

# Experimental Study on Boiler NO<sub>x</sub> Emission Characteristics Basing on Power Plant Efficiency

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**Abstract.** Nowadays, NO<sub>x</sub> emission was taken more and more seriously, Emission standard of air pollutants for thermal power plants was enacted newly by Chinese State Environmental Protection Department which is considered to be the strictest NO<sub>x</sub> emission standard up to now, but similar to other NO<sub>x</sub> controlling regulations in the world, the present NO<sub>x</sub> emission metering form mostly base on concentration limit value without referring to power plant efficiency. Thus, this paper proposes a new NO<sub>x</sub> emission evaluation index as Power Generation Emission Rate and Power Supply Emission Rate for first time, then proceed to study NO<sub>x</sub> emission characteristic by two experimental parts, first part was carried out under unit different load via 6 experimental cases, second part was carried out under unit same load via the other 6 experimental cases. The results indicates that, whether under different unit load, or under same unit load, the new NO<sub>x</sub> emission index can evaluate boiler de-nitration technology more precisely in a quantitative way and owns a better applicability than traditional NO<sub>x</sub> concentration value, Power Supply Emission Rate of NO<sub>x</sub> can evaluate NO<sub>x</sub> emission characteristic more directly while unit supply per kilowatt-hour power to grid, which offers a new direction for objective evaluation to different kinds of de-nitration technologies.

## 1 Introduction

As is known, Coal supply energy to world meanwhile pollute the environment in dust, sulfur dioxide, nitrogen oxides, carbon dioxide, ash and other forms, and nitrogen oxides is primary cause for hazy weather and air pollution in China[1,2]. The monitoring and controlling of coal fired power plant need to be strengthened due to its biggest coal consumption in China. The installed capacity of Chinese thermal power plant will reach one billion kilowatts and NO<sub>x</sub> emission will reach 11 million tons [3-5]. Therefore, controlling of NO<sub>x</sub> emission of coal fired power plant has become increasingly concerned in China, Emission Standard of Air Pollutants for Thermal Power Plants(GB13223-2011) which was enacted by Chinese State Environmental Protection Department is the strictest emission standard in the world up to now, according to its provision, the NO<sub>x</sub> emission mass concentration limit value should less than 100 mg/Nm<sup>3</sup>.

There are three main low NO<sub>x</sub> control technologies for most boilers: low NO<sub>x</sub> combustion technology (LNCT), Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) technologies for flue gas de-nitration. The efficiency of SCR is highest and easy to reach NO<sub>x</sub> emission standard, but initial investment and daily operation cost is also highest[6]. The initial investment, daily operation cost and efficiency of SNCR is medium[7]. The initial investment and daily operation cost of LNCT is relative lowest, although efficiency is lower, LNCT can reduce NO<sub>x</sub> emission before SCR device, which can effectively decrease device scale and daily operation cost of SCR[8]. LNCT is very suitable for control NO<sub>x</sub> formation, also exists contradiction between combustion efficiency and NO<sub>x</sub> decrease efficiency. If LNCT is used improperly, it will cause boiler combustion efficiency decrease, furnace slagging and corrosion increase, even power plant economical efficiency decrease[9,10]. Therefore, Implement of LNCT should ensure safety and efficiency

of power plant, and it is necessary to propose a new NO<sub>x</sub> evaluation methodology basing on power plant efficiency.

The economical operation of utility boiler not only related to enterprise economic benefit, but also related to energy conservation. Energy conservation needs to increase fuel conversion rate of thermal system, and coal consumption rate can reflect thermal efficiency performance of power plant, like equipment status, maintenance quality, operation and management level[11]. There are standard coal consumption rates for power generation and power supply, standard coal consumption rate for power generation(supply) defines standard coal consumption for each kilowatt-hour electric power generation(supply) in statistical period[12]. Lower efficiency of boiler combustion can cause power generation standard coal consumption rate increase, and higher power plant auxiliary power rate can cause power supply standard coal consumption rate increase even under same power generation standard coal consumption rate[13]. Obviously, power supply standard coal consumption rate is a comprehensive technical and economic index which can reflect efficiency of power plant.

