	ESP inlet	ESP outlet	SCR inlet	ESP inlet	WFGD inlet	WFGD outlet
Temperature, °C	143	140	358	91	89	47
Gas flow rate, N km ³ h ⁻¹	--	--	1072	1061	1103	1143
Gas velocity, m s ⁻¹	--	--	--	7.30	7.98	7.05
O ₂ , %	9	7.1	2.76	5.25	5.40	5.85

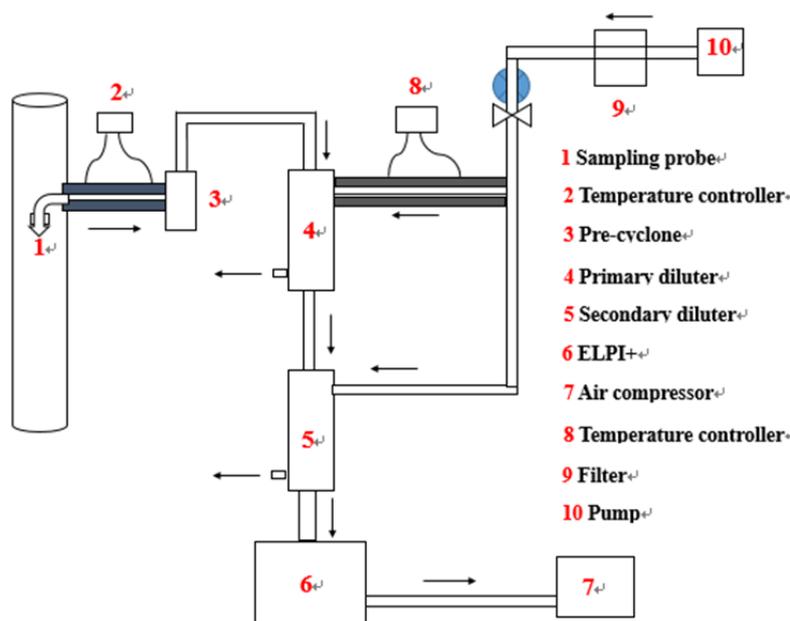


Fig. 1. The diagram of sampling system.

were at the SCR inlet and outlet (which is also the ESP inlet), WFGD inlet (the ESP outlet), and the WFGD outlet. Both units were run under stable operation conditions during the measurements.

PM Sample Analysis

These samples from the 1st stage to the 10th stage (0.03–2.5 μm) collected with Teflon membranes were selected and divided into three fractions, < 0.11 μm ($\text{PM}_{0.1}$), 0.11–1.00 μm ($\text{PM}_{0.1-1}$), and 1.00–2.50 μm ($\text{PM}_{1-2.5}$). At first, the Teflon membranes of the same fraction were put into a 15 ml capped plastic tube together. Then 10 ml ultrapure water was added into the plastic tube and made sure all the membranes were immersed in the water completely in the tube. Thirdly, the plastic tube was treated in ice bath by ultrasonic extraction for 40 minutes. At last, the extractions were injected into an Ion Chromatography (Dionex 600 and ICS-1000) to analyze cations (Na^+ , NH_4^+ , K^+ , Mg^{2+} , and Ca^{2+}) and anions (F^- , Cl^- , NO_3^- , and SO_4^{2-}).

RESULTS

PM_{2.5} Generations from Two Boilers

The particle size distribution at the ESP inlet of unit 1 was bimodal with peaks at 0.17 and > 2.5 μm (Fig. 2(a)). The mass concentrations of $\text{PM}_{0.1}$, $\text{PM}_{0.1-1}$ and $\text{PM}_{1-2.5}$ were 16.2, 501 and 1142 mg m^{-3} , respectively (Table 3). The percentages of $\text{PM}_{0.1}$, $\text{PM}_{0.1-1}$ and $\text{PM}_{1-2.5}$ of $\text{PM}_{2.5}$ were 0.90%, 30.2 and 68.8%, respectively (Fig. 2(b)). For unit 2, the size distribution at the SCR inlet was also bimodal and the peaks were at 0.17 and 1.96 μm , respectively. The mass concentration of $\text{PM}_{2.5}$ was 164 mg m^{-3} . The mass concentrations of $\text{PM}_{0.1}$ and $\text{PM}_{0.1-1}$ and $\text{PM}_{1-2.5}$ were 8.67, 56.4 and 98.6 mg m^{-3} , respectively (Table 3). The percentages of $\text{PM}_{0.1}$, $\text{PM}_{0.1-1}$ and $\text{PM}_{1-2.5}$ of $\text{PM}_{2.5}$ were 5.30% and 34.5% and 60.2%, respectively (Fig. 2(b)). In addition,

$\text{PM}_{2.5}$ emission factors before APCDs for unit 1 (at the ESP inlet) and unit 2 (at the SCR inlet) were 0.153 kg t^{-1} and 0.123 kg t^{-1} , respectively (Fig. 3).

