Experimental Study on Boiler Performance and NOx Emission for Coal-Fired Boilers of High Capacity

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Abstract: Nitrogen oxides (NOx) emissions and boiler efficiencies of seven 600MW and 1000MW boilers with different furnaces and burner types have been measured to analyze the effect of boiler configuration, burner type and coal type on NOx emission and boiler efficiency. The test data shows that the performance and NOx emission of the boilers are considerably impacted by boiler configuration, burner type and coal type. The high capacity boilers normally have high combustion efficiencies, and can achieve the designed efficiency value in most situations, The NOx emission levels of these boilers, however, have shown great differences. "W" flame boiler burning lean coal with a high combustion temperature and high excessive air ratio creates the highest NOx emission among the tested boilers. The boiler burning bituminous coal with high volatile content gives the lowest NOx emission. As for other boilers with different coal types, burner type and low -NOx combustion technologies, their NOx emissions are largely different. The new design technologies adopted by the new burners of the large boilers have important effects on NOx emission reducing, combustion stabilizing and combustion efficiency increasing. Variations of coal type and boiler operational parameters also have large effects on the boiler performance and the NOx emission. This study demonstrates that the NOx emission can be reduced by 10~20% by regulating the combustion conditions without changing boiler efficiency

Keywords: subcritical pressure boil; ultra supercritical boiler; boiler performance; combustion regulation; NOx emission.

1 Introduction

Coal is the chief primary energy source in China. The burning of coal produces various gases (i.e. COx, SOx, NOx etc), ash, droplets of tar, and other organic compounds, which are all released into the atmosphere and eventually cause air pollution. Among these pollutants, NOx plays a very important role and is blamed for ozonosphere destruction, acid rain and respiratory problems to mankind. Normally, one ton of coal burnt could produce 8 ~ 9 kg NOx [1,2]. In 2004, about 1.9 billion tons of coal was consumed in China and about 60% of them were used in electrical power plants[3]. With economic development growing faster, more and more coal would be consumed, which will lead to more severe NOx emission problems. In order to control NOx emission, the Chinese government introduced a NOx control legislation in 1996, which requires that the NOx emission from power plants must be less than 650mg / Nm. This figure was further reduced to 450mg/Nm^3 in the revised edition of 2003.

According to the mechanism of NOx formation, NOx emission is influenced by coal burning process. As for coal-fired boilers in power plants, the furnace configuration, burner type and coal type have large impacts on coal burning process in boiler; therefore, influence NOx emission greatly [4-6]. The impacts of furnace configuration, burner type, coal type and low-NOx combustion technologies on boiler efficiency, low-load combustion stability and NOx emission were studied in this paper for the 600MW and 1000MW coal-fired boilers of different power plants. The influences of boiler operation parameters were also studied. Optimal boiler efficiency and NOx emission were obtained by adjusting combustion and boiler operation parameters.

2 Boiler Efficiency and NOx Emission Test

Due to considerations for NOx pollution, all the 600MW and 1000MW boilers build recently in China have adopted low-NOx combustion technologies including new low-NOx burners. The authors investigated the performances and NOx emissions of seven 600MW and 1000MW boilers in Shandong and nearby provinces. The boiler types include wall firing boiler, quadrilateral tangential combustion boiler, and W - flame boiler. The coal types used in these boilers include anthracite, lean coal, bituminite, mixed coal, etc. The burner types include: swirl-flow burner and straight-flow burner.

2.1 Experimental methods

The testing standard used is GB1084-88 Performance Test Code for Utility Boiler. NOx emission was measured with a KM9106 flue gas analyzer. The gas samples were drawn out at the outlet of air preheater by grid method and then entered the flue gas analyzer through a gas mixer. Four or five sets of O_2 and NOx concentrations data were obtained at each experimental condition, and all of the data were corrected based on 6% O_2 concentration or the excess air ratio 1.4 according to the standard of GB12233-2003 (Atmosphere Pollutants Emission Standards for Thermal Power Plants).

Flue gas temperatures were measured at the outlet of air preheater. An isovel sampling device was used to take fly ash samples out from the flue to determine carbon contents in the fly ashes. Slag samples were collected manually at the outlet of a submerged ash conveyor.

Coal powder samples were obtained at the outlet of each coal feeder, and then were performed a chemical analysis as well as an elemental analysis immediately. Combustion loss and heat loss were determined with the above data, and boiler combustion efficiency was calculated.