Essentially, implement of low NO<sub>x</sub> control technology will definitely relate to boiler safety and efficiency, but present NO<sub>x</sub> emission controlling regulations in the world apply concentration limit value, but without referring to power plant efficiency. According to coal consumption rate, this paper proposes a new NO<sub>x</sub> emission evaluation index basing on coal fired power plant efficiency for first time, then study NO<sub>x</sub> emission characteristics under power plant same load and different load conditions relating to power plant current running efficiency, which offer a new direction for objective evaluation to different kinds of de-nitration measures.

## 2 Experiments

### 2.1 Experimental unit

The experimental boiler was carried out on No. 2 boiler of one power generation company in Liaoning province of China, the unit is equipped with a supercritical pressure parameter, single reheat once-through boiler, the installed combustion system is formed by sides wall opposed firing of Radial Bias Combustion burners, which is included 4 elevations and each elevation has 12 burners average locates on two side walls, and the main design parameters of boiler is given in table 1.

**Table 1.** Main design parameters of unit

| Item                                     | Unit | Value   |
|--|------|---------|
| Unit maximum power load                  | MW   | 880     |
| Boiler maximum continuous rated output   | t/h  | 520     |
| Superheating steam outlet pressure       | MPa  | 13.802  |
| Superheating steam outlet temperature    | °C   | 540     |
| Designed Coal Consumption                | t/h  | 67.76   |
| Reheating steam inlet/outlet pressure    | MPa  | 2.7/2.5 |
| Reheating steam inlet/outlet temperature | °C   | 327/540 |
| Boiler efficiency                        | %    | 92      |

### 2.2 Experimental coal

The coal burned by experimental boiler was mixed coal of 70% Shenhua coal and 30% Junggar coal, whose low heat value is 20.52MJ/kg, and the proximate and ultimate analysis of coal during experimental period is given in table 2.

### 2.3 Experimental methodology

The experimental study of this paper are divided into two parts, first part was carried out under unit different load via 6 experimental cases, second part was carried out under unit same load via the other 6 experimental cases. The Boiler SCR device inlet NO<sub>x</sub> emission concentrations of each case are different, but the outlets are same through adjustment of ammonia spraying in SCR device. After reach each case and become stable, record data hourly and continuously record 10 hours, then make average value of that 10 data before as final case data to analysis these parameter characteristic.

**Table 2.** Proximate and ultimate analysis of coal sample

| Proximate analysis (%) |                 |                 |                  | Ultimate analysis (%) |                 |                 |                 |                 |
|------------------------|-----------------|-----------------|------------------|-----------------------|-----------------|-----------------|-----------------|-----------------|
| M <sub>ar</sub>        | V <sub>ar</sub> | A <sub>ar</sub> | FC <sub>ar</sub> | C <sub>ar</sub>       | H <sub>ar</sub> | N <sub>ar</sub> | S <sub>ar</sub> | O <sub>ar</sub> |
| 14.4                   | 25.1            | 17.0            | 43.5             | 54                    | 3.08            | 0.68            | 0.84            | 9.99            |

## 3 NO<sub>x</sub> emission evaluation index

For study NO<sub>x</sub> emission characteristic basing on power plant efficiency, combined with standard coal consumption rate[14], this paper proposes a new NO<sub>x</sub> emission evaluation index as Power Generation Emission Rate (PGER) and Power Supply Emission Rate (PSER) of NO<sub>x</sub> and formula are shown as:

$$\eta'_{NOx} = \frac{m_{NOx}}{1000 \times P_{MW}} \quad (1)$$

$$\eta_{NOx} = \frac{m_{NOx}}{1000 \times P_{MW} \times (1 - \frac{\beta_p}{100})} \quad (2)$$

## 4 Results and discussion

### 4.1. NO<sub>x</sub> emission characteristic under different unit load

The unit was respectively maintained running at 56%, 62%, 68%, 74%, 80% and 100% rated load via adjustment of coal flow and air flow of boiler in first part 6 experimental cases, and data recording are shown in table 3.

Originate from parameter of first 6 experimental cases in table 3, the line plots of flue gas volume flow, NO<sub>x</sub> emission mass flow before and after SCR are shown in Fig. 1; The NO<sub>x</sub> Emission mass concentration, PGER and PSER of NO<sub>x</sub> before SCR are shown in Fig.2; The NO<sub>x</sub> emission mass concentration, PGER and PSER of NO<sub>x</sub> after SCR are shown in Fig.3.

