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RESEARCH ARTICLE

Permitted emissions of major air pollutants from coal-fired power plants in China based on best available control technology

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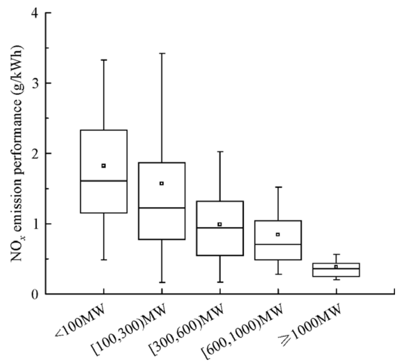
HIGHLIGHTS

- We proposed the SO_2 and NO_x emission performance standards for coal-fired power plants based on the best available control technology.
- The CFPGUs' SO_2 emission performance reference values should be 0.34 g/kWh for active units in general areas and 0.13 g/kWh for newly built units and active units in key areas.
- The CFPGUs' NO_x emission performance standard reference values should be 0.35 g/kWh for active units in general areas and 0.175 g/kWh for new units and active units in key areas.

GRAPHIC ABSTRACT



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ABSTRACT

Based on the activity level and technical information of coal-fired power-generating units (CFPGU) obtained in China from 2011 to 2015, we, 1) analyzed the time and spatial distribution of SO_2 and NO_x emission performance of CFPGUs in China; 2) studied the impact of installed capacity, sulfur content of coal combustion, and unit operation starting time on CFPGUs' pollutant emission performance; and 3) proposed the SO_2 and NO_x emission performance standards for coal-fired power plants based on the best available control technology. Our results show that: 1) the larger the capacity of a CFPGU, the higher the control level and the faster the improvement; 2) the CFPGUs in the developed eastern regions had significantly lower SO_2 and NO_x emission performance values than those in other provinces due to better economic and technological development and higher environmental management levels; 3) the SO_2 and NO_x emission performance of the Chinese thermal power industry was significantly affected by the single-unit capacity, coal sulfur content, and unit operation starting time; and 4) based on the achievability analysis of best available pollution control technology, we believe that the CFPGUs' SO_2 emission performance reference values should be 0.34 g/kWh for active units in general areas, 0.8 g/kWh for active units in high-sulfur coal areas, and 0.13 g/kWh for newly built units and active units in key areas. In addition, the NO_x emission performance reference values should be 0.35 g/kWh for active units in general areas and 0.175 g/kWh for new units and active units in key areas.

1 Introduction

How to determine the permitted emissions of enterprises is the most crucial technical link of scientific, rational, and effective implementation of a fixed pollution source environmental management system. At present, four main methods to appraise and determine the permitted emissions have been studied and applied: environmental quality allocation method, represented by the A-P value method; allocation method based on an economic index; allocation method based on specific criteria; and an integrated allocation method based on a mathematical model. Among these, the allocation method based on specific criteria, of which the emission performance

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method is typical, comprehensively considers the production technology level, energy utilization efficiency, and pollution control status of the enterprise; the appraisal method is simple and operational. Thus this method has been widely recognized and applied in environmental management practices (Wang and Pan, 2005; Xu, 2005; Zhu, 2006; Han, 2007; Liu et al., 2007; Shi and Lu, 2008; Burtraw and Szambelan, 2009; Wang, 2011; Chan et al., 2012; Crossland et al., 2013; Jin, 2013; Zhang et al., 2013; Zhang and Chen, 2014; Qiu, 2016). Emission performance refers to the level of pollutant emissions per unit of product produced, reflecting the environmental behavior of an enterprise. The thermal power industry pollutant emission performance standard, also known as the generation performance standard (GPS), is a pollutant emission standard developed based on electricity output and refers to the amount of pollutants emitted per 1 kWh of electricity produced by a power plant (Zhu et al., 2003). The power generation performance standard is based on multiple factors such as process technology, clean production level, resource and energy consumption, and pollution control status of generator units, which can reflect the emission intensity of pollutants and the environmental efficiency of power generators (Xu et al., 2013). The use of the emission performance method to determine the permitted emission limits of enterprises can take into account both the production and pollution control capabilities of enterprises, can effectively promote enterprises with poor environmental performance to improve their environmental behavior, is conducive to the improvement of the enterprise production technology and pollution control level, and has a positive effect on structural adjustment. Also, the emission performance method is highly flexible and can be adjusted based on various factors such as environmental quality, social economy, and management requirements in different regions. It is a technical method for permitted emission appraisal that best reflects fairness and efficiency. For example, many researchers have utilized the emission performance method as a pollution allocation method (Zhu et al., 2003; Xu et al., 2013; Zhang and Bai, 2015), and the emission performance method have also been used in designing the control scenarios on SO_2 and NO_x in China (Zhou et al., 2010; Zhong et al., 2016). What's more, in the acid rain program, the United States adopted the emission performance method to allocate SO_2 and NO_x emission allowances for power generation equipment, to implement dual control on emission performance and fuel use, and to implement a total air pollutant emissions control and trading system, achieving a substantial reduction in total pollutant emissions and yielding significant environmental benefits (Liang, 2010; Wu, 2011).

In December 2016, the Technical Specification for the Application and Issuance of a Pollutant Discharge Permit of the Thermal Power Industry issued by the Ministry of Environmental Protection of China stipulated that the emission performance method should be used to determine the permitted emissions of existing thermal power units, based on current emission standards that thermal power units are implementing, that is, the permitted emissions of generator units are appraised and decided according to the multiplication of emission performance value and production capacity. The selection of the emission performance value plays a decisive role in the appraisal of the thermal power industry's pollutant discharge permitted in China. Permitted total emissions are an important means to further implement the environmental quality improvement goals when all the enterprises meet the emission standard but still fail to meet the environmental quality requirements. Therefore, permitted total emissions should be closely related to the environment quality and should be determined in combination with the technical and economic feasibility. Especially, in areas where environmental quality fails to meet standards, it is necessary to impose stricter control over the total amount of pollutants emitted by enterprises and institutions through stricter permitted total emissions so as to promote the improvement of environmental quality. However, at the present stage, the emission performance value for appraising thermal power enterprises' permitted total emissions in China is mainly selected based on the national or local pollutant emission standard. Similar to the appraisal basis for permitted emission concentration, it is very difficult to exert the real control role of permitted total emissions. We systematically evaluated Chinese thermal power enterprises' SO_2 and NO_x actual emission performance levels and analyzed emission characteristics and influential factors. Based on this, we are the first to propose a method to determine the permitted total emissions of thermal power enterprises based on the control level of the best feasible pollution prevention and control technology, with a view to provide technical support for further improving the scientificity and accuracy of pollutant permitted basic work.