2.2 Test data of boiler efficiency and NOx emission

The technical parameters of seven boilers is shown in Table 1.

Tab.1 The performance and NOx emission of boilers with different configurations and burner modes

unit type	subcritical 600MW	subcritical 600MW	subcritical 660MW	supercritical 600MW	supercritical 660MW	supercritical 660MW	supercritical 1000MW
power plant	Liaocheng	Hequ	Dezhou	Feixian	Weifang	Huangdao	Zouxian
boiler capacity t/h	2027	2028	2209	1913	2102	2102	3033
combustion mode	W-flame	quadrilateral tangential	wall firing	wall firing	quadrilateral tangential	quadrilateral tangential	wall firing
burner type	(a)	(b)	(c)	(d)	(e)	(f)	(g)
coal type	anthracite & lean coal	bituminous coal (high volatile	anthracite & lean coal	bituminous coal	lean coal	bituminous coal	bituminous coal (high volatile
test condition	rated condition	rated condition	rated condition	rated condition	rated condition	rated condition	rated condition
oxygen concentration, %	5.97	2.85	5.875	3.825	6.05	4.9	3.03
boiler design efficiency, %	92.50	93.60	92.55	93.38	92.0	93.58	93.8
boiler test efficiency, %	92.967	94.12	89.77	93.94	92.37	94.835	94.825
design min. stable load %	50	30	50	30	50	30	30
test min. stable load %	49.58	29.88	49.12	38	55	35.68	46.3
NOx emission mg/Nm^3	1097	367	578.5	818	958	449	326
V_{ad}%	8.76	37.82(V_{daf})	15.79	26.76	10.67	27.82	26.89
Nad%	1.04	0.87(N_{ar})	------	------	------	------	0.875
V_{daf}%	10.53	37	12.8	38	15.63	39.79	39
N_{ar}%	0.94	0.90	0.94	0.29	1.01	0.98	1.11

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Note: NOx emissions in the table have been revised to 6% oxygen concentration.
(a) slit spray burner arranged at fore and rear arch wall, tertiary air used for adjusting flame length and staged combustion
(b) straight-flow and swing burner with big proportion of CCOFA (closed-coupled over fired air) and SOFA (separated over fired air)
(c) dual adjusting swirl-flow burner, four OFA1 (over fired air) and OFA2 nozzles arranged into two layers on the top
(d) axial swirl –flow burner
(e) coaxial combustion system with 6 layers dense powder nozzles at the top and 6 layers thin powder nozzles below, SOFA nozzles arranged at the corners
(f) coaxial combustion system with 2 layers CCOFA nozzles and 5 layers OFA nozzles which can sway horizontally.
(g) Low NOx swirl-flow burner (HT-NR3) with one layer of 10 AAP (after air port) nozzles on the top.

3 Influencing Factors on Boiler Performance and NOx Emission

3.1 Impacts of boiler mode and coal type on boiler performance and NOx emission

Data in Table 1 shows that NOx emission and boiler performance vary with different boiler types, coal types and burner types. Both design and test miminum stable load of boilers burning bituminous coal are about 50% lower than boilers burning anthracite and lean coal. For the boilers at Huangdao, WeiFang, Zouxian, and Feixian power plants, test minimum load doesn't achieve the design value since the coal types used were not the design ones. Compared with boilers burning bituminous coal, boilers burning anthracite and lean coals have higher NOx emission and lower boiler efficiency. This indicates that boiler mode and coal type have big impacts on boiler performance and NOx emission.

Normally, boilers burning higher volatile coal produce less NOx[7,8]. The reasons are: (1) coal combustion characteristics influence the design of the furnace and burner. Coal with high volatile has better ignition behavior, which can tolerate lower furnace temperature, hence inhibit the generation of both fuel NOx and thermal NOx. (2) Combustion characteristics of coal influence the boiler operation mode. Coal with high volatile can burn out easily, and can also allow a low excess air ratio, which restrains the conversion of fuel nitrogen to NOx. (3) Combustion characteristics of coal influence the oxygen concentration in furnace significantly. A large portion of oxygen is consumed by combustion of volatile in ignition process, which enhances the reduction atmosphere and restricts the generation of NOx.

