Study on ultra-low NOX emission technology of 660 MW ultra-supercritical circulating fluidized bed boiler

Shengwei Xin 1,3, Yingping Li 2, Peng Zhang 1, Changhua Hu 1 and Hu Wang 1
1SHENHUA Group CFB Technology R&D Center, Xi’an, Shaanxi, 710065, China;
2SHENHUA GUONENG ENERGY Group, Beijing, 100033, China
3Email: xinswei@163.com

Abstract. For the first 660MW ultra-supercritical circulating fluidized bed boiler in China, the original NOX emission concentration would be controlled and maintained below 50mg/Nm3, by improving the uniformity of bed temperature and bed pressure, strengthening the secondary air fractional combustion, optimizing the combustion temperature and operating oxygen and so on. Meanwhile, selective non-catalytic reduction (SNCR) technology with urea as reducing agent is selected as the auxiliary method to ensure the boiler achieves ultra-low NOX emission under full load conditions.

1. Introduction
The supercritical unit is one of the main technologies of clean coal power generation with high power generation efficiency and low pollutant emission, it’s also the most realistic and effective way to solve the problems of power shortage, low energy efficiency and environmental pollution[1]. Circulating fluidized bed (CFB) combustion technology, as one of the main coal combustion modes in China, has the advantages of wide range of fuel application, good load regulation performance and low pollutant emission[2]. The combination of the CFB combustion and the ultra-supercritical parameters will be the inevitable development direction of the future CFB boiler.

The original NOX emission concentration of CFB boiler is usually between 100~300mg/Nm3[3], which cannot meet the national standard limit that NOx emission concentration is lower than 100mg/Nm3, and the NOX emission concentration implemented in some areas is lower than the ultra-low emission standard of 50mg/Nm3, so CFB boiler is faced with the problem that NOX emission must be further reduced. Many scholars at home and abroad are committed to optimizing combustion conditions to control NOX generation[4]. The factors affecting NOX emission of CFB boiler are combustion temperature and uniformity, excess air coefficient, graded combustion and so on[5-8]. In addition, the deep reduction technology of NOX in CFB boiler, which is dominated by selective non-catalytic reduction (SNCR) technology, is also affected by the type of reductant, reaction temperature, ammonia-nitrogen ratio and so on[9-12].

2. Boiler type
660MW high-efficiency ultra-supercritical CFB boiler adopts single furnace, single air distribution plate, M-shaped arrangement structure and CFB combustion mode. The boiler is composed of 1 furnace, 4 steam-cooled cyclones, 4 loop seals, 4 external heat exchangers(EHEs), 8 slag coolers and 2 rotary air preheaters, etc. The tail part adopts double flue, the re heater adopts baffle for temperature
regulation, and the starting bed material adding system adopts mechanical conveying mode. Figure 1 is a diagram of the structure of the 660MW ultra-supercritical CFB boiler.

![Figure 1. Schematic diagram of 660MW ultra-supercritical CFB boiler.](image)

3. NO\textsubscript{X} control measures

3.1. The principle and influencing factors of NO\textsubscript{X} generation
The formation of NO\textsubscript{X} is mainly divided into thermal-NO\textsubscript{X}, fuel-NO\textsubscript{X} and fast-NO\textsubscript{X}. Since the combustion temperature in CFB boiler is maintained between 850–950\textdegree C, the NO\textsubscript{X} generated by combustion is almost all fuel-NO\textsubscript{X}, and its source is the conversion of nitrogen elements in coal\cite{13}. According to the formation mechanism of NO\textsubscript{X}, it can be seen that the generation of NO\textsubscript{X} in CFB boiler is mainly related to the following factors:

1. The coal quality. Nitrogen content, volatile content and so on in coal.
2. The excess air coefficient. Reducing the excess air coefficient can limit the oxygen concentration in the reaction zone to a certain extent, which can control the generation of fuel type-NO\textsubscript{X}.
3. The combustion temperature and its uniformity. With the increase of combustion temperature in the furnace, the emission of NO\textsubscript{X} will increase. The uniformity of the bed temperature will also contribute to the generation of NO\textsubscript{X}.
4. The desulphurizer. Dry desulphurization is usually used in CFB boiler, and limestone is used as desulphurizer, which can effectively reduce the emission of SO\textsubscript{2}, but the high content of limestone in the furnace (high ratio of calcium to sulfur) will increase the emission of NO\textsubscript{X}.