2 Data and methods

2.1 Data source

Taking 2010 as the base year, and based on the data for every unit in the power industry and on-site inspection results of 30 provinces (autonomous regions and municipalities, excluding Tibet) in the total inspection report from 2011 to 2015 in China, we performed the following: Summarized the data from pure coal-fired generator units that implement the Thermal Power Plant Air Pollutant Emission Standards (GB13223), analyzed the installed capacity, power generation, heat supply, coal consumption, sulfur content of coal combustion, volatile matter, pollution control technology, desulfurization efficiency, and denitrification efficiency of each coal-fired power-generating unit (CFPGU) from 2010 to 2015, and calculated and analyzed SO_2 emissions, NO_x emissions, and their corresponding emission performance. The 2010 data were obtained from the first national pollution survey data.

2.2 Calculation method

Due to the uneven operation of the online monitoring system of CFPGUs in China during the "12th Five-Year Plan" period, to ensure the comparability of data, we used the material balance method to calculate the SO_2 emissions (E_{SO_2}) (unit: ton) of CFPGUs in the study area. The calculation formula is

$$E_{SO_2} = M \times S \times \alpha \times (1-\eta) \times 10^4, \quad (1)$$

where M, S, α, and η are the power (heat) generation coal consumption (unit: 10,000 tons), power (heat) generation coal average sulfur content (%), SO_2 emission coefficient, and comprehensive desulfurization efficiency (%), respectively.

NO_x emissions E_{NO_x} (unit: ton) were calculated using the pollutant coefficient method, and the calculation formula is

$$E_{NO_x} = M \times pf \times (1-\eta) \times 10, \quad (2)$$

where M, pf, and η are the coal consumption (unit: 10000 tons), NO_x pollutant production intensity (unit: kg per ton of coal), and comprehensive denitrification efficiency (%), respectively. Among them, for units put into operation prior to 2010, the pollutant intensity of NO_x production was determined based on the data from the first national survey of pollution sources in 2010; for units built and put into operation after 2010, the pollutant intensity of NO_x production was determined based on unit capacity, volatile matter of coal combustion, and combustion mode, based on the values according to the new unit emission coefficient in the addendum Table 5-2-1 of the Detailed Calculating Rules For Total Emission Reduction of Major Pollutants for the "12th Five-Year Plan" Period (Ministry of Environmental Protection, 2011)

The major air pollutant emission performance (EP, unit: g/kWh) of CFPGUs was calculated according to pollutant emissions and unit generating capacity (power generation and heat supply) of generator units. The calculation formula is

$$EP = \frac{E}{(D \times 10 + H \times 0.278 \times 0.3) \times 10}, \quad (3)$$

where D and H are the power generation (unit: kWh) and heat supply (in MJ/year), respectively.

2.3 Calculation parameters

2.3.1 Installed capacity

Through survey and analysis, we obtained the distribution of the installed capacity of CFPGUs in China from 2010 to 2015. From 2010 to 2015, the proportion of large-capacity CFPGUs nationwide increased annually. In 2015, the total installed capacity of CFPGUs in Chinese independent power plants and self-supply power plants was approximately 930 million kW, of which 64.4% of the units were units with a single-unit capacity less than or equal to 100 MW, i.e., a decrease of 5 percentage points from 2010; the proportion of CFPGUs with a single-unit capacity above 300 MW accounted for approximately 20% of all units, i.e., up 7 percentage points from 2010. The coal-fired power plant capacity distribution from 2010 to 2015 is shown in Fig. 1.

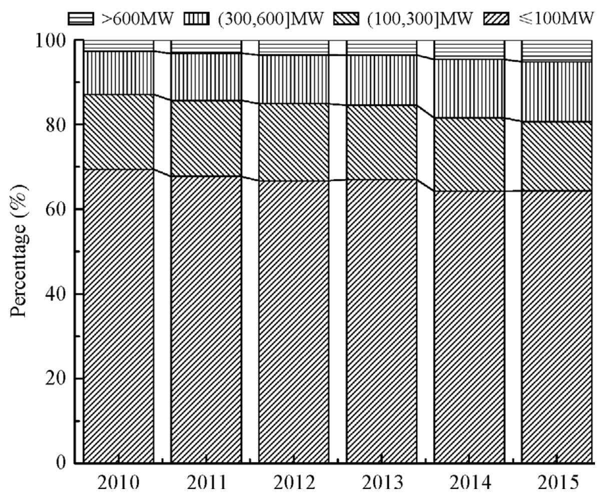

Fig. 1 Coal-fired unit capacity distribution in China from 2010 to 2015

2.3.2 Power generation and coal consumption

Through survey and analysis, we obtained the power generation and coal consumption of CFPGUs in China from 2010 to 2015. In 2015, the generating capacity of CFPGUs in China was approximately 3942.8 billion kWh, and the coal consumption was approximately 2.09 billion tons, up by 22.5% and 13.8%, respectively, from 2010. Figure 2 shows the trend of changes in power generation and coal consumption of CFPGUs in China from 2010 to 2015. Further calculation of standard coal consumption of CFPGUs each year shows that the standard coal consumption of national CFPGUs declined annually from 2010 to 2015.

