Development and prospect of lignite burning power generation in circulating fluidized bed boiler

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Abstract. At present, direct-combustion of lignite for generating electricity is a meaningful way to utilize lignite. The development status of lignite power generation and lignite CFB boiler technology is introduced in this paper. From the aspects of combustion stability, boiler efficiency and pollutant discharge, the technical and economic comparative analysis of lignite power generation technology of pulverized coal boiler and CFB boiler is carried out. As a result, CFB boilers burning lignite have more advantages than pulverized coal boilers in combustion stability, boiler efficiency, and pollutant emission reduction. The development of 600-1000MW ultra-supercritical CFB boiler units burning high moisture lignite is feasible and has certain strategic advantages.

1. Introduction

It is estimated that the world’s lignite geological reserves of about 4 trillion tons, accounting for about 40 percent of the world’s total coal reserves. China is rich in lignite resources, with an unlimited amount of 319.4 billion tons within 2000m buried depth proven reserves of 129.1 billion tons, accounting for 13% of the its proven reserves [1]. The proven lignite is mainly distributed in North and Southwest China. Most of the lignite in North China is Jurassic old lignite, but almost all of the lignite in Southwest China is Tertiary younger lignite. The eastern part of Inner Mongolia accounts for more than 3/4 of the national lignite geological reserves [2]. China’s lignite has the characteristics of “two high and three low”: high volatile matter, high moisture content, low ash melting point, low density, and low calorific value. Lignite is easy to weathering and rupture, easy to oxidize spontaneous combustion, challenging to wash and store, resulting in higher transportation cost per unit energy, which is not suitable for long-distance transportation and storage. Lignite is mainly used as a low-order fuel, used primarily in power generation, gas generation, chemical industry and other fields, used in the pit power station.

Combined with the statistical analysis of the operation of lignite pulverized coal (PC) boiler in service in recent years, the pulverizing system of PC furnace should adopt fan grinding when burning high moisture lignite [3]. Fan grinding needs to be equipped independently with multi-typhoon fan grinding system, which is higher than the conventional medium speed grinding price. As a high-speed coal mill, the impeller and the strike plate of the fan mill are rotated at high speed, the wear is severe, the replacement is frequent, a particular vehicle is needed to disassemble and assemble the fan mill.
during maintenance, the maintenance cost of the system is high. Most PC boilers are prone to fire problems, unstable combustion, and flameout when burning inferior coal, especially lignite with high moisture content, high ash content, and low calorific value [4].

Circulating Fluidized Bed (CFB) boiler becomes the development direction of large-scale coal-fired power plant units in the next stage because of its advantages of strong coal quality adaptability, strong peak-shaving ability, and large development space [5]. It is one of the best commercialized clean coal technologies. CFB boiler has the combustion efficiency close to or reach the same capacity as PC furnace, and can burn inferior fuel, which is of great significance to solve the shortage of coal resources in China. This paper summarizes the research progress and development status of lignite CFB power generation technology at home and abroad. Through the analysis of typical lignite characteristics, the characteristics of CFB boiler and PC boiler in body design, boiler efficiency, and pollutant emission reduction are compared. It has a specific guiding function for a low calorific value lignite power generation project.

2. Current situation of lignite CFB technology

Statistics show that more than 20 CFB units have been put into operation (seen Table 1). It has been proved that the CFB boiler units with lignite have the following characteristics:

1. The fuel preparation system is simple and requires only one or two coal crushing systems, no pulverizing system, and no explosion risk.
2. High CaO content in ash composition, self-desulfurization of CaO in coal ash, and reduction of desulfurization cost.
3. Generally, the operating bed temperature is low (850~950°C), the coking problem of the boiler can be avoided, and the low-temperature combustion can help to reduce the NOX original generation.
4. The ash content of lignite is relatively low, the total amount of ash is less, the wear on the heating surface is low, the operation cost of ash removal equipment is low, and the reliability is high.
5. Desulfurization in the furnace, low temperature of the acid dew point of flue gas, lower temperature of exhaust gas than PC boiler, and less heat loss of exhaust gas.

