Ultra-low emission transformation of 600 MW supercritical circulating fluidized bed boilers unit

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Abstract. With the introduction of ultra-low emission environmental protection policies in national and local coal-fired power plants, ultra-low emission transformation of coal-fired power plants is required to be carried out in an all-round way. Under this background, the first 600 MW supercritical circulating fluidized bed (SCCFB) boiler unit in the world have carried out the demonstration of the technical route of ultra-low emission transformation and the research of key technologies. By adopting limestone desulphurization and low nitrogen combustion in furnace, selective non-catalytic reduction (SNCR) technology outside furnace and the integrated desulfurization and dust removal process of flue gas circulating fluidized bed (CFB-FGD), the unit realizes the technical route of ultra-low emission, and has good investment and operation economy, which can adapt to the development trend of environmental protection in the future. The CFB-FGD and dust removal system can further improve the operation economy of the boiler by setting pre-electrostatic precipitator (pre-ESP), designing double-tower and optimizing the single-tower switching mode, optimizing the pressure margin of the induced draft fan, and adopting the coordinated desulfurization operation mode inside and outside the furnace. The research results can provide a reference for the selection of ultra-low emission transformation for 660MW ultra-supercritical CFB boiler unit.

1. Introduction
Circulating fluidized bed (CFB) power generation technology is a clean coal combustion technology developed in recent decades. Because of its large-scale clean and efficient use of low calorific value fuels (coal slime, gangue, etc.), it has been widely used at home and abroad [1]. China has made remarkable progress in SCCFB boiler technology in recent years. Since the first 600 MW supercritical circulating fluidized bed (SCCFB) boiler was put into operation in the world in 2013, more than forty 350MW SCCFB boilers have been put into operation in China by December 2019, which makes the total installed capacity of SCCFB boilers in China account for more than 70% of the installed capacity of similar boilers in the world, which indicates that China occupies the leading level in the manufacturing and operation technology of large coal-fired CFB boilers in the world [2].

Since December 2015, relevant national ministries and local governments have successively issued targets and time schedule requirements for the transformation of ultra-low emissions about coal-fired units, that is, under the standard oxygen content of 6%, the emission concentrations of dust, sulfur dioxide (SO\textsubscript{2}) and nitrogen oxides (NO\textsubscript{x}) are no more than 10,35,50 mg/Nm\textsuperscript{3}, respectively [3]. For most CFB boilers, only relying on low nitrogen combustion in the furnace, NO\textsubscript{x} the original emission...
is also higher than 100 mg/Nm$^3$. In the case of limestone desulphurization in the furnace, the SO$_2$ emission concentration is also far higher than the ultra-low emission standard. Therefore, in the current environmental protection situation, compared with pulverized coal boilers, the advantages of high efficiency desulfurization and nitrogen suppression in CFB boilers are no longer obvious, so ultra-low emission transformation must be carried out.

Taking 600 MW SCCFB boiler unit as an example, the technical route of ultra-low emission transformation of power plant is demonstrated from the aspects of technology maturity and operation economy, which provides a reference for the selection of ultra-low emission technical route of 660 MW ultra-supercritical CFB boiler unit under development.

2. Brief introduction of boilers and existing environmental protection facilities

2.1. Introduction of boiler

600MW SCCFB boiler was designed and manufactured by DONGFANG BOILER GROUP CO., LTD. The maximum continuous evaporation of the boiler is 1900t/h, the pressure of main-steam is 25.4MPa, the temperature of the super steam/reheat steam are 571°C/569°C. The low calorific value of the designed coal is 15.17MJ/kg, the sulfur content of which is 3.3%. The boiler efficiency is not less than 91.01% (According to ASME TVC4-1998). The boiler is single furnace of breeches-leg, H-type arrangement, 6 steam-cooled cyclones arranged both side of the furnace. The unit adopt platen super-heater and external heat exchanger, the steam-water system adopts start-up circulation system with boiler circulating pump. The coal characteristics of 600MW SCCFB boiler is shown in Table 1.