2.3.3 Pollution control technology

Through survey and analysis, we obtained the changes in the installed capacity of CFPGUs that were equipped with desulfurization and denitrification facilities in China from 2010 to 2015, as shown in Fig. 3. From 2010 to 2015, the transformation of desulfurization and denitrification pro-

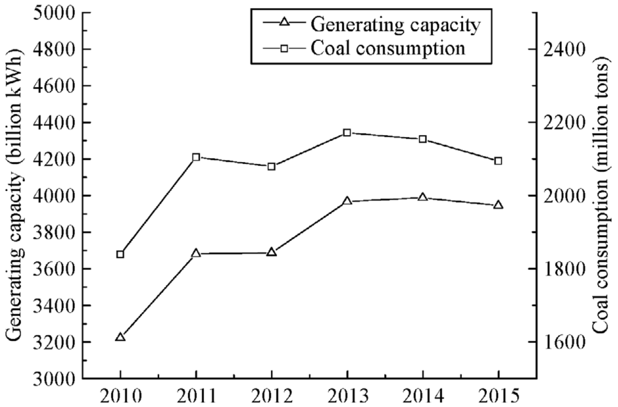

Fig. 2 Power generation and coal consumption of coal-fired power-generating units in China from 2010 to 2015

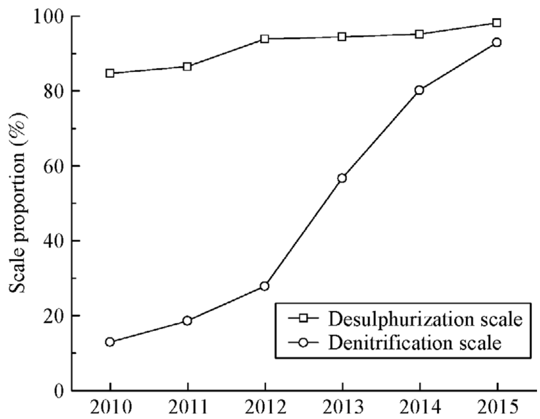

Fig. 3 Nationwide coal-fired power-generating units' total desulfurization and denitrification scale proportion from 2010 to 2015

cesses of CFPGUs progressed rapidly. In terms of desulphurization, after 2012, the number of units using flue gas desulfurization technology continued to increase. In 2015, the installed capacity of desulphurization units in China totaled 860 million kW, accounting for more than 98% of the total national installed capacity of coal-fired power plants, representing an increase of 14 percentage points over 2010. In terms of denitrification, starting from 2013, the nationwide large-scale retrofitting of flue gas denitrification was implemented. In 2015, the installed capacity of CFPGUs in China totaled 810 million kW, accounting for approximately 93% of the total national installed capacity of coal-fired power plants, an increase of 80 percentage points over 2010.

3 Results and discussion

3.1 Spatiotemporal distribution of SO_2 and NO_x emission performance of CFPGUs in China

3.1.1 Temporal distribution characteristics of emission performance

In 2015, the SO_2 and NO_x emissions from CFPGUs of Chinese thermal power industry were 5.187 million tons and 5.331 million tons, down by 45% and 49%, respectively, from the 9.48 million tons and 10.522 million tons in 2010. In 2015, the average SO_2 and NO_x emissions performance of CFPGUs were 1.3 g/kWh and 1.4 g/kWh, respectively. In comparison to the average emission performance of 1.97 g/kWh of SO_2 and 0.94 g/kWh of NO_x in the United States in 2014 (Office of Air and Radiation, 2006; EPA, 2006; 2017), there is still a large gap in NO_x. In terms of changes over time, the average SO_2 and NO_x emission performance of CFPGUs in 2015 decreased by 56% and 58%, respectively, from that in 2010. This is due in part to the increasing stringent emission standards and control requirements of the thermal power industry. In particular, the *EmissionStandard of Air Pollutants for Thermal Power Plants (GB13223-2011)*, implemented on January 1, 2012, placed higher requirements on the control level of SO_2, NO_x and other major air pollutants. The decrease in SO_2 and NO_x emission performance also reflects the overall technological advancement and the improvement of pollution prevention and control technology of the thermal power industry. CFPGUs of different capacities showed different degrees of reduction in emission performance. As for CFPGUs with a single-unit capacity>600 MW, the average SO_2 emission performance decreased from 1.13 g/kWh in 2010 to 0.38 g/kWh in 2015, with an annual reduction rate of approximately 19%; the average NO_x emission performance decreased from 2.21 g/kWh to 0.53 g/kWh in 2015, with an annual reduction rate of approximately 25%, and the reduction rate increased annually. As for CFPGUs with a single-unit capacity of (300 MW, 600 MW], the average SO_2 emission performance decreased from 1.72 g/kWh in 2010 to 0.63 g/kWh in 2015, with an annual reduction rate of approximately 18%; the average NO_x emission performance decreased from 2.84 g/kWh in 2010 to 0.77 g/kWh in 2015, with an annual reduction rate of approximately 23%. As for CFPGUs with a single-unit capacity $\leqslant$300 MW, the average SO_2 emission performance decreased from 1.39 g/kWh in 2010 to 0.64 g/kWh in 2015, with an annual reduction rate of approximately 14%, and the average NO_x emission performance decreased from 1.17 g/kWh in 2010 to 0.57 g/kWh in 2015, with an annual reduction rate of approximately 13%. In general, the larger the capacity of the CFPGUs, the lower the SO_2 and NO_x emission performance values and the faster the annual reduction rate. Changes in the national CFPGUs' SO_2 and NO_x emission performance over time are shown in Fig. 4.

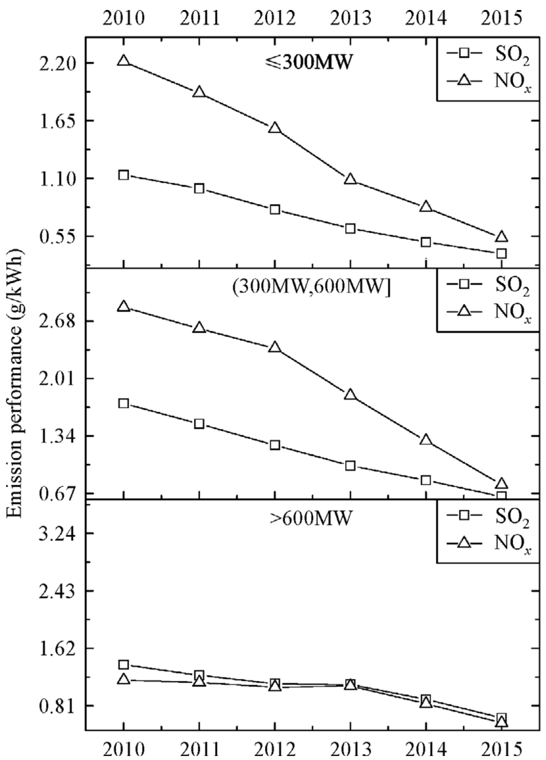

Fig. 4 Nationwide coal-fired units' SO_2 and NO_x emission performance changes over time