Table 1. Project cases of CFB boiler burning lignite in the world.

| Project name                                   | Unit capacity | Country              |
|------------------------------------------------|---------------|----------------------|
| State Power Yunnan Kaiyuan Power Plant         | 2×300 MW      | Yunnan               |
| Kyan project, Bahrain, Malaysia                | 1×300 MW      | Malaysia             |
| Datang Honghe Power Plant                      | 2×300 MW      | Yunnan               |
| Inspection Division Power Plant                 | 2×300 MW      | Yunnan               |
| Philippine CALACA Power Station                | 2×150 MW      | Philippines          |
| South Su Power Station, Indonesia               | 2×135 MW      | Indonesia            |
| Barmer Project, India                          | 8×135 MW      | India                |
| Coal-fired power stations STANRI BiH           | 1×300 MW      | Bosnia and Herzegovina|
| Barović Power Station                          | 1×350 MW      | Bosnia and Herzegovina|

Domestic and foreign scholars have researched the combustion technology of lignite in CFB boiler, and achieved initial results. Zhou [6] studied the emission characteristics of high volatile lignite pollutants on the CFB combustion test bench with thermal power of 3MW. Under different primary and secondary air ratio conditions, by changing the elevation of secondary air, the influence law of different primary and secondary air ratio and secondary air elevation on boiler pollutant discharge characteristics and combustion efficiency is obtained, and the operating oxygen quantity is adjusted to obtain the influence law of oxygen quantity on NOX and SO2 discharge. Li [7] tested the combustion characteristics, emission characteristics, ash and slag characteristics of Pinoasa coal, Rosia coal, and Tismana coal on the 3MW combustion test bench, which provides reference data for the design of 600MW supercritical CFB boiler in ROVENARI, ROMANIA. The results showed that the CFB combustion of the three fuels has good combustion stability and safety, there is no risk of coking,
slagging, and contamination in the design bed temperature. At the same time, the burst characteristics are strong, the ignition and burnout characteristics are excellent, and the pollutant emission is low, so it is very suitable for CFB combustion. Berrin Engin [8] studied 18 kinds of low-quality lignite running stability and pollutant emission on a 30kWth CFB burner. The results show that the temperature range of stable combustion of low order lignite is $725\pm 50^\circ C$, and for all lignite, the stable combustion temperature is generally $850\pm 50^\circ C$; Under stable conditions, the CO, NO$_x$, SO$_2$ emission from different lignite combustion is $120-600\text{mg/Nm}^3$, $420\text{mg/Nm}^3$, $1100-18000\text{mg/Nm}^3$, respectively. The control cost of pollutants is relatively low. Therefore, CFB boiler burning low calorific value lignite shows good characteristics in combustion stability, combustion efficiency, and pollutant control.

3. Comparative study between CFB boiler and PC boiler

3.1. Boiler combustion stability

CFB boiler has the characteristics of low-temperature combustion ($850-950^\circ C$) and high concentration material circulation in the furnace, which reduces the risk of slagging in the furnace without any special measures. There are a large number of circulating materials in the furnace, the coal only accounts for $1/40-1/30$ of the circulating materials, and the lignite has high volatile content and is easy to combustion. CFB boiler is effortless to achieve stable and efficient combustion, the boiler minimum non-oil steady combustion load does not exceed 30% boiler maximum continuous rating (BMCR).

For PC boilers, lower furnace volume heat load and cross-section heat load should be selected to reduce the possibility of slagging in the furnace. In addition, because of the low ash melting point of lignite, the lower temperature of the furnace outlet must be selected. While lower volume and cross-section heat load, lower temperature of furnace outlet mean more gigantic furnace cross-sectional area and volume. That is to say, in order to solve the problem of easy slagging of lignite, the PC boiler must sacrifice the advantages of high combustion temperature, high heat load, a small section of the furnace, and a small volume of CFB boiler, and indirectly weaken the advantage of the low cost of PC boiler. The lower furnace temperature also reduces the low load stable combustion characteristics of PC boiler, and the minimum non-oil stable combustion load of high water lignite used in the PC boiler is as high as 50~60% BMCR.

3.2. Boiler efficiency

According to the specific coal type, the boiler efficiency is calculated by using the counterbalance principle, and the CFB boiler and PC boiler are compared:

(1) Heat loss due to exhaust gas $q_2$. The flue gas acid-dew-point decreases after desulphurization in the CFB boiler, the exhaust temperature can be taken as a lower value ($128^\circ C$), while the exhaust temperature of PC boiler is $135^\circ C$, the excess air coefficient of CFB boiler is 1.18, while that of PC boiler is 1.2. A lower exhaust temperature and a smaller excess air coefficient make heat loss due to exhaust gas less in CFB boiler.

(2) Solid incomplete combustion loss $q_4$ and heat dissipation loss $q_5$. Both the mechanical incomplete combustion loss and heat dissipation loss of PC boiler are slightly smaller than that of CFB boiler, and the calculated difference between them is 0.33.

(3) Physical heat loss of ash and slag $q_6$. The slag discharge of CFB boiler includes slag discharge and desulphurization product. Therefore, under the same conditions, the ash content of CFB boiler is larger than that of PC boiler. When lignite is desulphurized in the CFB boiler, the Ca/S ratio is very low, the amount of additional limestone is very small, and the ash content of CFB boiler and the PC boiler is not different.