PM_{2.5} Emissions after APCDs

The size distributions of mass concentration of each unit at the outlet of different APCDs were bimodal with peaks at 0.17–0.26 μm and > 1.6 μm (Fig. 2(a)). For unit 1, the $\text{PM}_{2.5}$ mass concentration at the ESP outlet was 392 mg m^{-3} . And $\text{PM}_{0.1}$, $\text{PM}_{0.1-1}$ and $\text{PM}_{1-2.5}$ accounted for 2.90%, 32.8% and 64.3% of $\text{PM}_{2.5}$, respectively (Fig. 2(b)). For unit 2, the $\text{PM}_{2.5}$ mass concentrations at the SCR inlet, the ESP outlet, and the WFGD outlet were 163, 4.04, and 3.93 mg m^{-3} , respectively. At WFGD outlet, $\text{PM}_{0.1}$, $\text{PM}_{0.1-1}$, and $\text{PM}_{1-2.5}$ accounted for 38.9%, 34.0%, and 24.1% of $\text{PM}_{2.5}$, respectively.

Particle removal efficiencies by different APCDs were calculated and shown in Fig. 4. For unit 1, the efficiency of removing $\text{PM}_{2.5}$ by the ESP was 76.4%. The efficiencies of particles of different segmental size ranges were different, i.e., the efficiencies for $\text{PM}_{0.1}$, $\text{PM}_{0.1-1}$ and $\text{PM}_{1-2.5}$ were 29.6%, 74.3%, and 77.9%, respectively. For unit 2, the removal efficiencies of $\text{PM}_{2.5}$ by ESP were 97.5% (96.3%, 96.3%, and 98.2% for $\text{PM}_{0.1}$, $\text{PM}_{0.1-1}$ and $\text{PM}_{1-2.5}$, respectively). In contrast, the WFGD removed 24.8% of $\text{PM}_{0.1-1}$ and 48.7% of $\text{PM}_{1-2.5}$, respectively, but increased $\text{PM}_{0.1}$ emission by 507%. The overall removal efficiency for the WFGD on $\text{PM}_{2.5}$ was therefore only 2.57%. At the SCR inlet and outlet, the $\text{PM}_{2.5}$ mass concentrations were very similar, so its effects on $\text{PM}_{2.5}$ mass concentration reduction is negligible. Therefore, $\text{PM}_{2.5}$ emission factors considering APCDs of unit 1 and unit 2 were 0.014 kg t^{-1} and 0.003 kg t^{-1} , respectively (Fig. 3).

