An Investigation of SO₃ Control Routes in Ultra-low Emission Coal-fired Power Plants

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ABSTRACT

With the implementation of ultra-low emission systems in coal-fired power plants in China, the emission of sulfur trioxide (SO₃) has become an important issue in pollution control. However, systematic research and evaluation of SO₃ control routes based on the existing ultra-low emission systems are still lacking. We assigned 148 coal-fired power plants to four categories based on their ultra-low emission control routes and selected a representative power plant from each category for comprehensive field testing. The results indicated great variability in the synergistic SO₃ removal capability of different air pollution control devices and routes, resulting in removal efficiencies that ranged from 27% to 94%. Control Route 1, which lacked both a low-low temperature electrostatic precipitator (LLTESP) and a wet electrostatic precipitator (WESP), exhibited the lowest removal efficiency. The two routes equipped with either an LLTESP or a WESP (Control Routes 2 and 3) reduced the SO₃ concentration in the flue gas produced by medium-sulfur-coal combustion to below 10 mg m⁻³, whereas Control Route 4, which utilized both an LLTESP and a WESP, reduced the SO₃ concentration to below 5 mg m⁻³. Furthermore, sampling the emissions of the 148 power plants revealed that only 14% of the power plants complied with the 5 mg m⁻³ standard for SO₃, although 44% and 64% of them complied with the 10 mg m⁻³ and the 20 mg m⁻³ standard, respectively. Our study evaluated the control routes within the context of the whole process, which can guide subsequent research and engineering practices.

Keywords: Coal-fired power plants; Ultra-low emission; SO₃ emission; Control route; Synergistic removal.

INTRODUCTION

The intensive implementation of ultra-low emission (ULE) at coal-fired power plants (CFPPs) in China has expedited comprehensive improvements in the air pollution control, especially the reduction of particulate matter (PM), sulfur dioxide (SO₂) and nitrogen oxides (NO_x) (Ni *et al.*, 2018). However, sulfur trioxide (SO₃) which have various negative impacts on human health and ecological environment, still need to be addressed (Wu *et al.*, 2017c; Shen *et al.*, 2019; Zheng *et al.*, 2019). In conventional environmental facilities, the selective catalytic reduction (SCR) devices for NO_x removal convert 0.5–1.5% of sulfur dioxide (SO₂) into SO₃ (Ji *et al.*, 2016; Xu *et al.*, 2018; Zheng *et al.*, 2019). The approaches to remove SO₃ include the use of a low-low temperature electrostatic precipitator (LLTESP) and a wet electrostatic precipitator (WESP), which both have a

synergistic removal efficiency of > 70% (Bin *et al.*, 2017; Chen *et al.*, 2017; Yang *et al.*, 2018). Besides, wet limestone-gypsum flue gas desulfurization (WFGD) also has an approximate removal efficiency of 50% (Zheng *et al.*, 2018).

Specifically, Ji *et al.* (2016) reported that the oxidation rate of SO₂ was controlled but the DeNO_x activity of the catalyst was maintained by using adequate amount of vanadium (V) and suitable catalyst volume. Kwon *et al.* (2016) reported that adding molybdenum to an SCR catalyst inhibited the adsorption of SO₂, and adding tungsten improved the low-temperature activity of the catalyst. These two approaches, combining with controlling the catalyst wall thickness, effectively reduced the SO₂/SO₃ conversion rate of the SCR catalyst.

The SO₃ removal efficiency of WFGD would be affected by the inlet SO₃ concentration, slurry temperature, liquid-to-gas ratio, and inlet flue gas temperature, with the inlet SO₃ concentration and flue gas temperature exerting the strongest influence (Pan *et al.*, 2017b; Zheng *et al.*, 2018). WFGD with double scrubbers has a SO₃ removal efficiency of 50–65%, which is much higher than that of the single-scrubber WFGD (30–40%) (Pan *et al.*, 2017a).