For boiler NO<sub>x</sub> emission characteristic before SCR, as load increase in Fig.1, the flue gas volume flow and NO<sub>x</sub> emission mass flow before SCR increase gradually. As boiler load increase in Fig.2, the NO<sub>x</sub> emission mass concentration before SCR no obviously trend, basically fluctuate around 270Nmg/m<sup>3</sup>, but PGER and PSER of NO<sub>x</sub> before SCR decreases gradually and sorted by size is sequence 1>2>3>4>5>6(case No.), and it is result of monotonously trend parameter interactions among NO<sub>x</sub> emission mass flow and unit power load in (1) and (2).

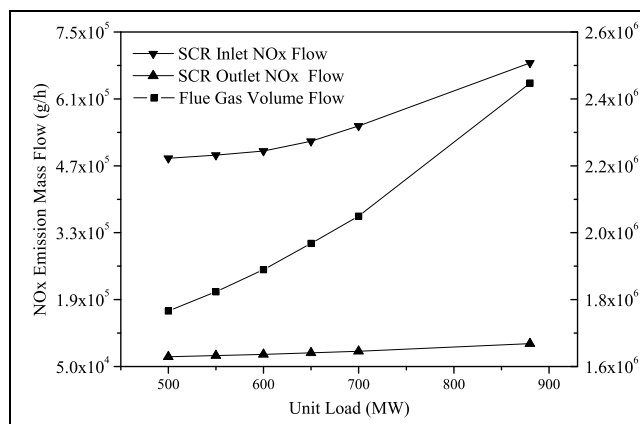
**Table 3.** Parameter of experimental cases under different unit load

| N o. | Unit Power Gene. Load (MW) | Aux. Power Rate (%) | Coal Flow (t/h) | Air Flow (t/h) | NO <sub>x</sub> before SCR (mg/N m <sup>3</sup> ) | NO <sub>x</sub> after SCR (mg/N m <sup>3</sup> ) |
|------|----------------------------|---------------------|-----------------|----------------|---|--|
| 1    | 500                        | 6.5                 | 219             | 2140           | 275   | 40   |
| 2    | 550                        | 6.3                 | 231             | 2206           | 270   | 40   |
| 3    | 600                        | 6.0                 | 248             | 2281           | 265   | 40   |
| 4    | 650                        | 5.8                 | 266             | 2370           | 265   | 40   |
| 5    | 700                        | 5.6                 | 283             | 2464           | 270   | 40   |
| 6    | 880                        | 4.8                 | 363             | 2926           | 280   | 40   |

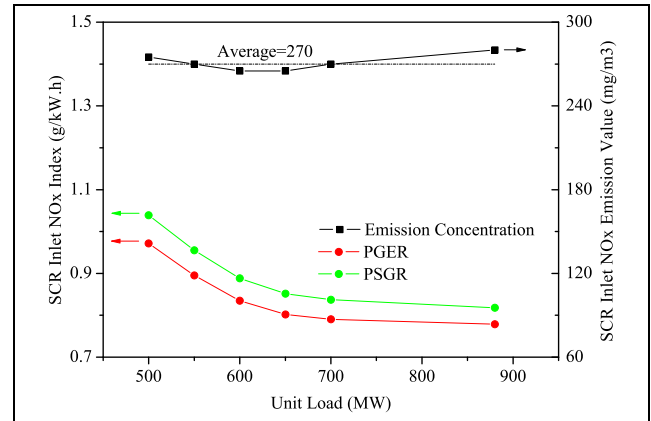
For  $\text{NO}_x$  emission evaluation before SCR of experimental boiler under different unit load, basing on traditional concentration value, the  $\text{NO}_x$  emission mass concentration has no obviously trend as unit load change. Basing on new  $\text{NO}_x$  emission evaluation index, the  $\text{NO}_x$  emission mass per kilowatt-hour get smaller as unit load increase which means  $\text{NO}_x$  emission mass per kilowatt-hour get bigger as unit load decrease, which is same as [15]. Obviously, PGER and PSER of  $\text{NO}_x$  can evaluate boiler low  $\text{NO}_x$  combustion technology more precisely in a quantitative way under different unit load, and new  $\text{NO}_x$  evaluation index basing on power plant efficiency owns a better applicability in scientific research than traditional  $\text{NO}_x$  concentration value.