### Table 1. Coal characteristics of 600MW SCCFB boiler.

| item            | symbol | unit | designed coal | checked coal |
|-----------------|--------|------|---------------|--------------|
| moisture        | $M_t$  | %    | 7.58          | 7.5          |
| air-drying-based moisture | $M_{ad}$ | %     | 1.58          | 1.59         |
| received base ash | $A_{ar}$ | %    | 43.82         | 44.92        |
| volatiles       | $V_{daf}$ | %    | 14.74         | 14.67        |
| carbon          | $C_{ar}$ | %    | 41.08         | 39.13        |
| hydrogen        | $H_{ar}$ | %    | 1.62          | 1.55         |
| nitrogen        | $N_{ar}$ | %    | 2.06          | 2.89         |
| oxygen          | $O_{ar}$ | %    | 0.54          | 0.51         |
| sulfur          | $S_{tar}$ | %    | 3.3           | 3.5          |
| low calorific value | $Q_{net,v,ar}$ | MJ/kg | 15.17        | 14.7         |

2.2. Profile of existing environmental facilities

Three sets of pneumatic separation limestone preparation system and limestone addition system are set up in the present desulfurization system of boiler. The desulfurization efficiency of boiler design is 96.7%, SO$_2$ emission concentration is not higher than 380 mg/Nm$^3$. The maximum coal-fired sulfur content ($S_{tar,\%}$) of the boiler is 2.5% at present, the actual SO$_2$ emission concentration is about 300 mg/Nm$^3$, the calcium-sulfur ratio (Ca/S) is about 2.1. According to the inlet maximum emission concentration of 5500 mg/Nm$^3$, the desulfurization efficiency in the furnace is 94.55% at present.

The boiler equipped with two sets of electric-bag filter, each set using horizontal, two electric field two bag field parallel design, dust emission concentration is not more than 30 mg/Nm$^3$. The design efficiency of electric-bag filter is 99.94%, in which the design efficiency of electric area is 90%, and that of bag area is 99.4%. The current dust emission concentration is about 15~20 mg/Nm$^3$.

The boiler is not equipped with flue gas denitrification unit, mainly through CFB low temperature combustion, classified air supply and operation adjustment to control NO$_X$ generation, the designed NO$_X$ emission concentration is not higher than 160 mg/Nm$^3$. The current NO$_X$ emission concentration is about 120 mg/Nm$^3$. 


Therefore, from the current operating situation of 600 MW SCCFB boiler unit, there is still a certain gap between the current emission concentrations of dust, SO\(_2\) and NO\(_X\) and the ultra-low emission standards, so it is necessary to carry out ultra-low emission transformation.

3. The principle of ultra-low emission transformation

CFB boiler ultra-low emission transformation should not change the boiler operation mode, maximize the inherent advantages of desulphurization and nitrogen suppression in the furnace, deeply tap the potential of pollutant control in CFB boiler, and the comprehensive annual cost including equipment investment depreciation, system operation and equipment maintenance is low in the service life of the equipment.

1. Using the existing desulphurization system in furnace, the most economical Ca/S in furnace is adopted, and the combined desulfurization inside and outside furnace are brought into play to reduce the investment and operation cost of the desulfurization system outside furnace.

2. Give full play to the advantages of low nitrogen combustion in the furnace and reduce NO\(_X\) original emission concentration.

3. Fully consider the water source, site and other conditions, reduce the original equipment or construction of the demolition, move, as far as possible no new land.

4. Reduce the impact of ultra-low emission transformation on the boiler main project, flue flow layout smooth.

5. The technical route of ultra-low emission transformation should be scientific and reasonable, the risk is controllable, it has good environmental compatibility, reduces secondary pollution, adapts to the trend of environmental protection policy in the future, and simultaneously considers the effects of desulphurization waste-water, smoke plume, heavy metal removal and so on.

4. Selection of flue gas denitrification process outside furnace

At present, the flue gas denitrification process is mainly divided into selective catalytic reduction (SCR) process and selective non-catalytic reduction (SNCR) process. Although the SCR denitrification process has high denitrification efficiency, it needs to add a large number of catalysts, and the temperature requirement of the injection point is strict, which is generally suitable for pulverized coal boiler. Compared with the SCR process, the SNCR process does not need to increase the catalyst, the system is simple, the investment operation cost is low, and the denitrification efficiency is generally 75%~80% [4]. The SNCR denitration process is generally used in CFB boiler in view of the characteristics of low temperature-graded combustion and less NO\(_X\) production in CFB boiler, and urea or ammonia water is injected into the cyclone inlet of the boiler as the reducing agent, and the reducing agent reacts with the NO\(_X\) in the flue gas produces non-toxic and pollution-free N\(_2\) and H\(_2\)O [5].