The SO₃ removal efficiency of an electrostatic precipitator

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(ESP) is typically around 20% and is mainly affected by factors such as the flue gas temperature and ash composition (Qi and Yuan, 2013; Galloway *et al.*, 2015). In an LLTESP, the pretreatment heat recovery device would reduce the flue gas temperature to be lower than the acid dew point, causing the SO₃ in the flue gas to be condensed into sulfuric mist, adsorbed by fly ash, and then removed by the ESP along with the other ash (Chen *et al.*, 2017). When the dust-to-sulfur mass ratio (D/S) is greater than 100, the SO₃ removal efficiency can exceed 80% (Zheng *et al.*, 2019). Similarly, extending the retention time of the flue gas in a WESP or reducing the inlet flue gas temperature of the WESP also improves the SO₃ removal efficiency (Chang *et al.*, 2011; Huang *et al.*, 2016).

Related studies have mostly focused on a single air pollutant removal facility or control route. The comparison of different control routes has not been reported. Consequently, effective strategies and routes for SO₃ emission control are still lacking. In this study, the synthetical SO₃ removal efficiencies of four ULE power plants were analyzed on the basis of whole-process field tests. In addition, the SO₃ removal efficiencies of 148 sampled CFPPs adopting different ULE control routes were analyzed to evaluate whether they will meet the varied SO₃ emission limits. Accordingly, this study proposed effective strategies and routes for SO₃ control to comply with different SO₃ emission limits.

MATERIAL AND METHODS

The Sampled CFPPs' Description SCR and WFGD are the conventional methods of NO_x and SO₂ removal in CFPPs, respectively. According to the analysis of SO₃ removal capacity of different PM removal technologies mentioned above, the ULE control routes of CFPPs can be mainly divided into four types as shown in Table 1. On this basis, this study compiled statistical data regarding the control routes of 148 CFPPs (62,685 MW) across 22 provinces in China. Additionally, the adaptability of these routes to different emission limits was studied. The capacity of the CFPPs ranged from 100 to 1000 MW. The boiler types included tangential firing, opposed firing, and W-flame. The types of coal included lignite, bituminous coal, meagre coal, and anthracite. As revealed in Table 1, among the 148 CFPPs, Control Route 1 was employed in most CFPPs (51%). Control Routes 2 and 3 were used in 27% and 19% of CFPPs, respectively. Compared with other control routes, Control Route 4 was less applied (3%).

Typical Plant Description

In order to investigate SO₃ removal efficiency of the aforementioned control routes, four 600 MW ULE CFPPs

were selected to perform whole-process field testing. Table 2 provides details of the four CFPPs, including key design parameters of the boiler, SCR, ESP, WFGD and WESP.

As revealed in Table 3, the four ULE CFPPs used bituminous coal with a volatile content of 25–39%, calorific value of 20–22 MJ kg⁻¹, sulfur content of 0.61–2.06%, and ash content of 20–27%.

Description of Testing Method

Fig. 1 illustrates measuring points for performance testing of CFPPs mentioned above. The controlled condensation method was employed to determine the SO₃ concentration according to the national and industrial standards of China (GB/T-21508, 2008; DL/T-998, 2016). Specifically, the sampling pipe was first heated to ≥ 180°C, and water temperature in the spiral condenser absorption tube was maintained at 60°C for sampling SO₃ condensate in the flue gas. The collected samples were titrated using an NaOH standard solution. SO₃ concentration of the flue gas was calculated according to Eq. (1):

$$\text{SO}_3 = T_{\text{SO}_3} \times \frac{V}{V'} \quad (1)$$

where SO₃ (mg m⁻³) is SO₃ concentration of the flue gas, T_{SO₃} (mg mL⁻¹) is the titer of SO₃ with NaOH standard solution, *v* (mL) is the NaOH standard solution consumption amounts, and *V* (m³) is the volume of dry flue gas sample.