(4) Desulfurization heat loss $q_7$. Under the condition of CFB combustion, the sulfur content of lignite coal is very low, the CaO content in coal ash is high, and the coal has a strong self-
desulfurization ability. CFB boiler can obtain high desulfurization efficiency with low Ca/S, the exothermic gain of sulfur salinization in the desulfurization reaction is much higher than that of limestone calcination heat loss, and the boiler efficiency gain is 0.2% according to the calculation of the desulfurization reaction process. PC boiler has no desulphurization gain.

(5) Fan gain. The fan pressure of CFB boiler is high, the air temperature increases obviously after passing through the fan. The air temperature increases about 15°C, and the fan gain is 0.7. After the cold air of PC boiler passes through the fan, the temperature rise is about 5°C, and the corresponding gain is about 0.2. Because the cold air of PC furnace passes through the fan, the temperature rise is small, and the efficiency calculation of PC boiler is often ignored.

Table 2. Calculation of boiler efficiency for different boilers.

| Project                          | Unit | CFB boiler | PC boiler |
|----------------------------------|------|------------|-----------|
| Heat loss due to exhaust gas     | %    | 4.5        | 5         |
| Gas incomplete combustion heat loss | %    | 0.3        | 0.3       |
| Solid incomplete combustion heat loss | %    | 0.9        | 0.60      |
| Surface radiation and convective heat loss | %    | 0.20       | 0.17      |
| Physical heat loss of ash and slag | %    | 0.27       | 0         |
| Desulphurization heat loss      | %    | -0.2       | 0         |
| No heat loss                     | %    | 0          | 0.3       |
| Fan gain                         | %    | -0.7       | -0.2      |
| Total heat loss                  | %    | 5.27       | 6.17      |
| Calculation of boiler efficiency | %    | 94.73      | 93.83     |

As can be seen from Table 2, the efficiency of CFB boiler that burnu lignite is slightly higher than PC boiler. Low calorific value lignite-fired from a 300MW subcritical CFB boiler in China, the boiler efficiency test reports show “Test coal for boiler combustion, under rated load conditions, the measured boiler efficiency (calculated by low calorific value) is 93.80% and 93.82%, respectively. After the modification of coal quality, reference temperature, smoke exhaust temperature, and atmospheric humidity, the boiler efficiency is 93.25% and 93.27%, respectively. The average efficiency is 93.26%, greater than the guaranteed value of 92.80%.” The actual operation data of the unit show that, the efficiency of CFB boiler can reach or even exceed that of PC boiler. Therefore, for low calorific value lignite, it is possible that the efficiency of CFB boiler is slightly higher than PC boiler.

3.3. Pollutant discharge
Taking a lignite in north-east China as an example, the coal quality data are detailed in Table 3. The NO\textsubscript{X} can be further reduced by optimizing CFB boiler design and organizing combustion in the boiler by combining with the new technology of pollution source control and cooperative control of boiler. Simultaneously, the desulfurization efficiency in the furnace is further improved under the condition of lower Ca/S by reasonable bed temperature selection.

3.3.1. NO\textsubscript{X} emission and emission reduction technologies. Since the combustion temperature of CFB boiler is lower than that of PC boiler, there will be little thermal-NO\textsubscript{X} in CFB boiler. Meanwhile, according to the current CFB “fluidization reconstruction” technology and low nitrogen combustion theory, the original NO\textsubscript{X} can be further reduced in boiler design from the aspects of increasing the uniformity of bed temperature and bed pressure, strengthening secondary air graded combustion, optimizing combustion temperature and operating oxygen content [9]. The emission concentration of NO\textsubscript{X} is expected to reach the ultra-low emission standard directly in the furnace, and no denitrification system can be set outside the furnace. At present, further improvement of the reliability of fuel feeding system of CFB boiler will significantly ensure the uniformity of materials and play a positive role in the high-efficiency nitrogen suppression in the furnace. Therefore, the NO\textsubscript{X} emission reduction costs of CFB boilers is lower than that of PC boilers.
3.3.2. $SO_2$ emission and emission reduction technologies. The coal quality data is used to calculate the original emission concentration of $SO_2$ according to the test rules of boiler performance of a power station (GB/T10184-2015). The sulphur of designed coal ($S_{tar}$) is 0.12%, the calculated original emission concentration of $SO_2$ is 543mg/Nm$^3$. The sulphur of checked coal ($S_{tar}$) is 0.38%, the calculated original emission concentration of $SO_2$ is 1780mg/Nm$^3$. The CFB boiler adopts desulphurization in furnace and lignite has certain self-desulfurization characteristics. When burning designed coal, the emission concentration of $SO_2$ can meet the ultra-low emission standard directly by desulphurization in the furnace. For checked coal, the emission concentration of $SO_2$ can be reduced to less than 100mg/Nm$^3$ by high-efficiency desulphurization in furnace, and a simple flue gas circulating fluidized bed desulfurization (CFB-FGD) equipment is installed outside the furnace, and the incompletely reactive limestone in the furnace is activated by water-spraying and humidifying, the emission concentration of $SO_2$ is controlled within 35mg/Nm$^3$ [10]. Compared with the wet desulfurization equipment of PC boiler, CFB limestone desulphurization in furnace combined with CFB-FGD equipment outside boiler, it has great advantages in the overall investment, operation and maintenance cost of the equipment.