For boiler  $\text{NO}_x$  emission characteristic after SCR, as boiler load increase in Fig.1, the  $\text{NO}_x$  emission mass flow after SCR increase gradually. As boiler load increase in Fig.3, the  $\text{NO}_x$  emission mass concentration after SCR are all  $40\text{Nm}/\text{m}^3$  because of SCR ammonia spraying controlling, but PGER and PSER of  $\text{NO}_x$  after SCR decreases gradually as sorted by size is sequence  $1>2>3>4>5>6$ (case No.), and it is also result of monotonously trend parameter interactions among  $\text{NO}_x$  emission mass flow and unit power load.

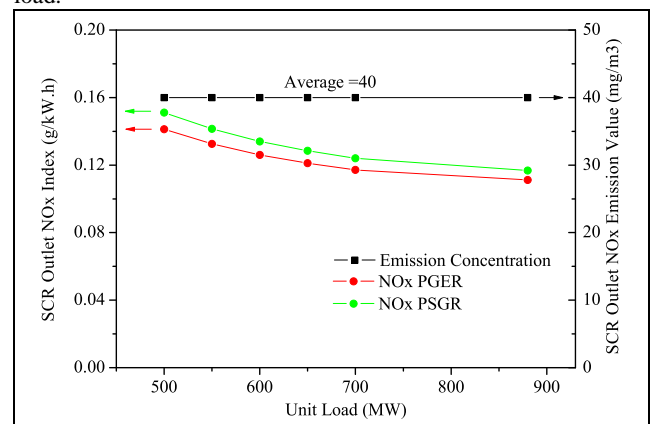
For  $\text{NO}_x$  emission evaluation after SCR of experimental boiler under different unit load, basing on traditional concentration value, the  $\text{NO}_x$  emissions mass concentration are all same after ammonia spraying. Basing on new  $\text{NO}_x$  emission evaluation index, the  $\text{NO}_x$  emission mass per kilowatt-hour decrease as unit load increase, which also means  $\text{NO}_x$  emission mass per kilowatt-hour get bigger as unit load get lower because SCR spray less ammonia, or  $\text{NO}_x$  emission mass per kilowatt-hour get smaller as unit load get higher because SCR spray more ammonia, but this will cause economic benefit decrease, corrosion and jam of air pre-heater increase [16]. Obviously, PGER and PSER of  $\text{NO}_x$  can evaluate boiler SCR technology more precisely in a quantitative way under different load, and new  $\text{NO}_x$  evaluation index basing on power plant efficiency owns a better applicability in production operation than traditional  $\text{NO}_x$  concentration value.



**Figure 1.** The change curves of flue gas volume flow,  $\text{NO}_x$  emission mass flow before and after SCR under different unit load.

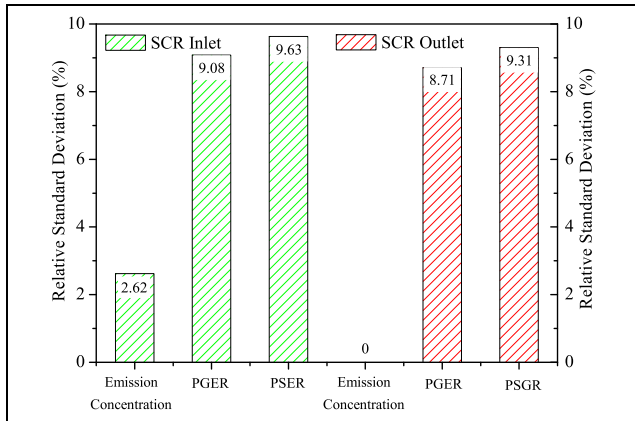


**Figure 2.** The change curves of  $\text{NO}_x$  Emission mass concentration, Power Generation Emission Rate and Power Supply Emission Rate of  $\text{NO}_x$  before SCR under different unit load.



**Figure 3.** The change curves of  $\text{NO}_x$  emission mass concentration, Power Generation Emission Rate and Power Supply Emission Rate of  $\text{NO}_x$  after SCR under different unit load.