The PM concentration was determined according to the national and industrial standards of China (GB/T-16157, 1996; DL/T-836, 2017). Specifically, an automatic isokinetic flue gas collector and the grid sampling method were used to collect samples. During the sampling process, the sampled flue gas volume, temperature, and pressure as well as the atmospheric pressure and weight of each sampling filter before and after sample collection were recorded. Subsequently, the PM concentration was calculated on the basis of the difference between the filter weight before and after sampling. The concentrations of several substances in the flue gas—including SO₂, NO_x, and oxygen—were determined using a flue gas analyzer (NGA2000; Rosemount, Germany). During the testing period, all the equipment in CFPPs were functioning properly, with the boilers fully loaded and the stable coal quality.

RESULTS AND DISCUSSION

Removal of Pollutants in the Four CFPPs

As revealed in Fig. 2, the DeNO_x efficiencies of the four

Table 1. Control route of the 148 sampled CFPPs.

Route	Technical route	Ratio (%)
Route 1	SCR + ESP/FF/EF + WFGD	51
Route 2	SCR + ESP/FF/EF + WFGD + WESP	27
Route 3	SCR + LLTESP + WFGD	19
Route 4	SCR + LLTESP + WFGD + WESP	3

Note: FF = Fabric filters, EF = Electrostatic-fabric filters.

Table 2. Description of four ULE CFPPs.

Devices	Items	Units	P-1	P-2	P-3	P-4
Boiler	Boiler capacity	MW	660	670	635	660
	BMCR	t h ⁻¹	2024	2102	2020	2024
	Boiler type	-	Tangential firing	Tangential firing	Opposed firing	Tangential firing
Control route		-	Route 1	Route 2	Route 3	Route 4
SCR	Catalyst type	-	Plate	Plate	Honeycomb	Plate
	Catalyst layer	-	3	3	3	2
	Catalyst volume	m ³	735.8	1075.8	873.6	593.2
ESP	ESP number	-	2	2	2	2
	Field stage	-	5	4	5	5
	Chamber	-	4	4	4	4
WFGD	Specific collection area	m ² m ⁻³ s ⁻¹	134.7	92.8	111.5	123.2
	Liquid-gas ratio	l Nm ⁻³	19.9	27.5	26.1	20.9
	Spraying layer	-	5	5 + 3	3 + 3	5
WESP	Tray layer	-	1	-	-	1
	High-efficiency spray layers	-	Yes	No	Yes	No
	High-efficiency mist removal devices	-	Yes	No	Yes	No
WESP	WESP number	-	-	1	-	1
	Field stage	-	-	4	-	4
	Chamber	-	-	2	-	2
	Specific collection area	m ² m ⁻³ s ⁻¹	-	30.7	-	23.2

Table 3. Coal properties of the four typical CFPPs.

Item	Unit	P-1	P-2	P-3	P-4
Coal type	-	Bituminous	Bituminous	Bituminous	Bituminous
Q _{net,ar}	MJ kg ⁻¹	20.77	21.89	19.68	20.84
V _{daf}	%	38.54	25.28	30.04	36.63
S _{t,ar}	%	0.61	2.06	1.14	0.83
A _{ar}	%	26.62	22.33	27.71	19.89

Note: ar = received basis; daf = dry ash-free basis.

Fig. 1. Schematic diagram of measurement points (MPs). Note: APH = air preheater; LTE = low-temperature economizer.

CFPPs were $\geq 85\%$, with the highest efficiency being 91.5%. Double-scrubber WFGD processes were employed in P-2 and P-3 because of the higher sulfur contents of the coal used, resulting in higher inlet SO₂ concentrations. By contrast, single-scrubber WFGD processes were used in P-1 and P-4; consequently, they had lower desulfurization efficiencies. P-3 and P-4 were installed with LLTESPs and achieved PM removal efficiencies of 99.95% and 99.93%, respectively; their outlet PM concentrations were 18.8 and 19.0 mg m⁻³, respectively. P-1 and P-2 were installed with ESPs and thus exhibited lower PM removal efficiencies; their outlet PM concentrations were 28.7 and 37.0 mg m⁻³, respectively. To improve the synergistic PM removal efficiency of WFGD,