3.1.2 Spatial distribution of emission performance

CFPGUs in China showed significant spatial differences in emission performance as well as obvious regional characteristics. For CFPGUs with a capacity less than or equal to 300 MW, Beijing, Hebei, Tianjin and Yunnan provinces (municipalities directly under the central government) showed better levels of SO_2 and NO_x emission control, and the emission performance values were significantly lower than those of other provinces. For CFPGUs with a single-unit capacity between 300 MW and 600 MW, Tianjin, Heilongjiang, Fujian and Zhejiang provinces had relatively low SO_2 emission performance values, while Tianjin, Chongqing, Guangdong, Xinjiang and Hubei had relatively low NO_x emission performance values. For CFPGUs with a single-unit capacity larger than 600 MW, the SO_2 emission performance in Beijing, Tianjin, Inner Mongolia, Xinjiang and Jiangsu was relatively low, and the NO_x emission performance in Hainan, Guangdong, Jiangxi, Shanghai and Hunan was relatively low. In general, due to the more advanced economic and technological development level and the high-intensity environmental management requirements in Beijing, Tianjin, Hebei and the surrounding areas, CFPGUs of various capacities in eastern regions showed better SO_2 and NO_x pollution control levels, and the average emission performance was generally lower than that in other regions. The SO_2 emission performance was relatively high in Chongqing, Sichuan, and Ningxia because their CFPGUs mainly used local high-sulfur coal as fuel. In addition, a comparative analysis of the overall distribution of the emission performance of CFPGUs with capacities at the three levels showed that the larger CFPGUs, the smaller the spatial difference in the air pollutant emission performance value. The SO_2 and NO_x emission performance of large-capacity CFPGUs (single-unit capacity greater than 600 MW) in most provinces in China was lower than 1 g/kWh. The spatial distribution of SO_2 and NO_x emission performance values of CFPGUs in China in 2015 are shown in Fig. 5 and Fig. 6.

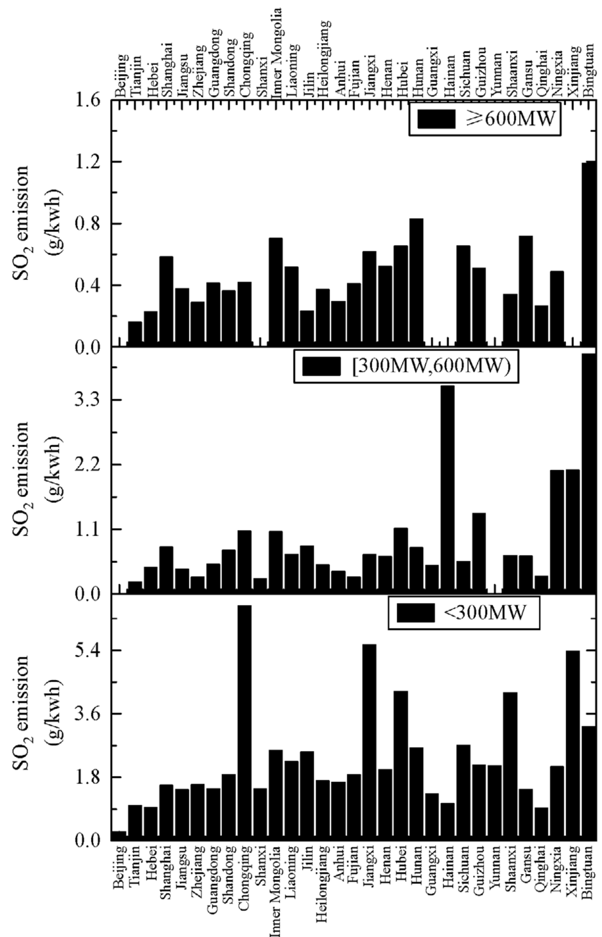

Fig. 5 Spatial distribution of nationwide coal-fired units' SO_2 emission performance in 2015

3.2 Characteristics of thermal power industry's SO_2 and NO_x emission performance in China

At present, there are few studies on the characteristics and influential factors of the thermal power industry's SO_2 and NO_x emission performance in China, and mostly are conducted in a certain province or region. For example, Zhu conducted a study on power industry's SO_2 emission performance in Jiangsu Province. The results show that the factors such as installed capacity, sulfur content of coal

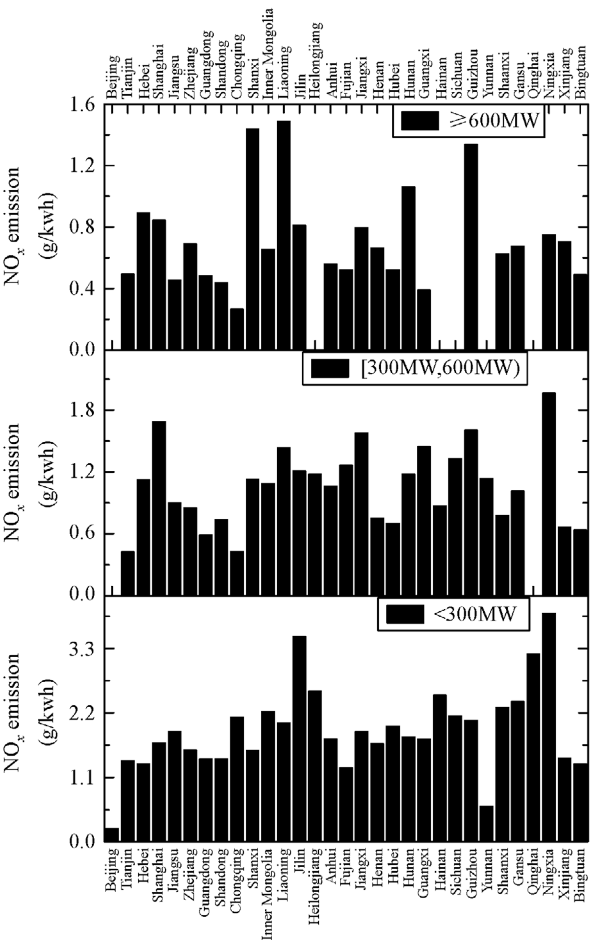

Fig. 6 Spatial distribution of nationwide coal-fired units' NO_x emission performance in 2015

combustion, and unit type may have an impact on pollutant emission performance. At the same sulfur content, the larger the installed capacity, the better the SO_2 emission performance of the generator unit, reflecting the superiority of high-capacity units in improving power generation efficiency and reducing pollutant emissions (Zhu, 2006). We systematically analyzed nationwide CFPGUs' SO_2 and NO_x emission performance from three aspects: installed capacity, sulfur content of coal combustion, and unit operation starting time.