For the W-flame boiler, the wall at the low section of furnace is covered by refractory to form a thermal insulation layer. The combustion temperature there could reach up to 1500 ℃ or enen higher, which is close to the theoretical combustion temperature. The high temperature could be beneficial to stabilize the combustion of anthracite and lean coals. Meanwhile, the oxygen concentration at the outlet of the economizer of flame furnace is controlled at 4%~5% to ensure burnout of coal. A high boiler efficiency could be earned with high furnace temperature and high excessive air ratio but also high NOx emission up to 1500mg/m^3[9-12]. For example, the test efficiency of the boiler at Liaocheng power plant can reach 92.97% at rated condition, which is higher than the design value 92.5%. NOx emission, however, also reaches 1100mg/m^3. Fuel NOx substantially generate in W-flame boiler due to high combustion temperature, thermal NOx can also be considerably produced by reason of the typical features of W-flame boiler: high furnace temperature, oxygen-enriched combustion, high thermal load and long combustion time in high temperature area, etc. As a result, W-flame boiler has the highest NOx emission which has far exceeded the country's emission standard.

The boiler of Weifang power plant installs straight-flow burners and quadrilateral tangential combustion technology. To ensure the burnout of lean coal used, the boiler is operated with high excess air ratio, high combustion temperature and high thermal load. All these reasons lead to high NOx emission up to 958 mg/Nm^3, which is next to W-flame boiler.

The boilers of Hequ, Huangdao, Zouxian power plants burn bituminous coal with efficiency above 94%, while the NOx emissions are kept below 450mg/Nm^3, of which the minimum value is 326mg/Nm^3. High efficiency and low NOx emissions of these boilers can be attributable to the high volatile coal used in the boilers. Volatile of the coal used is above 25% (37.82%, 27.28%，26.89% respectively), which makes the coal powder burn out easily. Good ignition behaviors permit low temperature in furnace and low excess air ratio (2.85%，4.9%, 3.03% respectively). Due to the reasons above, boilers of the three power plants generate much less NOx emissions compared with the W-flame boiler and the boiler burning lean coal.

Table 1 shows that the boilers of Weifang power plant and Huangdao power plant employ the same technology but have different boiler efficiencies and NOx emissions, that is because the coals used in these boilers are different. This indicates that coal characteristics have important impacts on boiler performance and NOx emission.

For different boilers burning different coals, the oxygen concentration changes from 2.85% to 6.05%, NOx emission varies from 367mg/m^3 to 958mg/m^3. Bituminous coal with high volatile does not need much oxygen (concentration from 2.85% to 4.9%) compared to 6% for blended coal, anthracite and lean coal. Among all the boiler operational parameters, average oxygen concentration in furnace and oxygen distribution have most obvious influences on NOx emission. For most boilers, NOx emissions rise with the increase of excess air ratio at furnace outlet This proves that the influences of coal type and oxygen concentration on NOx emission are interdependent. High volatile coal presents good ignition behavior, it demands low oxygen concentration and low furnace temperature which inhibit the formations of fuel NOx and thermal NOx, thus generates low NOx .

Generally, boiler type affects combustion directly, it can affect the combustion intensity and distribution, thus affects NOx emission. Due to the demands for temperature and oxygen concentration in furnaces, different coal types lead to different boiler efficiencies and NOx emissions.

3.2 Impacts of low NOx burner on boiler efficiency and NOx emission

Two types of coal burners were investigated: straight-flow burner and swirl-flow burner, which are used for quadrilateral tangential combustion and wall firing combustion respectively.

The straight-flow burner used for quadrilateral tangential combustion employs many new technologies to reduce NOx emission and enhance boiler efficiency as well as stabilize combustion at low-load conditions. The boiler at Huangdao power plant utilizes low NOx coaxial firing system (LNCFS) to reduce the conversion of volatile nitrogen to NOx with the method of fuel/air staging combustion technology. LNCFS consists of CCOFA nozzles, SOFA nozzles, CFS nozzles and WR coal powder nozzles. With the arrangement of CCOFA and SOFA at different heights in furnace, LNCFS divides the furnace into three zones: primary combustion zone, NOx reduction zone and fuel burnout zone. This improved air staging method can increase combustion efficiency and reduce NOx emission through optimizing excessive air ratio in each zone. A V-type bluff body installed in the wide rage(WR) nozzles can form a stable circumfluence area which can suck up the high temperature flue gas and stabilize combustion flame. This would reduce NOx emission, extend coal burning time, and increase boiler efficiency. The coaxial fire manner makes a portion of the secondary air staging in horizontal direction. This delays the mixing of coal with air in the primary combustion zone and reduces the generation of NOx. The application of LNCFS on the boiler at Huangdao power plant leads to high boiler efficiency and low NO_x emission with values of 93.58% and 449mg/m^3, respectively. The boiler at Weifang power plant also adopts the advanced coaxial fire system, and NOx emission from the boiler is 140mg/Nm^3, which is less than that from the W-flame boiler at Liaocheng power plant, although both boilers utilize the same fuel.