P-1 and P-3 were installed with PM removal equipment such as trays, high-efficiency spray layers, and high-efficiency mist removal devices as shown in Table 2. The synergistic PM removal efficiencies of WFGD for P-1 and P-3 were 75.3% and 75.5%, respectively. While P-2 and P-4 were installed with WESPs, in which PM removal efficiencies reached 88.0% and 77.1%, respectively.

Whole-process SO₃ Testing

As illustrated in Fig. 3, because of the conversion effect of the SCR catalyst, the outlet SO₃ concentration was higher than the inlet SO₃ concentration in SCR process. The SO₂/SO₃ conversion rate was between 0.69% and 1.03%.

Fig. 2. Removal of NO_x, SO₂ and PM in the four CFPPs.

The ESPs installed in P-1 and P-2 are commonly used in practice. P-3 and P-4 were installed with LLTESPs. Because the low-temperature economizer used in the LLTESP could reduce the flue gas temperature to be lower than the acid dew point, the SO₃ in the flue gas was condensed, adsorbed on the surface of ash, and then synergistically removed by the ESP (Navarrete *et al.*, 2015; Ma *et al.*, 2017; Wang *et al.*, 2019). Accordingly, the SO₃ removal efficiencies of P-3 and P-4 were notably higher than those of P-1 and P-2, reaching $\geq 70\%$. The SO₃ removal efficiency of the WFGD in the four CFPPs was between 36% and 63%, exhibiting a large variation. P-2 and P-3 both had double-scrubber WFGD process and therefore had higher SO₃ removal efficiency than P-1 and P-4. This result is consistent with the related literature (Pan *et al.*, 2017a). In addition, P-2 and P-4 were installed with WESPs that had an SO₃ removal efficiency of

$\geq 70\%$. It is reported that with merits of the low resistivity and high output voltage, WESP can improve the collection of submicron particles such as sulfuric acid mist (Bologa *et al.*, 2009; Yang *et al.*, 2018). The results also reveal that the air preheaters installed at the outlet of the SCR devices had SO₃ removal efficiencies of 10–22%. This finding might be attributable to ammonia (NH₃) that did not completely react during the SCR process eventually reacting with SO₃ in the flue gas to form ammonium bisulfate (Fleig *et al.*, 2009; Srivastava *et al.*, 2012).

Overall, because P-1 was not installed with highly efficient SO₃ removal devices, the outlet SO₃ concentration was merely reduced from 16.6 to 12.2 mg m⁻³, i.e., a removal efficiency of 27%. P-2 and P-3 were installed with a WESP and LLTESP, respectively, and the SO₃ concentration was respectively reduced from 57.7 to 9.0 mg m⁻³ and from 30.2

Fig. 3. SO_3 concentration and removal efficiency of four ULE CFPPs.

to 6.0 mg m^{-3} , corresponding to removal efficiencies of 84% and 80%, respectively. P-4 was installed with both a WESP and an LLTESP, and the final SO_3 emission concentration was only 1.4 mg m^{-3} , i.e., a removal efficiency of 94%. Excluding P-4, the SO_3 emission concentration of the remaining CFPPs exceeded the PM emission concentrations shown in Fig. 2. This indicates that the concentration of SO_3 -based condensable particulate matter emitted from some CFPPs may exceed the threshold of ULE standard for filterable particulate matter.