The bar chart of Relative Standard Deviation (RSD) of  $\text{NO}_x$  emission mass concentration, PGER and PSER of  $\text{NO}_x$  before and after SCR of 6 experimental cases are shown as Fig.4, if RSD is smaller, the data group has a better uniformity, vice versa. Whether before SCR or after SCR, RSD of PGER and PSER of  $\text{NO}_x$  are both bigger than  $\text{NO}_x$  emission mass concentration as Fig.4 shows, which indicates PGER and PSER of  $\text{NO}_x$  are easy to show variability because of relating to more factors, so it can evaluate  $\text{NO}_x$  emission of experimental boiler better. Meanwhile, RSD of PSER of  $\text{NO}_x$  are slightly bigger than PGER of  $\text{NO}_x$ , this is because auxiliary power rate of experimental unit decrease as unit load increase as table 3 shows, which has a same trend with PGER and PSER of  $\text{NO}_x$  and cause uniformity of  $\text{NO}_x$  power supply index get worse, the result indicates that PSER of  $\text{NO}_x$  can evaluate  $\text{NO}_x$  emission characteristic more directly while unit supply per kilowatt-hour power to grid under different load.



**Figure 4.** The bar charts of Relative Standard Deviation of NO<sub>x</sub> emission mass concentration, Power Generation Emission Rate and Power Supply Emission Rate of NO<sub>x</sub> before and after SCR under different unit load.

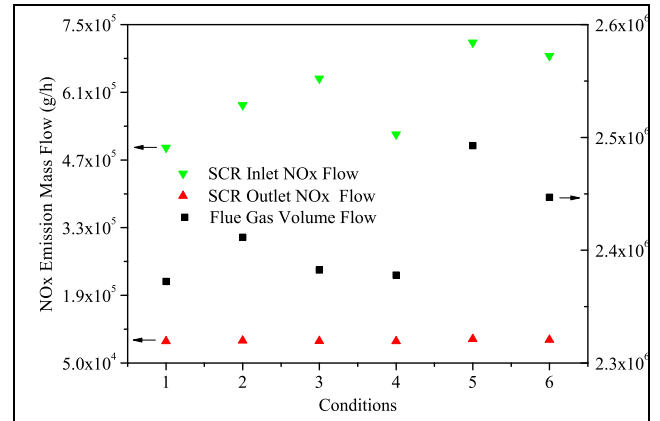
#### 4.2 NO<sub>x</sub> emission characteristic under same unit load

The unit was respectively maintained running at 100% rated load (average deviation around 880 MW is below 1%) via adjustment of coal flow and air flow in second part 6 experimental cases, parameter of each experimental case are close but not same, and data recording are shown in table 4.

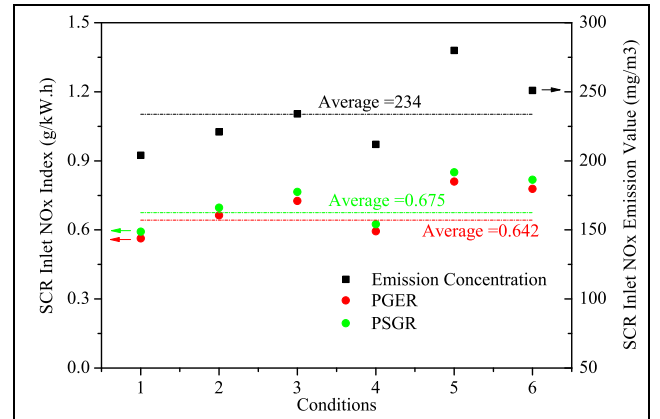
**Table 4.** Parameter of experimental cases under same unit load

| N o. | Unit Power Gene. Load (MW) | Aux. Power Rate (%) | Coal Flow (t/h) | Air Flow (t/h) | NO <sub>x</sub> before SCR (mg/N m <sup>3</sup> ) | NO <sub>x</sub> after SCR (mg/N m <sup>3</sup> ) |
|------|----------------------------|---------------------|-----------------|----------------|---|--|
| 1    | 880                        | 4.89                | 385             | 2815           | 209   | 40   |
| 2    | 880                        | 4.90                | 398             | 2857           | 242   | 40   |
| 3    | 880                        | 5.16                | 379             | 2832           | 268   | 40   |
| 4    | 880                        | 4.84                | 352             | 2844           | 220   | 40   |
| 5    | 880                        | 4.78                | 348             | 2995           | 286   | 40   |
| 6    | 880                        | 4.82                | 363             | 2926           | 280   | 40   |