Many modifications were introduced to different types of swirl-flow burners（dual adjusting swirl-flow burner in Dezhou power plant and HT-NR3 swirl-flow burner in Zouxian power plant, which can achieve staged combustion at the flow axial direction and avoid the formation of high temperature and oxygen rich zone, consequently reduce the NOx emissions. The principle of new dual adjusting swirl-flow burner is to introduce combustion air into the coal powder flow gradually and control the mixing process of the coal with air rationally in burner area to inhibit generation of NO_x and keep high boiler efficiency. At Dezhou power plant, the dual adjusting swirl-flow burners are installed on both the front wall

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and back wall of the furnace. Since the coal used in the boiler is blended coal of anthracite and lean coal, the primary combustion zone is covered by refractory to increase furnace temperature and stabilize combustion. Normally, a high furnace temperature would lead to a high NOx emission, but actually NOx emission from the boiler is much lower than that from the boiler at Weifang power plant. This clearly demonstrates the advantages of new type burner employed by the boiler at Dezhou power plant. The opposed wall-firing burner was applied at Zouxian power plant. There are 24 low NOx swirl-flow burners (HT-NR3) arranged into 3 layers in the front wall and the back wall of the boiler respectively. 10 AAP nozzles are arranged on the top of the burner. The HT-RN3 burners can improve the ignitability and the flame stability of high concentrated powder. These burners delay the mixture of the primary air and the secondary air and achieve the staged air supply. This creates fuel enrich and high temperature zones at the exit of the burners, and reduce the NOx emissions, and enhance the low load combustion stability without using extra oil. Over-fired air nozzles on the top of the burners ensure the coal powder to burn out easily, thus the boiler efficiency is increased. Among all the tested units, the boiler in Zouxian power plant has the highest efficiency of 94.83 %, and the lowest NOx emission of 326mg/Nm^3, which is lower than 449 mg/Nm^3 at Huangdao power plant.

Among all the boilers tested, the boiler at Hequ power plant has lower NOx emission and higher boiler efficiency. Undoubtedly, the fuel, that is, bituminous coal, used in the boiler plays an important role, but the most important factor is the advanced combustion system adopted by the boiler. The boiler employs straight-flow swaying burners. The primary air nozzles which can sway up and down within the angle range of 20ºare installed in five layers at each corner. The secondary air nozzles can sway up and down within the angle range of 30º. To reduce NOx emission, the large proportion of CCOFA and SOFA is applied which could not only guarantee air supply downstream but also obtain air staging. Three SOFA burnout chambers are arranged at the top of each burner to ensure burnout of coal powder.

4 Regulation Test of Boiler Combustion Mode to Reduce NOx Emission

The boiler performance and NOx emission can be largely influenced by boiler operational parameters. Therefore, NOx emission and boiler efficiency can be improved by reasonably adjusting the boiler operational parameters. The parameters which can influence NOx emission mainly include: primary air velocity, powder concentration, powder granularity, auxiliary air distribution, powder distribution at each layers in furnaces, excessive air ratio, boiler load, etc. [13-15]. Through reasonably adjusting combustion mode and operational parameters, tests were carried out on different burners and coal types to investigate the influence of operational parameters on the boiler efficiency and NOx emission.

4.1 Regulation test of changing oxygen concentration at outlet of economizer

The amount of total air entering the boiler has an influence on the quantity of flue gas, the burnout of coal, etc. NOx emission and the boiler efficiency have been studied by changing the oxygen concentration at the outlet of the economizer of the boiler at Huangdao power plant.