When urea is used as reductant, the reaction can be expressed as an equation [5]:

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

The NO\(_X\) emission concentration of 600MW SCCFB boiler is not higher than 120 mg/Nm\(^3\), at present, the efficiency of SNCR denitrification process can reach more than 75%, considering the investment operation cost, the SNCR denitrification process is selected as the flue gas denitrification process outside the furnace to ensure that the NO\(_X\) emission concentration reaches the requirement of ultra-low emission.

5. Selection of flue gas desulfurization and dust process outside furnace

The flue gas circulating fluidized bed desulfurization (CFB-FGD) process and limestone-gypsum wet desulfurization process (WFGD) are the typical desulfurization processes outside furnace. SO\(_2\) ultra-low emission can be achieved by the combination of the above two desulfurization processes and the limestone desulfurization process in furnace. Application of large-scale engineering proof [6]: the dust removal process is determined with the selection of desulphurization process outside the furnace, for the CFB boiler with WFGD outside the furnace, it is recommended to use or improve the efficiency of
the existing filter, add high-efficiency mist remover at the outlet of the desulfurization tower to achieve ultra-low emission of dust; For the CFB boiler with CFB-FGD process outside the furnace, add high-efficiency bag filter at the outlet of the desulfurization tower to achieve ultra-low emission.

5.1. Comparison of the advantages and disadvantages of two desulphurization and dust removal

Table 2 is a comparison of the advantages and disadvantages of WFGD and dust removal and CFB-FGD and dust removal process. It can be seen from the comparison that the WFGD process outside the furnace has the characteristics of high desulfurization efficiency, wide sulfur separation adaptability and low calcium-sulfur ratio outside the furnace, but combined with the trend of environmental protection in the future, the desulfurization system must be equipped with zero discharge system of waste-water, chimney anticorrosion and plume treatment system. The CFB-FGD process outside the furnace has the characteristics of simple system, small area, less water consumption, no desulfurization waste-water and smoke plume, synergistic removal of SO$_3$ and heavy metals. In January 2017, the State Ministry of Environmental Protection issued the Technical Policy on pollution Control of Thermal Power plants, which clearly stipulates that CFB-FGD outside the furnace technology should be used in arid and water-short areas, as well as in areas with large environmental capacity.

**Table 2. Comparison of technology and economy between WFGD and CFB-FGD.**

| Item                              | WFGD process                                      | CFB-FGD process                                   |
|-----------------------------------|---------------------------------------------------|---------------------------------------------------|
| Sulfur adaptation                 | To meet the requirements of higher sulfur coal    | SO$_2$ concentration is less than 3000mg/Nm$^3$   |
| Desulphurization efficiency       | Higher than 98%                                   | Higher than 95%                                   |
| Calcium sulfur ratio              | 1.03~1.05                                         | 1.3~1.8                                           |
| System resistance                 | low                                               | high                                             |
| SO$_3$ and Hg removal effect      | 30%                                               | 90%                                              |
| Flue and chimney anticorrosion    | requirements without GGH                          | none                                             |
| inlet dust requirements           | less than 20mg/Nm$^3$                             | none                                             |
| Desulfurization waste             | yes                                               | no                                               |
| System power consumption          | 3000kW                                            | 1000kW                                           |
| Operation requirements            | high                                              | low                                              |
| Desulphurizer monovalent          | limestone, between 100 and 200 yuan per ton        | quicklime, between 350 and 500 yuan per ton       |
| Cover area                        | ~2500m$^2$                                        | ~1500m$^2$                                       |
| Investment cost $^a$              | +5000000 yuan                                     | standard                                         |
| Operation and maintenance cost $^a$| +1000000 yuan per year                            | standard                                         |
| Combined cost $^b$                | +1300000 yuan per year                            | standard                                         |

$^a$ The coal sulphur content is 2.5% and the annual operating hours are calculated as 3600h.

$^b$ Desulfurization system service life is calculated on a 15-year basis, combined annual cost equal to investment cost divide by 15 and sum operating cost maintenance cost.