3.2.1 SO_2 emission performance

3.2.1.1 Installed capacity

We surveyed the SO_2 emission data of 274 national CFPGUs using the limestone-gypsum wet desulfurization process and coal with a sulfur content of 0.9%–1.1% in 2015. Our results show that when using a similar sulfur content of coal combustion and pollution control technology, the larger the installed capacity of CFPGUs, the lower the average SO_2 emission performance and the better the environmental behavior. The SO_2 emission performance of CFPGUs with a single-unit capacity less than 100 MW was significantly higher than that of units greater than 100 MW. The average SO_2 emission performance of CFPGUs with a single-unit capacity above 600 MW was less than 1 g/kWh, and the larger the scale, the smaller the performance reduction magnitude and speed.

Within the scope of the study, the SO_2 emission performance of CFPGUs using the limestone-gypsum wet desulfurization process and coal with a sulfur content that ranged from 0.9% to 1.1% in 2015 is shown in Fig. 7.

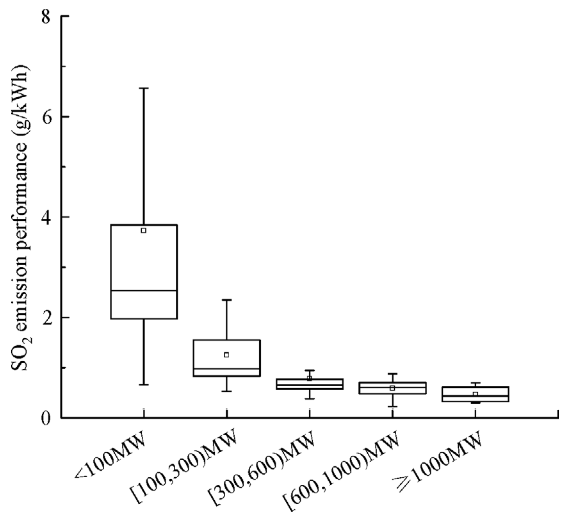

Fig. 7 SO_2 emission performance of nationwide coal-fired units with different capacities in 2015

3.2.1.2 Sulfur content of coal combustion

To further study the effect of the coal sulfur content on SO_2 emission performance, we investigated 681 CFPGUs using the limestone-gypsum wet desulfurization process with a capacity between 100 MW and 300 MW, 300 MW and 600 MW, and above 600 MW, and conducted SO_2 emission performance analysis. Our results show that with an increase in the sulfur content, the SO_2 emission performance significantly increased. This is because when the same pollution prevention and control technology is used in a generator unit, the higher the sulfur content, the higher the generated SO_2 concentration and the greater the emission performance value. The SO_2 emission performance changes of CFPGUs with different coal sulfur contents are shown in Fig. 8.

3.2.1.3 Unit operation starting time

There are some differences in the operation and management of pollution control facilities between the existing units that implement the pollution control technology upgrades and the new units that adopt the advanced technologies directly, which may result in different actual

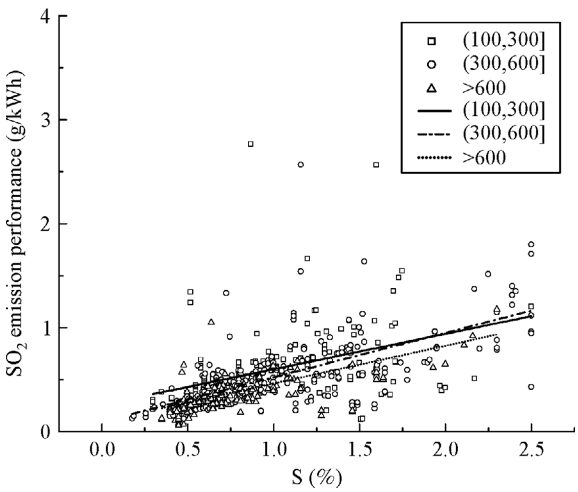

Fig. 8 SO_2 emission performance of coal-fired units with different coal sulfur contents

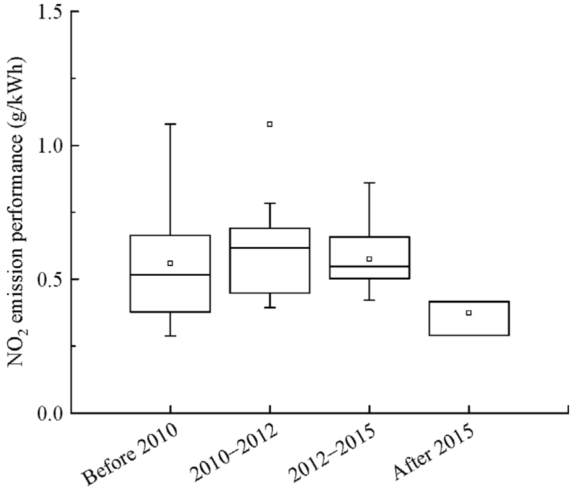

Fig. 9 SO_2 emission performance of coal-fired units with different operation starting time