| Table 3. Coal quality data of a lignite in the northeast. |
|-----------------|-----------------|-------------|-----------------|-----------------|
| Project         | Symbol          | Unit        | Designed coal   | Checked coal    |
| moisture        | $M_t$           | %           | 39.7            | 42.4            |
| air-drying-based moisture | $M_{ad}$ | %           | 16.26           | 17.46           |
| received base ash | $A_{ar}$ | %           | 15.96           | 16.40           |
| volatiles       | $V_{daf}$       | %           | 66.17           | 61.36           |
| carbon          | $C_{ar}$        | %           | 31.16           | 29.6            |
| hydrogen        | $H_{ar}$        | %           | 2.92            | 2.81            |
| nitrogen        | $N_{ar}$        | %           | 0.27            | 0.22            |
| oxygen          | $O_{ar}$        | %           | 9.87            | 8.19            |
| sulfur          | $S_{tar}$       | %           | 0.12            | 0.38            |
| low calorific value | $Q_{net,v,ar}$ | kcal        | 2725            | 2598            |

To sum up, the inherent advantage of high-efficiency desulphurization and nitrogen suppression in CFB boiler furnace can be brought into play in the selection of boiler, which can further reduce the original formation concentration of NO$X$ and improve the desulfurization efficiency in the furnace. Even under the current ultra-low emission standards, the cost of pollutant treatment can be further reduced by technical research. Therefore, CFB boilers have more advantages than PC boilers in pollutant emission reduction.

4. Feasibility analysis of ultra-supercritical CFB boiler burning lignite

At present, the domestic supercritical CFB boiler technology is in the stage of rapid development. With the continuous improvement of energy-saving and emission reduction requirements, the requirements of the thermal power industry for unit performance parameters are also increasing. China has completed the breakthrough of CFB power generation technology in supercritical parameters by independent technology, and is about to enter the era of ultra-supercritical parameters. The ultra-supercritical CFB power generation technology for burning lignite will make full use of the wide adaptability of CFB boiler fuel and make it have obvious advantages in combustion stability, boiler efficiency, and pollutant emission reduction.

The problem of material uniformity in CFB boiler caused by the large-scale boiler is still the difficulty of boiler design, which further affects the NO$X$ source generation inhibition and deep removal of $SO_2$. Based on the theory of “fluidization reconstruction” proposed by Tsinghua University [11], the quality of boiler bed can be improved by optimizing coal feed granularity, optimizing bed pressure, improving separator efficiency, and the operation performance of the feeder, which can further reduce the original generation of NO$X$ and improve the desulfurization efficiency in
the furnace. Research found that generally the diameter of lignite $d_{50}=3$ mm or so, and the combustion process has strong burst performance, so compared with other gangue, anthracite, lignite has better adaptability to the capacity of CFB boiler [7]. Other key technologies, such as high-temperature heating surface safety, low load main reheat temperature guarantee, low-cost realization of ultra-low emission, and so on, are all being tackled one by one. Therefore, the development of ultra-supercritical parameters of 600-1000 MW CFB boiler burning lignite is feasible, and has more advantages than other coal types, which is of great significance for further consolidating China’s leading position in the field of CFB power generation technology, changing China’s energy structure, improving the energy efficiency of inferior fuels and “Belt and Road” going out strategy.

5. Conclusions
(1) Along with the development of lignite power generation technology and the accumulation of operation experience of lignite boiler in China, lignite power generation technology with PC boiler and CFB boiler as the main combustion mode has been basically formed, thus meeting the demand of energy development strategy in China.

(2) The results of the technical and economic analysis show that compared with PC boiler, the lowest stable combustion load of CFB boiler is less than 30%BMCR, and the unique low-temperature combustion characteristic can effectively solve the problem of boiler slagging easily. Boiler combustion efficiency can reach 93%, low-cost desulphurization and denitrification, and environmental protection facilities are reliable and straightforward.

(3) The operating practice of active lignite boilers in recent years shows that an important direction of lignite power generation technology is to develop CFB boiler units of 600~1000MW grades with ultra-low emission and ultra-low energy consumption at low cost.

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