Emission Characteristics of Water-Soluble Ions

Fig. 5 shows the contents of major water-soluble ions

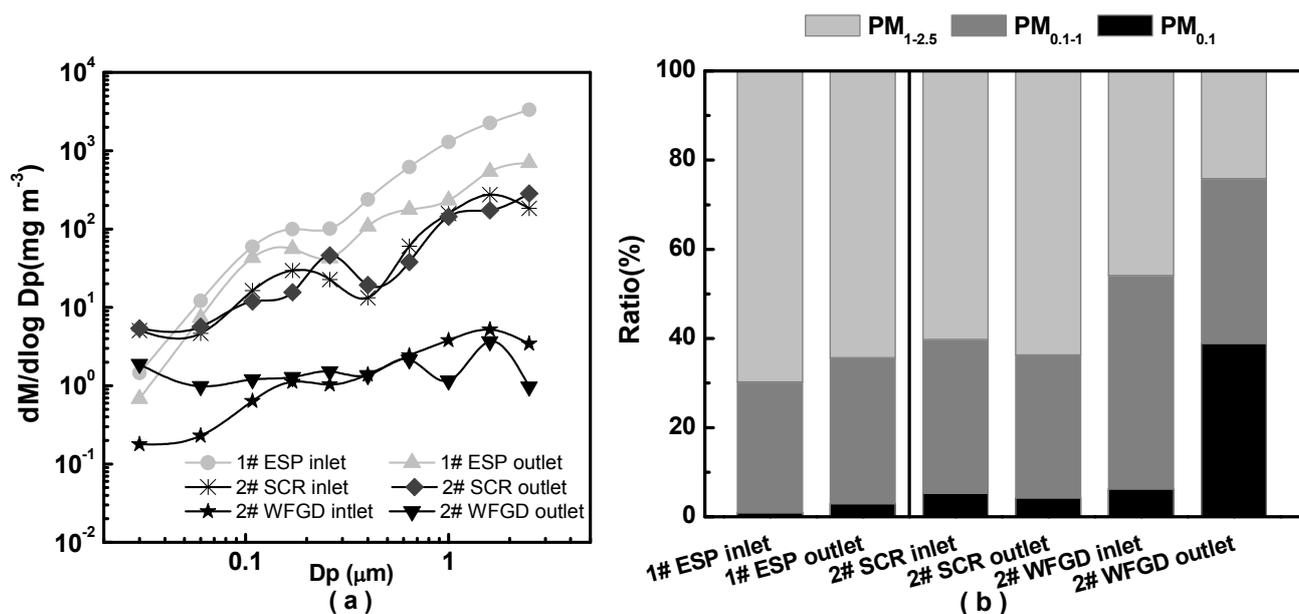


Fig. 2. Particle size distributions (a) and mass fractions (b) of PM_{2.5} from two units.

Table 3. Mass concentrations of each fraction of PM_{2.5} (unit: mg m⁻³).

Unit	Sampling location	PM _{0.1}	PM _{0.1-1}	PM _{1-2.5}
1#	ESP inlet	16.2	501	1142
	ESP outlet	11.4	129	252
2#	SCR inlet	8.67	56.4	98.6
	ESP inlet	6.84	52.2	104
	WFGD inlet	0.25	1.94	1.85
	WFGD outlet	1.53	1.45	0.95

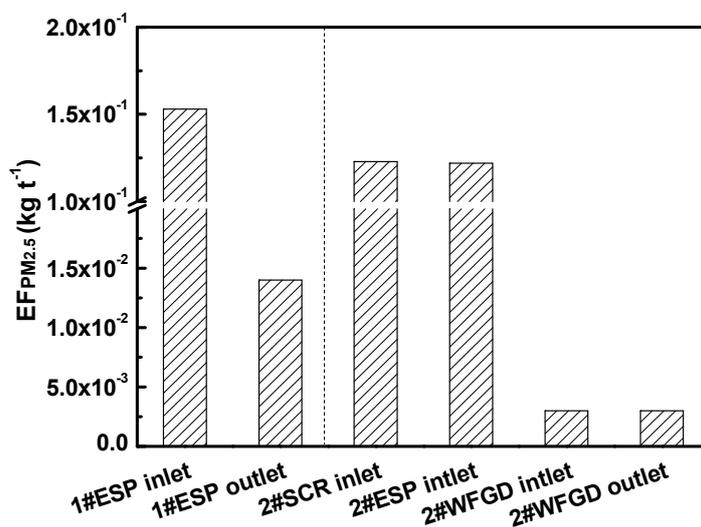


Fig. 3. PM_{2.5} emission factor before and after APCDs.

(Ca²⁺, NH₄⁺, and SO₄²⁻) in PM_{2.5} at the WFGD inlet and outlet. At the WFGD inlet, SO₄²⁻ concentration in PM_{2.5} was 0.16 mg m⁻³, accounting for 4.08% of PM_{2.5}. At the WFGD outlet, SO₄²⁻ in PM_{2.5} was 0.25 mg m⁻³, 6.25% of PM_{2.5}. Similarly, Ca²⁺ concentration increased from 0.05 mg m⁻³ to 0.20 mg m⁻³ and NH₄⁺ concentration increased

from 0.24 mg m⁻³ to 0.84 mg m⁻³ after the WFGD. From the WFGD inlet and outlet, the concentrations of SO₄²⁻ and Ca²⁺ in PM_{0.1-1} showed the biggest increases compared with those in PM_{0.1} and PM_{1-2.5}, and NH₄⁺ concentrations in PM_{0.1-1} also increased to the largest extents compared with NH₄⁺ concentration in PM_{0.1} and PM_{1-2.5}.