emission performance levels. Therefore, we analyzed the emission performance characteristics of new and old units and considered two main factors in dividing the CFPGUs' operation starting time: 1) on January 1, 2012, the *Thermal Power Plant Air Pollutant Emission Standards (GB13223-2011)* were put into effect, which imposed higher requirements on the SO_2 and NO_x and other major air pollutants' control level; in particular, newly built, rebuilt, and expanded thermal power units approved by the environmental impact assessment documents after January 1, 2012 must meet the higher emission standard. 2) During the "12th Five-Year Plan" period, the Chinese government further imposed ultra-low emission reconstruction requirements on newly built, renovated, and expanded thermal power generator units, requiring that the emission concentration of air pollutants after the reform basically reach the emission limit of gas turbine units. Based on this, we classified four periods for CFPGUs' operation starting time as follows: Prior to January 1, 2010; January 1, 2010 (inclusive)–January 1, 2012; January 1, 2012 (inclusive)–January 1, 2015; and post-January 1, 2015 (inclusive). In addition, we analyzed the SO_2 emission performance of 90 CFPGUs using the limestone-gypsum wet desulfurization process with a single-unit capacity over 600 MW and 0.8%–1.2% coal sulfur content. Our results show that when the unit capacity, pollution control measures, and coal sulfur content were consistent, the SO_2 emission performance level of new units was better. The SO_2 emission performance changes of CFPGUs with different operation starting time are shown in Fig. 9.

3.2.2 NO_x emission performance

3.2.2.1 Installed capacity

We surveyed the NO_x emissions data of 305 CFPGUs using a low nitrogen burner, the SCR process, and coal with volatile matter(Vdaf) between 20%–37% in 2015. Our analysis results show that similar to the SO_2 emission performance, the NO_x emission performance significantly decreased with increasing single-unit capacity. When the volatile matter and pollution control technology were similar, the larger the installed capacity of the CFPGUs, the lower the average NO_x emission performance, and the better the environment performance. Within the scope of the study, the NO_x emission performance of CFPGUs using low nitrogen burners and SCR processes with volatile matter between 20%–37% in 2015 is shown in Fig. 10.

3.2.2.2 Unit performance in the operation starting time

We analyzed new and old units for NO_x emission

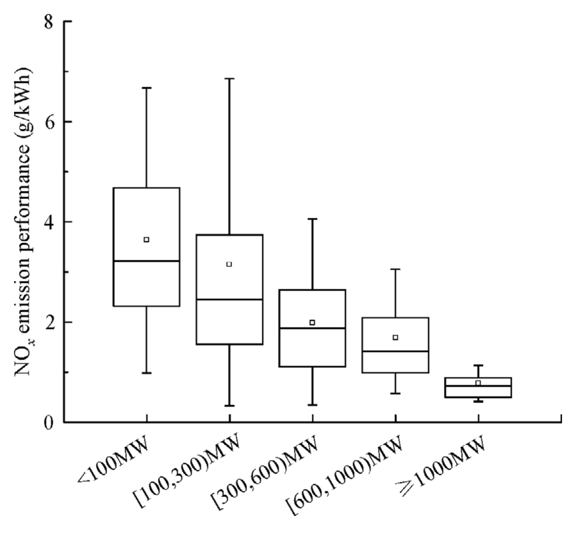

Fig. 10 NO_x emission performance of Chinese coal-fired units with different capacities in 2015

performance characteristics. We classified the units in accordance with the four periods of CFPGU operation starting time: prior to January 1, 2010; January 1, 2010 (inclusive)–January 1, 2012; January 1, 2012 (inclusive)–January 1, 2015; and post-January 1, 2015 (inclusive), and analyzed the NO_x emission performance value of CFPGUs with a single-unit capacity over 600 MW and using a low nitrogen burner, the SCR process, and coal with volatile matter between 20%–37%. Our results show that when the unit capacity, pollution control measures, and volatile matter were consistent, the NO_x emission performance level of new units was better (Fig. 11).

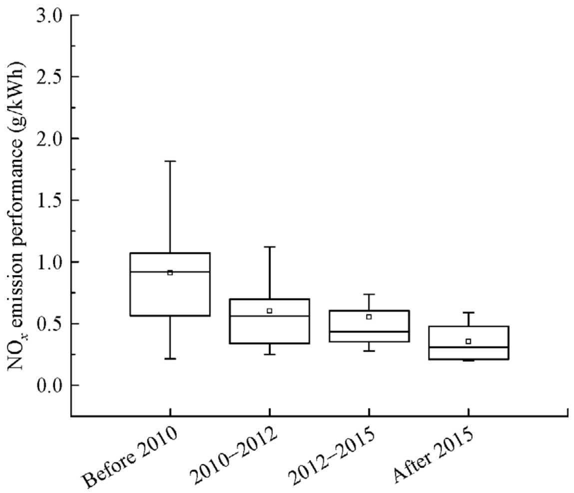

Fig. 11 NO_x emission performance of coal-fired units with different operation starting time

Integrated above analysis, the installed capacity, sulfur content of coal combustion, and the unit operating starting time as influence factors which have an impact on pollutant emission performance will be taken into account when proposing the SO_2 and NO_x emission performance standards as shown in Section 3.3.

3.3 Emission performance standard based on best available control technology

3.3.1 SO_2 optimal control level

Flue gas desulfurization is one of the main ways to control SO_2 emissions from thermal power plants, and its technology is mature and reliable. At present, the flue gas desulfurization processes around the world mainly include the limestone-gypsum wet method, semi-dry method, flue gas CFB dry method, seawater method, electron beam method, and ammonia water washing method. Among them, limestone-gypsum wet desulfurization, which has a high desulfurization efficiency, rich sources of absorbents, low prices, and by-products that can be recycled, is the most mature and best performing desulfurization process in the world, with stable operating conditions for coal-fired power plants, is suitable for flue gas desulfurization of any type of coal, and its general desulfurization efficiency is not lower than 95% (Zhong et al., 2016).

At present, the limestone-gypsum wet method is the most widely used desulfurization technology in the thermal power industry in China. In particular, almost all large units over 300 MW have adopted the limestone-gypsum wet method. According to the statistics in this article, in 2015, CFPGUs that adopted the limestone-gypsum wet method accounted for 88.4% of the total installed capacity; seawater desulphurization accounted for approximately 2.6% of the total installed capacity; flue gas circulating fluidized bed desulphurization accounted for approximately 2.0% of the total installed capacity; and ammonia desulfurization accounted for approximately 1.1% of the total installed capacity, in addition to limited applications of the dry/semi-dry method, acid-base method and magnesium method.