Adaptability Analysis of Different Control Routes

The following assumptions were first made: The obtained SO_3 removal efficiencies of the four CFPPs were assumed to be the comprehensive SO_3 removal efficiencies of the four control routes; the three SO_3 emission limits were set as 5, 10, and 20 mg m^{-3} , respectively; every 1% of sulfur content of coal generates an SO_2 concentration of 2100 mg m^{-3} ; and the concentration of SO_3 generated in a boiler is 1% of the SO_2 concentration (Zheng *et al.*, 2019). Eq. (2) was used to determine the sulfur content required for different control routes in response to the three SO_3 emission limits:

$$S_{ar} = \frac{C_{\text{SO}_3} \times 100}{2100 \times 0.01 \times (100 - \eta)} \quad (2)$$

where S_{ar} (%) is the as-received sulfur content of coal, C_{SO_3} (mg m^{-3}) is the SO_3 emission limit, and η (%) is the SO_3 removal efficiency corresponding to the control route of

each CFPP.

As illustrated in Table 4, Route 1 had the lowest SO_3 removal efficiency; hence, its adaptability to the SO_3 emission limits was poor. To meet the 5, 10, and 20 mg m^{-3} SO_3 limits, the sulfur content must be maintained at $\leq 0.32\%$, $\leq 0.65\%$, and $\leq 1.30\%$, respectively. Routes 2 and 3 exhibited higher SO_3 removal efficiencies and therefore more favorable adaptability. To meet the 5 mg m^{-3} limit, the sulfur content of Routes 2 and 3 must be maintained at $\leq 1.52\%$ and $\leq 1.21\%$, respectively; this range covers all CFPPs using low-sulfur-content coal (sulfur content $\leq 1\%$). To meet the 10 mg m^{-3} limit, the sulfur content of Routes 2 and 3 must be maintained at $\leq 3.04\%$ and $\leq 2.41\%$, respectively; this range covers all CFPPs using coal with medium sulfur content (1–2.5%). To meet the 20 mg m^{-3} limit, the sulfur content of Routes 2 and 3 must be maintained at $\leq 6.09\%$ and $\leq 4.83\%$, respectively, corresponding to the coal with high sulfur content ($> 2.5\%$). The SO_3 removal efficiency of Route 4 was 94%, indicating the strongest adaptability. To meet the strictest emission limit of 5 mg m^{-3} , the sulfur content only needed to be maintained at $\leq 3.76\%$, which covers most of the CFPPs in China.

Table 4. Sulfur content required for different control routes under various emission limits.

Control Route	5 mg m^{-3}	10 mg m^{-3}	20 mg m^{-3}
Route 1	0.32	0.65	1.30
Route 2	1.52	3.04	> 5
Route 3	1.21	2.41	4.83
Route 4	3.76	> 5	> 5

Analysis of Compliance with SO₃ Emission Limit for 148 Sampled Plants

As revealed in Fig. 4, among the 148 sampled CFPPs, those that employed Route 1 exhibited poor adaptability to emission standards. Specifically, these CFPPs did not meet the 5 mg m⁻³ emission limit, and only 4% and 29% met the 10 and 20 mg m⁻³ limits, respectively. The CFPPs that used Routes 2 and 3 demonstrated superior adaptability to emission standards compared with those using Route 1. Specifically, 20% of Route 2 CFPPs and 28% of Route 3 CFPPs met the 5 mg m⁻³ limit; 83% of Route 2 CFPPs and 86% of Route 3 CFPPs met the 10 mg m⁻³ limit; and all Route 2 and Route 3 CFPPs met the 20 mg m⁻³ limit. Finally, all Route 4 CFPPs met the 5 mg m⁻³ limit. However, most of the 148 CFPPs employed Route 1, whereas Route 4 was used only for specific purposes. Among the 148 CFPPs, only 14% met the 5 mg m⁻³ limit; 44% met the 10 mg m⁻³ limit; and 64% met the 20 mg m⁻³ limit. This indicates that some of the existing ULE CFPPs require adjustment or modification to meet such standards.