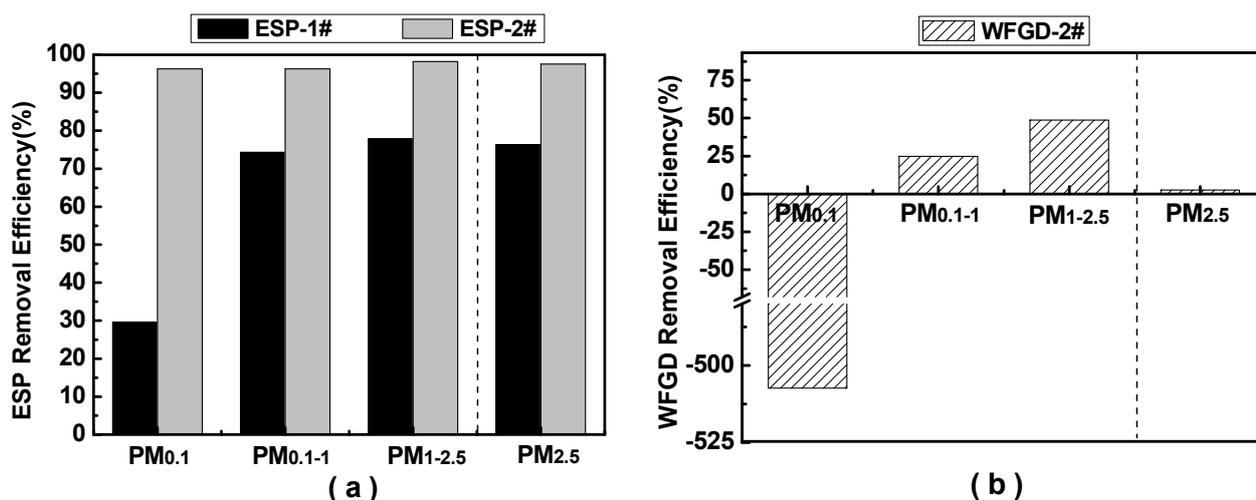


Fig. 4. Particle removal efficiency by different APCDs: (a) the ESP; (b) the WFGD.

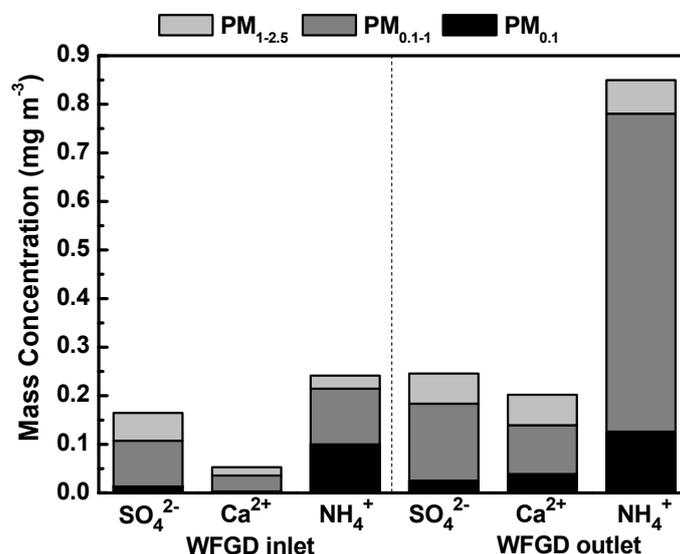


Fig. 5. Water soluble ion concentrations in each fraction of PM_{2.5} at the WFGD inlet and outlet of Unit 2.

DISCUSSION

PM_{2.5} Reduction by Technology Improvement

In this study, as shown in Fig. 2 and Table 2, unit 2 with larger installed capacity and LNB can significantly reduce PM_{2.5} generation. The PM_{2.5} emission factor of the unit 2 boiler was 20% lower than that of the unit 1 (Fig. 3). This result revealed that the improvement of combustion technologies could prevent PM_{2.5} from generation. Higher combustion efficiency of larger boiler reduced coal consumption and thus indirectly minimized the emission factor as well (Yi *et al.*, 2012). In addition, LNB, designed to reduce NO_x generation by staged combustion, could lead to lower flame temperature so that less volatile components and metal could volatilize or vapor and condense to form fine particles (Flagan and Seinfeld, 1988). However, the first-stage combustion is in reducing atmosphere that favors for metal component vaporizing, which benefits fine particles formation (Quann and Sarofim, 1982; Flagan and Seinfeld,

1988). Contradictory conclusions were reported in previous studies on the effect of LNB on particles generation. For example, some of the studies found that the LNB reduce PM_{2.5} formation (Mcelroy *et al.*, 1982; Taylor and Flagan, 1982; Yu *et al.*, 2013). But others obtained opposite results (Cato *et al.*, 1977; Nettleton, 1979). It appears that LNB takes different effects on the different fractions of PM_{2.5}. For example, LNB reduced total PM_{2.5} mass concentration even though it increased the number concentration of particles smaller than 60 nm (Liu, 2007; Liu *et al.*, 2010).