Through the systematic study of technical principles, technical characteristics, applicable conditions, technical development and application status, relevant process parameters, and the best control effect of various types of flue gas desulfurization technologies, we summarized application conditions and the best possible control effects of various types of flue gas desulfurization technologies (Table 1) (Zhu and Wang, 2014; Liu at al., 2015; Zhu et al., 2016; Department of Science, Technology and Standards, 2017). The ultra low emission technology based on the limestone-gypsum wet desulfurization process shown in the Table 1 is the feasible technology for ultra-low emission.

3.3.2 NO_x optimal control level

According to our analysis, as of 2015, the denitrification processes used in the national thermal power industry were mainly selective catalytic reduction (SCR), accounting for 91.3% of the total installed capacity, followed by non-selective catalytic reduction (SNCR), accounting for approximately 7.4%, and SNCR + SCR, CFB boiler cycle oxidation absorption (COA), and other processes, together accounting for approximately 1.3%.

SCR denitrification technology is currently the most advanced flue gas denitrification process with the best practical performance. At present, newly built and active pulverized coal furnaces in China mainly use SCR technology. Among several major denitrification technologies, SCR has the highest denitrification efficiency, and the denitrification efficiency can reach at least 90% based on the rational selection and optimization of reactors and catalysts.

Through the systematic study of technical principles, technical characteristics, applicable conditions, technical

Table 1 Desulfurization technology optimal control level

Device name		Removal effect	Applicable conditions
Limestone-gypsum wet method		95%–98%	All
Ultra low emission technology based on the limestone-gypsum wet desulfurization process	Traditional desulfurization technology efficacy	99%	Low-sulfur coal with inlet concentration less than 1000
	Dual-cycle desulfurization process	99%	Low-sulfur coal with an inlet concentration of 1000–2000, medium-sulfur coal of 2000–6002 and high-sulfur coal of more than 6000
	Composite tower desulfurization technology	99%	Low-sulfur coal with an inlet concentration of 1000–2000 and medium-sulfur coal of 2000–6001
	Single-tower dual-zone technology, rotary exchange coupling wet desulfurization technology	99%	Low-sulfur coal with an inlet concentration of 1000–2000, medium-sulfur coal of 2000–6002 and high-sulfur coal of more than 6000
Flue gas circulating fluidized bed		95%	All
Ammonia desulfurization		98%	Acid recovery of the sulfur industry, small and medium-sized pulverized coal furnaces
Seawater desulfurization		99%	Coastal power plants with better sea area diffusion conditions and sulfur content not higher than 1 can be regarded as ultra-low technology
Magnesium desulfurization		95%	All

development and application status, relevant process parameters, and the best control effect of various types of NO_x pollution prevention and control technologies, we summarized applicable conditions and the best possible control effect of various types of NO_x pollution prevention and control technologies (Table 2 and Table 3) (Zhu and Wang, 2014; Liu et al., 2015; Department of Science, Technology and Standards, 2017).The available technology as shown in Table 3 is the feasible technology for ultra low emission.

3.3.3 Design of SO_2 emission performance standard

The thermal power industry SO_2 emission performance value is determined based on the optimal achievable emission level of thermal power generation boiler under different types of pollution prevention and control technologies and the standard flue gas quantity per unit product. The standard flue gas quantity per unit product is determined mainly based on smoke volume per ton of fuel, fuel consumption due to power generation, and the heat value of each type of fuel. According to the analysis of factors affecting CFPGUs' SO_2 emission performance in Section 3.2, the installed capacity, coal sulfur content, and operation starting time all had significant impacts on SO_2 emission performance. Taking into account the purpose of promoting industrial upgrade, enhancing industrial process technology, and controlling pollution through emission permit management, we calculated the standard flue gas quantity of large-scale units above 600 MW and proposed an SO_2 emission performance standard system design for new and old pollution sources in different regions.

Based on the results in Section 3.3.1, we calculated the optimal achievable emission concentration levels for various types of flue gas desulfurization technologies in

Table 2 NO_x pollution control feasible technology

NO_x control technology	Removal effect	Application scope
Low nitrogen burner	50%	Bituminous coal
SCR	90%	Varies with catalyst layer number
SNCR	30%–50%	For small and medium-sized pulverized coal furnaces
	40%–75%	For circulating fluidized beds
	70%	Circulating fluidized beds with SNCR + catalytic oxidation absorption
SNCR/SCR combined flue gas denitrification	55%–85%	For pulverized coal furnace and circulating fluidized beds

Table 3 Best available control technology combination for emission concentration ⩽ 50 mg/m^3

Combustion method	Coal type		Boiler capacity (MW)	Maximum production concentration (mg/m^3)	Feasible technology combination
	Anthracite		All	850	No advanced technology
Tangentially burning	Lean coal		All	800	
	Bituminous coal	20% ⩽ Vdaf ⩽ 28%	⩽100	400	Low-NO_x combustion retrofit + SCR (3 + 1)[a] or SNCR/SCR combined denitrification (300 MW and below)
			200	350	
			300	320	
			⩾600	290	
		28% ⩽ Vdaf ⩽ 37%	⩽100	300	
			200	290	
			300	240	
			⩾600	200	Low-NO_x combustion retrofit + SCR (2 + 1)[a]
		37% < Vdaf	⩽100	290	Low nitrogen combustion retrofit + SCR (3 + 1)[a] or SNCR/SCR combined denitrification (300 MW and below)
			200	240	
			300	200	Low-NO_x combustion retrofit + SCR (2 + 1)[a]
			⩾600	180	
	Lignite		⩽100	300	Low-NO_x combustion retrofit + SCR (3 + 1)[a] or SNCR/SCR combined denitrification (300 MW and below units)
			200	260	
			300	200	Low-NO_x combustion retrofit + SCR (2 + 1)[a]
			⩾600	200	
Wall-burning	Lean coal		All	650	No advanced technology
	Bituminous coal	20% ⩽ Vdaf ⩽ 28%	All	450	Low NO_x combustion retrofit + SCR (3 + 1)[a]
		28% ⩽ Vdaf ⩽ 37%		380	
		37% < Vdaf		260	
	Lignite		All	260	
	Lean coal		All	800	
CFB	Bituminous coal, lignite		All	150	Low nitrogen combustion retrofit + SNCR
	Anthracite, lean coal		All	200	Low-NO_x combustion retrofit + SNCR/SCR combined denitrification

Note: [a] Denitrification catalyst layer different regions and further determined the optimal achievable SO_2 emission performance standards and feasible technology combinations, as shown in Table 4. This was done by comprehensively considering the technical characteristics, applicability, economy, and removal efficiency of various types of flue gas desulphurization processes. In addition, considering that coal sulfur content had significant impacts on SO_2 emission performance, the emission performance value is proposed with the weighted average sulfur content set to 0.92% for the national thermal power units, and the weighted average sulfur content set to 2.20% for high-sulfur coal areas.