3.2. Measures for low nitrogen combustion of boiler
The 660MW ultra-supercritical CFB boiler is used mixture of the coal sludge, the gangue and the final raw coal. The mixing ratio of coal sludge, the gangue and the final raw coal in the designed coal is 55\%:20\%:25\%, and the mixing ratio of coal sludge, the gangue and the final raw coal in the checked coal is 35\%:35\%:30\%. The specific coal quality is shown in table 1.

The nitrogen content in the designed coal is low, which reduces the formation of fuel NO\textsubscript{X}, but its volatile is high, which is not conducive to the control of NO\textsubscript{X} emission. According to the low nitrogen combustion theory of CFB, the boiler is designed to reduce the original NO\textsubscript{X} concentration from the aspects of improving bed temperature, uniformity of bed temperature and bed pressure, strengthening secondary air graded combustion, optimizing combustion temperature and operating oxygen\cite{14}.
Table 1. Coal characteristics of 660MW ultra-supercritical CFB boiler.

| item                  | symbol | unit | designed coal | checked coal |
|-----------------------|--------|------|---------------|--------------|
| moisture              | Mₘ %   | 19.10| 14.00         |
| air-drying-based      | Mₘₐd% | 2.41 | 2.32          |
| received base ash     | Aₘₐr % | 31.34| 37.18         |
| volatiles             | Vₘₐf % | 33.52| 35.37         |
| fixed carbon          | FₘₐCₘ %| 32.95| 31.55         |
| carbon                | Cₘₐr % | 39.51| 37.96         |
| hydrogen              | Hₘₐr % | 2.21 | 2.28          |
| nitrogen              | Nₘₐr % | 0.40 | 0.39          |
| oxygen                | Oₘₐr % | 6.81 | 7.39          |
| sulfur                | Sₘₐr % | 0.63 | 0.80          |
| net calorific power   | Qₘₐt,ₘₐv,ₘₐr MJ/kg | 14.52| 13.99         |

3.2.1. Uniformity design of bed temperature and bed pressure. The uniformity of the combustion field in the CFB boiler is a necessary condition to ensure the low NOx emission. A large number of practical experience has proved that the premise of low NOx emission are the temperature field in the furnace is uniform, the combustion is stable, and the local coking is not generated. The uniform combustion measures of the boiler are as follows:

1) Primary air uniformity design.

Ensuring the uniformity of static pressure distribution of primary wind in water-cooled air chamber is the premise of ensuring uniform distribution of primary wind. In the design of 660 MW ultra-supercritical CFB boiler, the static pressure distribution of different feed modes of primary air is calculated and simulated, and the uniformity of static pressure distribution of different feed modes is compared. Scheme one adopts the 6-points feed mode (as shown in Figure 2), a single point and one side feed method is used in the second scheme (as shown in Figure 3). Obviously, the static pressure distribution of the feeding mode of the first scheme is better than that of the second scheme, which can ensure the good fluidization of the material. Finally, it is determined that the primary air feeding mode of the boiler is shown in Figure 4, that is, the hot primary air is fed from 6-points on the back side of the water-cooled air chamber.

![Figure 2](image_url1)  
**Figure 2.** Static pressure distribution of 6-points feed mode of primary air.  

![Figure 3](image_url2)  
**Figure 3.** Static pressure distribution of single side feed mode of primary air.
(2) Uniformity design of coal feeding.

The boiler adopts the coal feeding mode of "front wall feeding coal, back wall feeding sludge". The front wall is equipped with 12 coal falling ports, the rear wall is equipped with 8 sludge guns, and the rear wall is arranged with 8 slag discharge ports (as shown in Figure 5). The uniformity design of multi-point coal feeding is combined with the uniform distribution of primary air to ensure the uniform mixing of fuel and combustion air in the furnace and to ensure the combustion uniformity in the boiler. And then the design of the multi-point slag discharge of the wall can improve the particle size distribution of the material in the furnace by adjusting the rotating speed of the slag cooler of the different sections, and ensure the uniformity of the materials in the furnace.

(3) Cyclone uniformity arrangement.

Figure 6 is the layout diagram of cyclones. The boiler adopts a four-cyclone and a four-loop seal to be arranged symmetrically along the center line of the furnace, so that the geometric symmetry of the external circulation loop is ensured, and meanwhile, the external circulation loop is numerically simulated (as shown in Figure 7), the distribution of the mass flow rate and the corresponding flow rate deviation of the four furnace outlets for a period of time is obtained, and the solid mass flow rate of the outlet of the furnace is dynamically changed. For the M-type four-cyclones furnace scheme, the maximum deviation of the self-flow rate of the four exits is 7.9%, that is, the maximum flow rate deviation between different cyclone is 7.9%, which ensures the return uniformity of the cycle and reduces the influence of circulating ash on the combustion uniformity in the furnace.