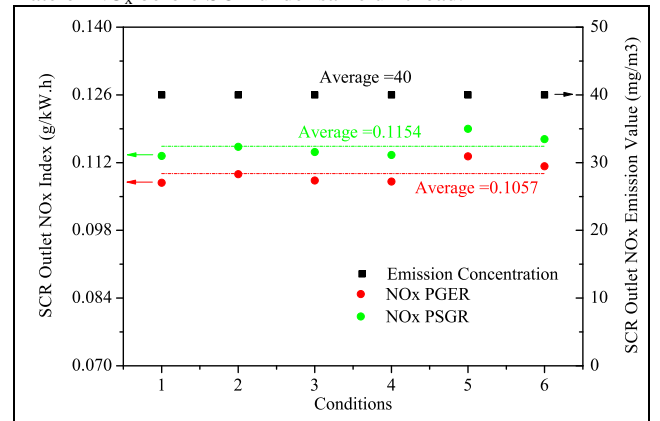
Originate from parameter of 6 experimental cases in table 4, The scatter plots of flue gas volume flow, NO<sub>x</sub> emission mass flow before and after SCR of boiler are shown in Fig.5, the NO<sub>x</sub> emission mass concentration, PGER and PSER of NO<sub>x</sub> before SCR are shown in Fig. 6, The NO<sub>x</sub> emission mass concentration, PGER and PSER of NO<sub>x</sub> after SCR are shown in Fig.7.



**Figure 5.** The scatter plots of flue gas volume flow, NO<sub>x</sub> emission mass flow before and after SCR under same unit load.



**Figure 6.** The scatter plots of NO<sub>x</sub> Emission mass concentration, Power Generation Emission Rate and Power Supply Emission Rate of NO<sub>x</sub> before SCR under same unit load.



**Figure 7.** The change curves of NO<sub>x</sub> emission mass concentration, Power Generation Emission Rate and Power Supply Emission Rate of NO<sub>x</sub> after SCR under same unit load.

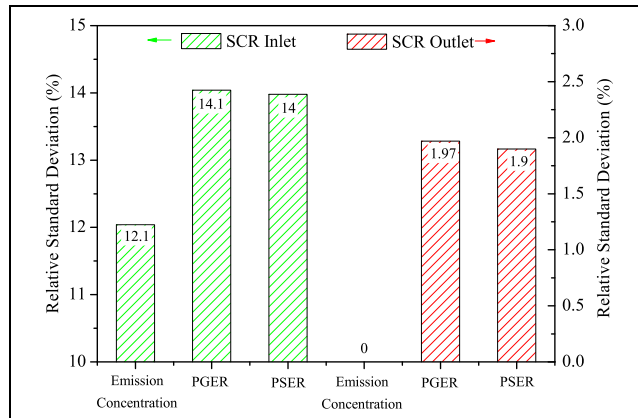
For boiler NO<sub>x</sub> emission characteristic before SCR under same unit load, as Fig.5 shows, the flue gas volume flow and NO<sub>x</sub> emission mass flow before SCR sorted by size is sequence 5>6>3>2>4>1(case No.). As Fig.6 shows, the NO<sub>x</sub> emission mass concentration before SCR, PGER and PSER of NO<sub>x</sub> before SCR sorted by size is also sequence 5>6>3>2>4>1(case No.).

For NO<sub>x</sub> emission evaluation before SCR of experimental boiler under same unit load, whether basing on tradition concentration value, or basing on new NO<sub>x</sub> emission evaluation index, the sequence of above NO<sub>x</sub>

emission parameter of each case sorted by size are same, it is because boiler coal flow and air flow get bigger, the flue gas flow will become bigger[17], and then boiler NO<sub>x</sub> emission content will get more[18,19], so NO<sub>x</sub> emission trend is consistent with boiler flue gas flow change, which indicate that new NO<sub>x</sub> evaluation index can reflect boiler low NO<sub>x</sub> combustion technology emission characteristic same as traditional NO<sub>x</sub> concentration value while under same unit load.

For boiler NO<sub>x</sub> emission characteristic after SCR under same unit load, as Fig.5 shows, the NO<sub>x</sub> emission mass flow after SCR sorted by size is sequence 5>6>3>2>4>1(case No.), the NO<sub>x</sub> emission mass concentration after SCR are all 40Nmg/m<sup>3</sup> (average deviation is below 1%) because of SCR ammonia spraying, but PGER and PSER of NO<sub>x</sub> after SCR sorted by size is also sequence 5>6>3>2>4>1(case No.).