During the tests, the heat load, the amount and the pressure of first air, the pressure difference of air boxes, the burners in services and their angle are kept constant; only the oxygen concentration at outlet of the economizer is varied changed. The influences of oxygen concentration on the boiler efficiency and NOx emission are shown in figure 1.

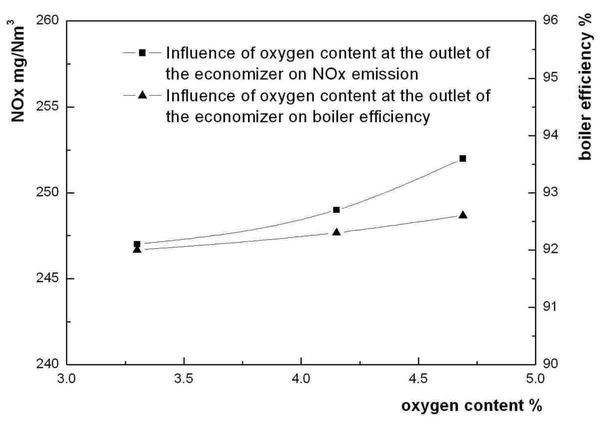

Fig.1 Influence of oxygen content at outlet of economizer on boilerefficiency and NOx emission

With the increase of oxygen concentration, the flue gas quantity increases, which leads to increase of flue gas loss but decrease of physical incomplete burning loss. In the testing range of oxygen concentration from 3.3% to 4.7%, the descent of physical incomplete burning loss is larger than the ascent of flue gas loss, so the boiler efficiency increases with increase of oxygen concentration. Meanwhile, NOx emission also increases. The reason is that the increase of air leads to the temperature in combustion area going up, which enhances generation of NOx. The effects of coal type were also studied. When using lean coal, the oxygen concentration should be kept at around 4.25% to reduce the combustible content in fly ash. When using bituminous coal, the oxygen concentration should be kept at around 3.2%. The experiment shows that the boiler efficiency could be maintained at 94% for both cases, while NOx emission could be kept at a low level, less than 400mg/m^3.

For 660MW unit at Weifang power plant, when the load was reduced to 420MW, and the oxygen concentration at the outlet of the economizer increased from 4.2% to 6.0%, NOx emission increased by 34.81%, from 494.2mg/m^3 to 666.25mg/m^3.

4.2 Regulation test of over-fired air

The local air distribution and the burnable coal powder proportion are influenced by the regulation of over-fired air[16]. The boilers at the Huangdao and the Weifang power plants employ LNCFS. The horizontal swaying OFAs are arranged on the top of the furnaces. The concentric tangential combustion manner postpones the mixing of air and the coal powder to reduce the generation of NOx. The experiment carried out at Weifang power plant shows that NOx emission can be reduced by reducing secondary air at the bottom of the furnaces and increasing SOFA air at the top in the furnaces. The test results with the change of the SOFA air distribution mode are shown in Table 2.

Table 2 Test results with the change of air distribution mode on the boilerat Weifang power plant

Condition 1	1	2	3	4
SOFA-F	0	0	0	30
SOFA-E	0	0	0	30
SOFA-D	0	0	0	10
SOFA-C	0	10	0	5
SOFA-B	0	20	0	0
SOFA-A	0	30	0	0
CCOFA-B	15	0	0	0
CCOFA-A	25	0	0	0
Oxygen content at the outlet of the economizer (%)	5.4	5.4	5.4	5.4
NOx emission concentration (mg/Nm^3)	818.03	778.61	827.88	739.18

The adjustment of the SOFA swaying angle can also regulate combustion in furnace. When the horizontal angles of the SOFA of the boiler at Huangdao power plant adjust from 15º to 5º, the NOx emission increases from 253mg/m^3 to 269mg/m^3.

The figure 2 shows the test data under 1000MW load of unit in Zouxian power plant. The test was done through adjusting the over-fired air by changing the opening of the over-fired air box inlet, without changing the coal type, the coal supply, the primary air, the center air of burner and the over-fired air, the opening of internal and external secondary air. The air in the primary combustion zone, burnable coal powder proportion, the gas temperature and NOx emission all decrease as the over-fired air increases, while the fixed carbon C_{fh} in flying ash increases. When the over-fired air is low, the fixed carbon C_{fh} in the flying ash increases gradually. But it will increase rapidly when the over-fired air is above 750t/h. The excess air coefficient in combustion zone decreases as the over-fired air increases after it is above 750t/h, which leads to the increase of incomplete combustion and fixed carbon C_{fh} in flying ash. Although more over-fired air enters into the boiler from the top of

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the burners, the boiler efficiency decreases since the over-fired time is short and the mixture in over-fired zone is incomplete.