Fig. 5 presents statistics regarding the control routes and up-to-standard ratio of the 148 CFPPs at various sulfur contents. CFPPs using low-sulfur-content coal mostly produced flue gas with low PM concentration; hence, Route 1 was used in 85% of such CFPPs. Among the CFPPs using medium-sulfur-content coal, Route 1 was used in 46%, with the remaining CFPPs split equally between Routes 2 and 3. Regarding CFPPs using high-sulfur-content coal, the acid corrosion of the low-temperature economizer must be considered, meaning that such CFPPs do not generally employ an LLTESP. Accordingly, Routes 1 and 2 were employed by most of the CFPPs using high-sulfur-content

Fig. 4. Percentage of CFPPs meeting various emission standards.

coal. When the SO₃ emission limit was set as 5, 10, and 20 mg m⁻³, the percentage of CFPPs using low-sulfur-content coal meeting the emission limit was 15%, 30%, and 100%, respectively; that of CFPPs using medium-sulfur-content coal was 18%, 54%, and 59%, respectively; that of CFPPs using high-sulfur-content coal was 0%, 24%, and 58%; and that of all CFPPs was 14%, 44%, and 64%. Assuming that the emission limit was 5 mg m⁻³ for CFPPs using low-sulfur-content coal, 10 mg m⁻³ for CFPPs using medium-sulfur-content coal, and 20 mg m⁻³ for CFPPs using high-sulfur-content coal, then all CFPPs employing Routes 2, 3, and 4 could meet the emission limit, all CFPPs employing Route 1 could not meet the emission limit. Due to 51% CFPPs employing Route 1, indicating that only 49% of the 148 CFPPs could meet the emission limit in this scenario, and the CFPPs employing Route 1 still require adjustment or modification.

Fig. 5. The control routes and up-to-standard ratio of the 148 CFPPs at various sulfur contents.

Table 5. Adaptability of different SO₃ control routes.

Sulfur content (%)	20 mg m ⁻³	10 mg m ⁻³	5 mg m ⁻³
S ≤ 1%	Routes 1–4	Routes 2–4	Routes 2–4
1% < S ≤ 2.5%	Routes 2–4	Routes 2–4	Routes 2–4
S > 2.5%	Routes 2–4	Route 4	Route 4

Analysis of SO₃ Control Routes

As revealed in Table 5, when the emission limit was 20 mg m⁻³, Route 1 could be employed by CFPPs using low-sulfur-content coal; when the emission limit was reduced to 10 or 5 mg m⁻³, such CFPPs would have to be installed with an LLTESP or WESP. Regarding CFPPs using medium-sulfur-content coal, an LLTESP or WESP would have to be installed to meet all emission limits. When the emission limit was set as 20 mg m⁻³, an LLTESP or WESP would have to be installed in CFPPs using high-sulfur-content coal. However, when the emission limit was 10 or 5 mg m⁻³, Route 4 would have to be used in such CFPPs to meet the emission limit. It should be noted that the D/S must be controlled above 100 to avoid acid corrosion of low-temperature economizer (Zhang *et al.*, 2015; Zheng *et al.*, 2019).

As shown in Fig. 6, from the perspective of whole-process control, the following improvements can be implemented to enhance the synergistic control of SO₃ emission during various stages of SO₃ generation and removal:

SO₃ conversion in a boiler involves the joint effect of a homogeneous gas-phase reaction, catalytic process of fly ash particulate, catalytic processes of ash accumulated on pipe walls, and catalytic processes of metal oxides on pipe walls (Ahn *et al.*, 2011; Belo *et al.*, 2014; Xiao *et al.*, 2018). Adjusting the sulfur content of coal and optimizing the combustion conditions would facilitate control of SO₃ generation in boilers.

Regarding SCR system, related studies have indicated that adjusting the catalyst formulation, increasing the catalyst specific surface area and reducing the catalyst wall thickness inhibit the oxidation of SO₂ (Schwämmle *et al.*, 2013; Li *et al.*, 2015; Wang *et al.*, 2020). Therefore, gradually replacing existing catalysts with those causing a lower

SO₂/SO₃ conversion rate would control SO₃ synthesis, thereby complying with future emission standard.