5.2. Economic comparison of two desulphurization and dust removal

The comparison of different desulfurization and dust removal processes of 600 MW SCCFB unit is as follows: (1) The CFB-FGD and dust removal system saves more than 5 million investment than "WFGD, zero discharge of waste-water and treatment of smoke plume". (2) The operation and maintenance cost of CFB-FGD and dust removal system is 1 million China yuan lower than WFGD and dust removal system. (3) The comprehensive annual cost of CFB-FGD and dust removal system is 1 million and 3 thousand China yuan lower than WFGD and dust removal system. The combined annual cost is further reduced after co-desulfurization in and out of the furnace.
Therefore, the technical route of ultra-low emission transformation of 600MW SCCFB unit is as follows: limestone desulphurisation and low nitrogen combustion in furnace, SNCR denitrification, and integration of CFB-FGD and dust removal outside furnace, which can reduce the concentration of dust, SO$_2$ and NO$_X$ below 10,35,50 mg/Nm$^3$, respectively.

6. Design of integrated system for CFB-FGD and dust removal

6.1. Design of key parameter

The average sulfur content (S$_{ar}$) of coal used in 600MW SCCFB unit is 2.5% at present, the original emission concentration of SO$_2$ is 5500mg/Nm$^3$, the total desulfurization efficiency requirement is not less than 99.36%. According to operation experience, the economic efficiency range of desulphurization in furnace is 70%–80%. In order to ensure the boiler flue gas to achieve ultra-low emission more stably and reliably, and considering the design margin, the maximum SO$_2$ concentration in inlet of desulfurization tower is 1600 mg/Nm$^3$, and the desulfurization efficiency of CFB-FGD is not less than 97.8%.

6.2. Research on key technology

6.2.1. Filter layout plan. 600MW unit dust removal equipment is electric-bag filter, the existing filter is removed or recycled in the ultra-low emission transformation, from the technical point of view are feasible, but need to be combined with technical and economic comparison to determine.

Figure 1. The comparison of Ca/S in CFB-FGD when the pre-ESP was put into operation or not [7].

Zhang J S carried out experimental study on a 350MW SCCFB boiler, the operation economy is reflected by the calcium-sulfur ratio (Ca/S) of the CFB-FGD equipment after the pre-ESP is put into operation and withdrawn [7]. The results show that when run into the pre-ESP the Ca/S in CFB-FGD system is 0.3-0.6 lower than when un-run into the pre-ESP (Figure 1 [7]). So it is possible to improve the economy of desulphurization outside the furnace by setting the pre-ESP in front of CFB-FGD system. Therefore, the power plant is recycling for the existing filter, and the electric-bag filter only removes the bag area and retains two electric fields. It not only fully benefits the existing equipment, further reduces the cost of transformation, but also improves the economy of desulfurization system outside furnace.
6.2.2. Switch of single-double tower. At present, the annual average load rate of 600 MW unit is about 70%, and most of the time the load rate is 60%. Considering the economy of medium / low load operation and the reliability of desulfurization, the CFB-FGD system adopts "two desulfurization towers" arrangement. A single tower can meet the 60% BMCR load operation. In order to ensure the requirement of single tower operation below 60% load, the flue gas recirculation is set up, and the connecting flue and regulating baffle door are set between the two tower inlet flue and the two tower flue gas recirculation flue to realize the single and double tower switching. The flue gas regulating door is double shutter type, electric regulating type.

6.2.3. Pressure optimization of induced draft fan. After the power plant increases the desulphurization and dust removal system, the pressure of the induced draft fan (ID fan) is difficult to meet the system resistance requirements, so it is necessary to replace the ID fan. On the basis of operation experience [6], the system resistance of the newly added desulphurization and dust removal integrated equipment by about 3~3.5kPa, and the power consumption rate of the plant increased by 0.7%~1% under the full load condition. Considering that the load rate of the unit is not high at present, and the time period of the unit with full load working condition is short, a small margin is selected in the selection of the ID fan to ensure that the ID fan can run in the high efficiency area for a long time.

7. Conclusions

(1) The technical and economic analysis results show that the 600 MW SCCFB unit adopts the ultra-low emission transformation technical route of “limestone desulphurization and low nitrogen combustion in furnace, SNCR denitrification, CFB-FGD and dust removal outside furnace”, which is more reliable in technology, higher economy, and more suitable for the development trend of environmental protection in the future.

(2) The calculation and test results show that when the CFB-FGD and dust removal system is adopting outside the furnace, the pre-ESP is installed in front of the desulfurization tower, and the selection of small margin of the ID fan can further reduce the investment operation cost. The switching of single and double tower can ensure the operation economy and desulfurization stability of the unit.

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

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