(4) External heat exchangers uniformity arrangement.

Four external heat exchangers (EHEs) with medium temperature superheater are arranged in the boiler to eliminate the deviation of bed temperature along the width direction of large section furnace...
and reduce the deviation of bed temperature on furnace width at the same time. Figure 8 is the layout diagram of EHEs.

![Figure 8. Arrangement of boiler EHEs.](image)

![Figure 9. Numerical simulation calculation of fluidization characteristics and uniformity in furnace.](image)

To sum up, 660MW ultra-supercritical CFB boiler adopts 6-point primary air feeding, multi-point coal feeding design, cyclones and EHEs uniformity arrangement, which improves the uniformity of gas-solid two-phase flow of furnace and material circulation system. The fluidization characteristics and uniformity in the furnace are verified by numerical simulation based on Ansys Fluent software (shown in Figure 9). It can be seen that the uniformity of boiler furnace and material circulation system can be guaranteed.

3.2.2. Enhanced secondary air graded combustion. The dense phase zone combustion of CFB boiler is carried out in the reduction atmosphere, which makes the intermediate product of nitrogen combustion cannot be further oxidized to NO, but reduced to neutral N2, which can effectively control the formation of NOX.

Through the test of different primary air rate of the same boiler, it is shown that the NOX emission can be further reduced by reducing the primary air ratio on the premise of meeting the fluidization of materials in the furnace. Figure 10 shows the influence of the primary air ratio of CFB boiler on NOX emission. According to the experimental results of boiler plant, the NOX emission orderliness with different primary / secondary air ratio is simulated and studied. The suitable primary air rate is 40%.

![Figure 10. The effect of primary air ratio on NOx emissions.](image)

![Figure 11. Numerical calculation results of secondary air arrangements.](image)
(2) The secondary air is fed into the furnace cone section in layers from the lean phase zone to complete the combustion process, and it is helpful to improve the level combustion strength by raising the height of upper secondary tuyere properly, and produce a larger reduction area. At the same time, it is also beneficial to reduce the formation of NOX by properly reducing the input of the lower secondary air and increasing the amount of the upper secondary air [15].

3.2.3. Optimization of secondary design. The furnace section and furnace height of 660MW ultra-supercritical CFB boiler are larger and higher, so it is very important to design a reasonable secondary air nozzle. Figure 11 shows the numerical results of the secondary air arrangement of the boiler. It can be seen that the secondary tuyere of the front and rear walls is uniformly arranged, and the distance between the two layers of secondary tuyere is increased by more than 1.5 meters on the basis of 350 MW supercritical CFB boiler. Through numerical simulation calculation, reasonable secondary air speed and tuyere size are selected to ensure that the secondary air has sufficient stiffness and penetration ability, ensure the uniformity of temperature field in the furnace, and realize graded combustion.

3.2.4. Optimized bed temperature design. Reducing bed temperature of CFB boiler can effectively reduce the emission level of NOX, but too low bed temperature is disadvantageous to combustion and SNCR denitrification. Considering the coal quality, combustion efficiency and desulphurization efficiency, the bed temperature of the boiler in this project is 860 °C. According to the operation experience of CFB boiler, the steam temperature of reheater can be adjusted by EHEs, and the flue gas temperature at furnace outlet can be maintained at a high level at low load, which makes the screen superheater have better heat transfer characteristics at low load. The EHEs can ensure that the flue gas temperature at the furnace outlet is above 750 °C, which is beneficial to the guarantee temperature of the main steam and reheated steam, and can also ensure that the flue gas temperature of the boiler outlet meets the ammonia injection requirements of SNCR flue gas denitrification when the boiler is under low load.

3.2.5. Optimizing oxygen content in operation. The oxygen content in operation of CFB boiler directly affects NOX emission. In this boiler design scheme, the furnace height is increased and the burnout time of fuel is greatly increased, which can ensure the full combustion of fuel in the furnace. A series of measures to ensure the uniformity of bed temperature and bed pressure can be taken to ensure the normal operation of the boiler under the condition of low oxygen content. The excess air coefficient of boiler is 1.15, which can further reduce the concentration of NOX emission.