When the inlet flue gas duct of an ESP has sufficient space, a low-temperature economizer can be installed at this location to reduce the flue gas temperature lower than the acid dew point. Accordingly, the acidic adsorption of fly ash can be utilized to greatly improve the synergistic SO₃ removal capability of the ESP (Zhao *et al.*, 2018). This approach can also be employed to improve the PM removal capability and the synergistic PM removal capability of WFGD systems. In addition, the recovered flue gas residual heat can be used in other applications (Shanthakumar *et al.*, 2008; Bin *et al.*, 2017).

Studies have indicated that the SO₃ synergistic removal efficiency of WFGD is mainly affected by the inlet SO₃ concentration, slurry temperature, the inlet flue gas temperature, liquid-to-gas ratio, and spray coverage (Wu *et al.*, 2017b; Zheng *et al.*, 2018). Wu *et al.* (2017a) reported that the removal efficiency of SO₃ can be improved from 30–40% to greater than 60% by using a novel process based on heterogeneous vapor condensation. It is expected that SO₃ removal performance could be improved through further partial modification.

Regarding the WESP, the transformation can be considered when there is sufficient space at the tail of the boiler and it also requires the control of PM_{2.5}, Hg and other pollutants (Zheng *et al.*, 2017; Yang *et al.*, 2019). Recent studies indicate that the SO₃ removal efficiency of WESP can be effectively improved by reducing gas velocity, increasing corona power and optimizing the electrode when burning high-sulfur coal (Yang *et al.*, 2018).

When limitations exist in terms of coal property, modification space, or treatment for ABS deposition in air preheaters, SO₃-specific removal techniques that involve

Fig. 6. Schematic diagram of SO₃ emission control improvements. Note: ASI = alkaline sorbent injection.

powdered or slurry alkaline sorbents (e.g., those containing calcium, magnesium, or sodium) can be applied (Wolf and Seaba, 2012; Galloway and Padak, 2017; Zheng et al., 2020). This approach can be employed along with existing environmental facilities capable of synergistic SO₃ removal to meet SO₃ emission standard.

CONCLUSIONS

The SO₃ removal efficiencies of four typical ULE systems were assessed via field testing, and the removal capability of specific devices as well as the synergistic effects between the devices were analyzed. Additionally, we examined 148 power plants to determine whether their ULE systems enabled them to comply with various SO₃ emission standards. We also proposed control strategies for SO₃ that consider the whole process. Based on our experimental results and statistical analysis, the following conclusions can be drawn:

- 1) The SO₃ removal efficiencies of the power plants, which employed different control routes, ranged between 27% and 94%, with a fraction of the CFPPs emitting SO₃ at concentrations exceeding the current PM limit for ULE systems.
- 2) CFPPs employing Route 1 complied with the 20 mg m⁻³ SO₃ emission standard only when the coal's sulfur content was ≤ 1.30%. CFPPs employing Route 2 or 3 complied with the 10 mg m⁻³ standard when either low- or medium-sulfur coal was combusted. Route 4 displayed the best performance for SO₃ removal.
- 3) 14%, 44%, and 64% of the 148 sampled CFPPs complied with the 5, 10, and 20 mg m⁻³ SO₃ emission standards, respectively. If the standards were set to 5, 10, and 20 mg m⁻³ for low-, medium- and high-sulfur coal, respectively, 49% of the CFPPs would be in compliance.
- 4) To comply with the SO₃ emission standards, the sulfur content of the coal, boiler operating conditions, and SO₂/SO₃ conversion rate of catalysts in the SCR system should be examined and optimized. ESPs can be replaced with LLTESPs, and WFGD systems can be adjusted or modified according to factors such as the inlet flue gas temperature, liquid-to-gas ratio, and spray coverage. Where necessary, WESP or ASI technology can be implemented to enhance the SO₃ removal efficiency.

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DISCLAIMER

The authors declare no conflicts of interest.

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