For NO<sub>x</sub> emission evaluation after SCR of experimental boiler under same unit load, basing on traditional NO<sub>x</sub> concentration value, the NO<sub>x</sub> emission mass concentration are all same after ammonia spraying, which is irrelevant with combustion adjustment of boiler. Basing on new NO<sub>x</sub> emission evaluation index, the trend of boiler NO<sub>x</sub> emission mass per kilowatt-hour is consistent with flue gas flow change and related to coal flow and air flow of combustion, but it will help to save ammonia for spraying and increase power plant efficiency[20]. Obviously, PGER and PSER of NO<sub>x</sub> can evaluate boiler SCR technology more precisely in a quantitative way under same load, and new NO<sub>x</sub> evaluation index basing on power plant efficiency owns a better applicability in production operation than traditional NO<sub>x</sub> concentration value.



**Figure 8.** The bar charts of Relative Standard Deviation of NO<sub>x</sub> emission mass concentration, Power Generation Emission Rate and Power Supply Emission Rate of NO<sub>x</sub> before and after SCR under same unit load.

The bar chart of RSD of NO<sub>x</sub> emission mass concentration, PGER and PSER of NO<sub>x</sub> before and after SCR of 6 experimental cases are shown as Fig. 8. Whether before SCR or after SCR, RSD of PGER and PSER of NO<sub>x</sub> are both bigger than NO<sub>x</sub> emission mass concentration as Fig. 8 shows, this is consistent with conclusion of different load part. For difference, RSD of PSER of NO<sub>x</sub> are slightly smaller than PGER of NO<sub>x</sub>, it is because auxiliary power rate of experimental unit

sorted by size is sequence 3>2>1>4>6>5(case No.) as table 4 shows, which is different with sequence of above NO<sub>x</sub> emission parameter of each case sorted by size, so make uniformity of PSER of NO<sub>x</sub> get better, the result also indicates that PSER of NO<sub>x</sub> can evaluate NO<sub>x</sub> emission characteristic more directly while unit supply per kilowatt-hour power to grid under same load.

## 5 Conclusions

1) First proposes a NO<sub>x</sub> emission evaluation index basing on coal fired power plant efficiency, which offers a new direction for objective evaluation to different kinds of denitration measures.

2) For NO<sub>x</sub> emission evaluation of experimental boiler under different unit load, whether before SCR or after SCR, basing on new NO<sub>x</sub> emission evaluation index, the NO<sub>x</sub> emission mass per kilowatt-hour get smaller as unit load increase, which can't be find out by tradition NO<sub>x</sub> emission evaluation limit value. RSD of PGER and PSER of NO<sub>x</sub> are both bigger than NO<sub>x</sub> emission mass concentration, RSD of PSER of NO<sub>x</sub> are slightly bigger than PGER of NO<sub>x</sub>.

3) For NO<sub>x</sub> emission evaluation of experimental boiler under same unit load, whether before SCR or after SCR, new NO<sub>x</sub> evaluation index can reflect boiler low NO<sub>x</sub> combustion technology emission characteristic same as traditional NO<sub>x</sub> concentration value, but it will help to save ammonia for spraying and increase power plant efficiency. RSD of PGER and PSER of NO<sub>x</sub> are both bigger than NO<sub>x</sub> emission mass concentration. RSD of PSER of NO<sub>x</sub> are slightly smaller than PGER of NO<sub>x</sub>.

4) PGER and PSER of NO<sub>x</sub> can evaluate boiler NO<sub>x</sub> emission technology more precisely in a quantitative way, and new NO<sub>x</sub> evaluation index basing on power plant efficiency owns a better applicability in production operation than traditional NO<sub>x</sub> concentration value. PSER of NO<sub>x</sub> can evaluate NO<sub>x</sub> emission characteristic more directly while unit supply per kilowatt-hour power to grid.