4. Selection of flue gas denitrification process
At present, the flue gas denitrification process is mainly divided into selective catalytic reduction (SCR) SCR process and selective non-catalytic reduction (SNCR) process. SNCR process is to inject ammonia or urea and other reductants into high temperature flue gas to reduce NOX to N2. The chemical reaction of NOX is the same as that of SCR process, and the reductants used can be ammonia, urea and so on. Compared with SCR process, SNCR process system is simple, the investment and operation cost is low, and it is more suitable for application in CFB boiler. The basic principle of SNCR is to inject reducing agent ammonia or urea into furnace at 850 ℃ ~1150 ℃ without catalyst, and the reductant reacts with NOX in flue gas selectively and produces non-toxic, pollution-free N2 and H2O.

When urea is used as reductant, the reaction can be expressed as an equation:

\[ \text{2CO(NH}_2\text{)}_2 + 6\text{NO} \rightarrow 5\text{N}_2 + 4\text{H}_2\text{O} + 2\text{CO}_2 \]  

(1)

According to the design requirements of 660MW ultra-supercritical CFB boiler, the ultra-low emission of NOX can be achieved by operation regulation under the condition of stable boiler load, and the requirement of ultra-low emission has been met. SNCR denitrification process is used as
backup to ensure that the final NOX concentration in flue gas can meet the ultra-low emission requirements under full load.

5. Conclusions
High efficiency ultra-supercritical CFB boiler is the main development direction in the future. The technical scheme of ultra-low NOX emission of 660 MW ultra-supercritical CFB boiler being developed in China is studied, and the denitrification process route is selected.

(1) By improving the uniformity of the bed temperature and the bed pressure, optimizing design of the secondary air classification combustion, optimizing the combustion temperature and the operating oxygen content, the comprehensive effect of the measures can realize high-efficiency nitrogen suppression in the furnace, the original emission concentration of boiler NOX is less than 50 mg/m3.

(2) The SNCR technology with urea as reducing agent is selected as the auxiliary denitrification method to ensure the boiler to realize the ultra-low emission of NOX in flue gas under full load.

Acknowledgements
This work is financially supported by the National Key Research & Development Program of China (NO. 2016YFB0600201).

References
[1] Lv Junfu, Zhang Man, Yang Hairui 2014 Conceptual design of a simplified 660MW ultra-supercritical circulating fluidized bed boiler Proceedings of the CSEE 34
[2] Yue Guangxi, Lv Junfu, Xu Peng 2016 The up-to-date development and future of circulating fluidized bed combustion technology Electric Power 49
[3] Lyngfelt A, Ámand L E, Leckner B 1998 Reversed Air Staging-a Method for Reduction of N2O Emissions from Fluidized Bed Combustion of Coal Fuel 77
[4] Lyngfelt A, Ámand L E, Karlsson M 1995 Reduction of N2O Emissions from Fluidised Bed Combustion by Reversed Air Staging
[5] Liang Jianhong, Huang Zhong 2015 Research on circulating fluidized bed boiler NOX emissions optimizing and retrofit design Boiler Technology 45
[6] Ma Hui, Zhao Junping, Zhang Xiaodong 2015 Optimization of secondary air layout to reduce NOx emissions Power System Engineering 31
[7] Gong Z, Liu Z, Zhou T 2015 Combustion and NO Emission of Shenmu Char in a 2 MW Circulating Fluidized Bed Energy & Fuels 29
[8] Li Qingzhao, Zhao Changsui 2007 Latest advances in fundamental research on air-separation/flue gas recycling technology Journal of Engineering for Thermal Energy and Power 22
[9] Zhang Zhongfei, Chen Lili, Wang Yuejun 2015 Study on different ejection lances of SNCR in CFB boiler Chinese Journal of Environmental Engineering 9
[10] Du Pengfei, Bai Yang, Li Jingji 2015 The optimal design on the SNCR system in a 300 MWe CFB boiler Journal of Shenyang Institute of Engineering (Natural Science) 11
[11] Wang Fengjun, Jiang Xiaoguo, Zhang Zhiwei 2013 Deep denitrification of CFB boiler Boiler Manufacturing
[12] Li Jingji, Yang Hairui, Li Qiong 2013 Numerical simulation and optimization of SNCR system for CFB boilers Electric Power 46
[13] Li Jingji, Yang Hairui, Lv Junfu 2013 Junfu Low NOx Emission Characteristic of Low Energy Consumption CFB Boilers Journal of Combustion Science and Technology 4
[14] Zhou Tuo, Lv Qinggang, Li Shiyuan 2018 Research and application of low NOx emission in circulating fluidized bed boiler China Basic Science 4
[15] WU Jian-heng, HE Hong-zhou, YU Jin-shu 2014 The Influence on NOx Emission of Secondary-air in CFB Boiler JOURNAL OF ELECTRIC POWER 12