Compared with the average SO_2 emissions of CFPGUs of China shown in Section 3.1.1, the optimal achievable SO_2 emission performance standards is far below the actual emission level.

3.3.4 Design of the NO_x emission performance standard

The performance value of NO_x emissions from the thermal power industry is determined based on the optimal emission control level of coal-fired power generation boilers under different types of pollution prevention and control technologies and the standard flue gas quantity per unit product. The unit standard flue gas quantity is determined mainly based on smoke volume per ton of fuel, fuel consumption due to power generation, and the heat value of each type of fuel of CFPGUs. According to the analysis of factors affecting CFPGUs' NO_x emission performance in Section 3.2, the installed capacity and operation starting time significantly affected the NO_x emission performance. Taking into account the purpose of promoting industrial upgrade, enhancing industrial process technology, and controlling pollution through emission permit management, we calculated the standard flue gas quantity of large-scale units above 600 MW and proposed a NO_x emission performance standard system design for new and old pollution sources in different regions.

Based on the results in Section 3.3.2, we determined the CFPGUs' NO_x emission performance standards and feasible technology combinations based on the optimal achievable technology listed in Table 5. This was done by comprehensively considering the technical characteristics, applicability, economy, and optimal achievable control level of various types of NO_x control technologies, considering the best feasible control technology adopted in key areas.

Combined with the results in Section 3.1.1, the actual CFPGUs' NO_x control level is far from reaching the optimal achievable emission performance standard.

4 Conclusions

1) The SO_2 and NO_x emission performance status in Chinese thermal power industry showed significant

Table 4 SO_2 emission performance based on optimal control level

Region	Controlled outlet concentration (mg/m^3)	Emission performance (g/kWh)	Applicable technology	Applicable conditions
Active units in general areas	96	0.34	Limestone-gypsum method	All
			Circulating fluidized bed method	
			Seawater desulfurization	
Active units in high-sulfur coal areas	230	0.8	Limestone-gypsum method	All
			Circulating fluidized bed method	
			Seawater desulfurization	
All new units and active units in key areas	35	0.12	Traditional empty tower spray limestone gypsum method	Low-sulfur coal of inlet concentration of less than 1000
			Dual-cycle desulfurization technology	Low-sulfur coal of inlet concentration of 1000–2000, medium-sulfur coal of 2000–6000, high-sulfur coal of 6000 or more
			Complex tower desulfurization technology	Low-sulfur coal of inlet concentration of 1000–2000, medium-sulfur coal of 2000–6000
			Single-tower dual-zone technology	Low-sulfur coal of inlet concentration of 1000–2000, medium-sulfur coal of 2000–6000, high-sulfur coal of 6000 or more
			Rotary coupling wet desulfurization technology	Low-sulfur coal of inlet concentration of 1000–2000, medium-sulfur coal of 2000–6000, high-sulfur coal of 6000 or more
			Seawater desulfurization	Coastal power plants with better sea-area diffusion conditions below inlet concentration of 2000 can be used as ultra-low-tech

Table 5 NO_x emission performance based on optimal control level

Region	Controlled concentration (mg/m^3)	Emission performance (g/kWh)	Feasible technology	Notes
Active units in general areas	100	0.35	Low nitrogen retrofit + SCR	
			SNCR	For circulating fluidized bed
			SNCR/SCR combined flue gas denitrification	
All new units and active units in key areas	50	0.175	Low-nitrogen retrofit + SCR (3 + 1)	
			SNCR + catalytic oxidation absorption	For circulating fluidized beds
			SNCR/SCR combined flue gas denitrification	For circulating fluidized beds

temporal and spatial distribution characteristics. From a time series point of view, SO_2 and NO_x emission control in the Chinese thermal power industry significantly improved from 2010 to 2015 — the larger the generator unit capacity, the higher the control level and the faster the increase in speed. From a spatial distribution point of view, the SO_2 and NO_x emission performance of generator units in the developed eastern regions was obviously lower than that in other provinces due to better economic and technological development and a higher environmental management level.

2) The SO_2 and NO_x emission performance level in the Chinese thermal power industry was significantly affected by the capacity of single generator units, the coal sulfur content, and the operation starting time of the unit. The larger the single-unit capacity, the lower the SO_2 and NO_x emission performance value and the better the environmental performance. When the generator units used the same pollution prevention and control technology, the higher the coal sulfur content, the higher the emission performance value. At a certain coal sulfur content, the SO_2 emission performance exhibited large differences among five levels — less than or equal to 50 MW, between 50 MW and 100 MW, between 100 MW and 300 MW, between 300 MW and 600 MW, and above 600 MW. When the single-unit capacity was increased to more than 300 MW, the reduction rate of emission performance value gradually decreased.

3) Based on the achievability analysis of optimal pollution control technology, and by comprehensively considering the factors that influence the emission performance, such as the installed capacity, sulfur content and operation starting time, we proposed the following SO_2 emission performance standard reference values for Chinese thermal power industry CFPGUs: 0.34 g/kWh for active units in general areas, 0.8 g/kWh for active units in high-sulfur coal areas, and 0.13 g/kWh for newly built units and active units in key areas. The NO_x emission performance standards recommend are as follows: 0.35 g/kWh for active units in general areas and 0.175 g/kWh for newly built units and active units in key areas.

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