ESP has been one of the most efficient PM control devices in current coal-fired power plants (Wang and Hao, 2012; Xiong *et al.*, 2015). In 1990s, most ESPs in coal-fired power plants had three electric fields. In 1999, 79.98% of coal-fired power plants installed ESP and the average total PM removal efficiency was 98.22% (Gong and Zhang, 2010). ESP's performance has been largely improved which was driven by the increasing stricter regulations on PM emission since 1990s. At present, the ESP removal efficiency

for total PM has been enhanced to be more than 99% (Jiang et al., 2008; Xiong et al., 2015; Li et al., 2016). Likewise, its removal efficiency for PM_{2.5} has been enhanced. In this study, the removal efficiency of ESP showed great improvement, especially for PM_{0.1} (Fig.4). Compared with previous ESP installed decades ago, present ESPs often have more electric fields, higher particle charging efficiency, more reasonable vibration cleaning systems, and so on (Huang et al., 2003; Gong and Zhang, 2010; Pan et al., 2014). Besides, advanced technologies combined with ESP also play an important role in collection efficiency improvement. The ESP installed in Unit 2 adapted a kind of new technology, so called cold-side ESP, which employs a gas-gas heater (GGH) before the ESP. The GGH could decrease the temperature of flue gas before entering into the ESP to dew point temperature of SO₃ and HCl. The collection efficiency of ESP can be enhanced because of the enhancement of the conductivity of particles (Pudasainee et al., 2012; Zhao et al., 2014; Xiong et al., 2015; Li et al., 2016).

China has made policies to decrease the amount of smaller units and advocate building units in large capacity to favor LNB technologies for many years. This study shows clear benefit of the policy. In 2007, the capacity of generator units ≤ 100 MW contribute to 16.8% of total capacity, and 23.2% of the coal consumption used to generate power was consumed by generator units ≤ 100 MW (Wang et al., 2012). If all those generator units ≤ 100 MW were replaced by larger ones equipped with LNB and high-efficient PM control equipment, their PM_{2.5} emissions would be significantly reduced in China.

New Problems Caused by APCDs

Currently, almost all coal-fired power plants in China has equipped with WFGD systems to reduce SO₂ emission. The WFGD can further remove primary PM_{2.5} (especially PM_{1-2.5}), but it generates new particles (especially PM₁) (Meij, 1994; Farthing et al., 2004; Nielsen et al., 2002). In this study, the PM_{0.1} mass concentration presented a great increase even though the PM_{2.5} mass concentration at WFGD outlet showed a slight decrease (Fig. 2 and Table 2). Besides, the results of water-soluble ions, especially SO₄²⁻, Ca²⁺ and NH₄⁺ presented decreases in both ratios and concentrations at the WFGD outlet (Fig. 5). Most of the new particles come from the desulfurization solution in the fraction of fine particles, escaping from the demister (Wang et al., 2008; Yan et al., 2011), indicated by increasing water-soluble ion concentrations in PM_{2.5} such as SO₄²⁻, Ca²⁺, and NH₄⁺ (Li, 2013; Saarnio et al., 2014). Therefore, gypsum rain has often shown up nearby the power plants with WFGD (Lv et al., 2011; Liu et al., 2013). Increasing emission of NH₄⁺ and SO₄²⁻ by SCR installation was also discussed recently (Li et al., 2015).

CONCLUSIONS

This case study on different emission characteristics from two units in the same coal-fired power plant but with different combustion and emission control technologies, indicated significant benefit of PM_{2.5} emission reduction by

technological improvement. PM_{2.5} emission factors without APCDs of unit 1 and unit 2 were 0.153 g kg⁻¹ and 0.123 g kg⁻¹, respectively. The later was 20% lower than the former because of the improvement of combustion technologies. With the help of an improved cold-side ESP whose removal efficiency increased from 76.4% to 97.5%, PM_{2.5} emission factor further decreased from 0.014 kg t⁻¹ (the unit with normal ESP) to 0.003 kg t⁻¹ (the unit with a cold-side ESP and a wet flue gas desulphurization (WFGD)). Since the existing units with capacity no higher than 200 MW will soon be replaced by larger units equipped with high-efficient APCDs, great reduction in PM_{2.5} emission from coal-fired power plants is anticipated.

However, the application of flue gas denitrification and desulfurization devices may alter the emission of PM_{2.5} and their chemical compositions. Especially, the WFGD was found to cause additional emissions of water-soluble ions in PM_{2.5}, e.g., SO₄²⁻, Ca²⁺, and NH₄⁺. Further studies on such effects should be carried out, and greater caution should be taken in operating these APCDs, especially WFGD, to prevent increasing PM_{2.5} emissions from coal-fired power plants.

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