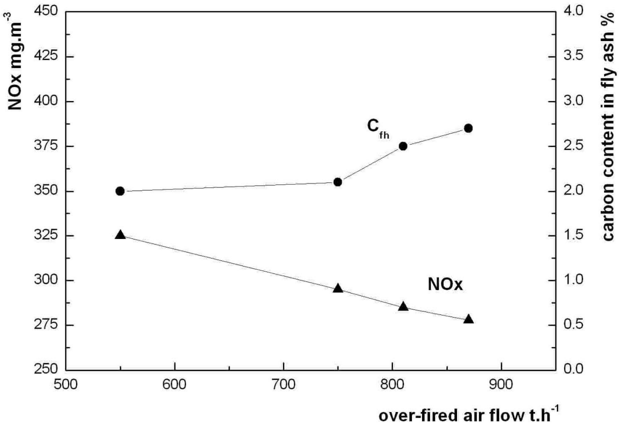

Fig.2 Influence of over-fired flow on carbon content in fly ash and NOx emission

4.3 Regulation test of changing boiler load and burner running mode

NOx emission increases with the boiler load since a high boiler load results in a high furnace temperature which can enhance NOx generation. Meanwhile, a high load is also beneficial to coal powder combustion and improve the boiler efficiency. NOx emission and the boiler efficiencies for the boilers at Liaocheng and Weifang power plants are shown in Table 3 with different boiler loads.

Table 3 Test results of boiler efficiency and NOx emission concentrationchanging with the boiler load

unit load	MW	600	500	400
boiler load at Liaocheng	t/h	1878.2	1607.8	1259.4
NOx emission	mg/Nm^3	1125.6	1003.6	953.4
boiler efficiency	%	92.967	90.32	89.66
boiler load at Weifang	t/h	1872.7	1566.1	1216.7
NOx emission	mg/Nm^3	729.8	658.05	615
boiler efficiency	%	92.826	92.248	91.741

The Running mode of burner should be adjusted according to the change of unit load. Table 4 shows the boiler test in Zouxian power plant with constant air opening and oxygen content while changing unit load and burner running mode. When the unit load decreased from 1000MW to 800MW, the carbon content in the flying ash with A、B、C、D、E five layers of burner operating is lower than that of whole A、B、C、D、E、F six layers of burner operating. Since the close of burners in F layer enhances the combustion in the burner zone and lowers the flame center , the distance of combustion is increased which makes the coal powder easier to burn out and reduces un-burnt carbon. Meanwhile, as the close of burners in F layer enhances the staged combustion and deoxidization of NOx generated in primary combustion zone, the NOx emission is reduced. According to the investigations in articles [17,20], the reduction of NOx emission could be even higher if the air opening and operational oxygen concentration are adjusted according to the change of the unit load and the burner running mode.

Table 4 Influence of unit load and burner running mode on flying ash and NOx emission

unit load MW	burner running mode	fixed carbon in flying ash %	NOx mission mg/m^3
1000	ABCDEF	2.3	299
800	ABCDE	1.7	264

5 Conclusions

Seven boilers of 600MW and 1000MW units installed recently have been studied. The boilers employ different burner types and combustion technologies, and burn different coals. The boilers exhibit different performances and NOx emission. The test and analysis results show that boiler performance and NOx emission are greatly influenced by the boiler configuration and the burner type, as well as the coal type. All the boilers except the one at Dezhou power plant attain high boiler efficiencies, and can achieve the design value. NOx emission, however, varies a lot in these boilers. The W-flame boiler burning lean coal demands the high furnace temperature and the high excessive air ratio, which lead to high NOx emission. The boilers at Hequ and Zouxian power plants, which employ quadrilateral tangential combustion and burn bituminous coal with high volatile content, have the lowest NOx emission. Operational parameters and boiler combustion mode also have big influence on boiler performance and NOx emission. The parameters should be regulated in time to optimize the boiler performance and NOx emission according to change of the coal type and the boiler load.

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