## Nomenclature

|    |                           |
|----|---------------------------|
| M  | moisture content, (%)     |
| V  | volatile content, (%)     |
| A  | ash content, (%)          |
| FC | fixed carbon content, (%) |
| C  | carbon content, (%)       |
| H  | hydrogen content, (%)     |
| N  | nitrogen content, (%)     |
| S  | sulphur content, (%)      |
| O  | oxygen content, (%)       |
| MJ | mega joule                |
| MW | megawatt                  |

## Greek symbols

|               |  |
|---------------|--|
| $\eta'_{NOx}$ | Power Generation Emission Rate of NO <sub>x</sub> , (g/kW.h) |
| $m_{NOx}$     | NO <sub>x</sub> emission mass flow, (g/h)                    |

$P_{MW}$  Unit power load, (MW)  
 $\eta_{NO_x}$  Power Supply Emission Rate of  $NO_x$ , (g/kW.h)  
 $\beta_p$  Auxiliary power rate, (%)

### Subscripts and superscripts

ar as received  
 p Power

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## References

- [1] Su Y., Mao Y., Xu Z., Coal-fired  $NO_x$  emission control technology, M. Beijing: Chemical Industry Press (2005).
- [2] Yang Z., Wang B., Lin M., et al., The hazards and control of atmospheric nitrogen oxides in air pollution, J. Inner Mongolia Petrochemical Industry (2008), pp. 21:24-26.
- [3] Wang F., Du Y., Liu Y., et al., The present development of flue gas denitrification technologies in domestic coal-fired power plants, J. Electric Power Environmental Protection (2007), pp. 23(3):20~23.
- [4] Pang X., Shi X., Fu Z., The  $NO_x$  emission reduction of thermal power plants, J. Northern Environment, (2012), pp. 24(4):69~71.
- [5] Wang X., Study of low nitrogen combustion technology on a 300MW tangential boiler, D. Wuhan, China: Huazhong University of Science and Technology (2013).
- [6] Zhang L., Pan W., Wu J., et al., Comparative analysis of combined-removal technology of various pollutants from coal-fired boiler, J. Journal of Shanghai University of Electric Power (2010), pp. 26(4):322-326.
- [7] Brain K., Linda L.,  $NO_x$  removal with combined selective catalytic reduction and selective non-catalytic reduction: pilot-scale test results, J. Air & Waste Management Association (1994), pp. 44:1186-1194.
- [8] Wang C., Operation cost and engineering application of low  $NO_x$  staged combustion technology for air, J. Electric Power (2011), pp. 44(7):49-52.
- [9] Wang E., Peng L., Luo Y., et al., The measurements for reducing the  $NO_x$  emissions of coal fired power plants in China, J. Boiler Technology (2003), pp. 34(5):48-52.
- [10] Cao Y., Xue Y., Zhao Z., Technical strategy of control  $NO_x$  emission of power plant coal-fired boiler, J. Thermal Power Generation (1999), pp. 6:27-30.
- [11] Yang Y., Calculation and analysis of auxiliary power consumption rate of thermal power plant, J. Huadian Technology (2011), pp. 33(10):56~59.
- [12] Hong J., Wang L., A calculation analysis of the coal consumption rate in power plants, J. Journal of Electric Power (1998), pp. 13(2):90~94.
- [13] Wang M., Verified and calculation of thermal efficiency and coal consumption rate of power supply of thermal power plant, J. Huazhong Electric (1996), pp. 9(3):6~10.
- [14] Qiu L., Hao Y., Ji X., An approach to calculation the standard coal consumption rate of power supply, J. Energy Conservation (2006), pp. 286(5):23~24.
- [15] Wang S., Zhu F., Wang H., et al., Sensitivity and correlation analysis on influence factors of  $NO_x$  generated concentration from coal-fired power plant, J. Acta Scientiae Circumstantiae (2012), pp. 32(9):2303-2309.
- [16] Hu M., Study on low  $NO_x$  combustion coupled with SNCR and SCR to control  $NO_x$  emissions, D. Hangzhou, China: Zhejiang University (2012).
- [17] Che D., Zhuang Z., Li J., et al., Boiler, M. Xi'an, China: Xi'an Jiaotong University Press (2008).
- [18] Wang Z., Tan Y., Sun S., et al., Effects of stereo-staged combustion on  $NO_x$  emission characteristics of tangentially fired boiler, J. Energy Conservation Technology (2012), pp. 30(6):504-507.
- [19] Zeng G., Sun S., Zhao Z., et al., Correlation study of HCN/ $NH_3$  releasing during coal pyrolysis and  $NO_x$  formation in CFB boiler under different temperature, J. Proceedings of the CSEE (2011), pp. 31(35):47-52.
- [20] Wu Z., The selection and application of denitrification technology of pulverized coal boiler, D. Guangzhou, China: South China University of Technology (2012).