Research on energy distribution characteristics of supercritical circulating fluidized bed boiler

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Abstract. Combining the typical supercritical CFB boilers with H-shaped and M-shaped arrangement, the energy consumption indicators were analyzed and compared. And the lower energy consumption CFB technology used in energy-saving technology transformation or design was studied. The energy distribution characteristics of supercritical CFB boiler units were further researched through the experiment, which proposes the optimization direction of the lower energy consumption CFB technology to reduce the service plant rate that can be applied for (ultra-)supercritical CFB boilers.

1. Introduction
Circulating fluidized bed (CFB) power generation technology has been rapidly developed in China and abroad for nearly three decades due to its extensive coal quality adaptability and excellent environmental performance[1-2]. The world's first 600MW supercritical CFB boiler unit designed and manufactured with complete independent intellectual property rights in China was put into commercial operation, which indicates that China's CFB power generation technology has reached the international leading level. Furthermore, the related technology development and application developed 350MW supercritical CFB boiler units, which also realized industrialization [3]. At the same time, the research and development of the project of ultra-supercritical Circulating Fluidized Bed boiler technology is carried out in China, which marks the development of China's CFB boiler technology is accelerating to move toward ultra-supercritical CFB boiler technology.

On September 12, 2014, the National Development and Reform Commission, Ministry of Environmental Protection and National Energy Administration in China jointly issued the Action Plan for the Upgrade and Reconstruction of Coal Energy Saving and Emission Reduction. It is clearly stipulated that the average net coal consumption of the newly-built coal-fired generating units is less than 300 g/kw · h, and the existing coal-fired generating units after transformation less than 310 g/kw · h. Therefore, for CFB boiler units, the technical core of energy-saving technology is still to improve boiler efficiency and reduce power supply for station. With the improvement of the capacity and parameters of domestic CFB boiler units and the potential of technology in design, operation adjustment and equipment transformation[4-5], the boiler efficiency is significantly improved and its service power rate is also reduced. In the early stage, a large number of research and practical application of the energy-saving technology has been carried out[6-7]. In recent years, new energy-saving and consumption-reducing technologies, such as “the State Specification Design theory”, wind-water combined slag coolers and rotary air preheater etc, have been successfully applied in related projects of the plant, and the results are remarkable[8-9].
This work will focus on the analysis of the energy-saving technologies used in two typical supercritical CFB boiler units of different structural types. The test was carried out to study the energy distribution characteristics. And the energy saving potential was explored for the power supply for station. This work provides the lower energy consumption CFB technology and optimized research directions for the design and transformation of (ultra-)supercritical CFB boilers.

2. Energy-saving technology of supercritical CFB boiler

2.1. Energy-saving technology transformation of 600MW supercritical CFB boiler

Sichuan Baima 600MW supercritical CFB boiler is double-legged, single-furnace, H-shaped arrangement with external heat exchangers. Three drum type slag coolers are arranged on the left or right side of the boiler furnace. The tail flue air preheater is a four-barrel rotary air preheater. The removal of nitrogen oxide from the boiler is carried out by staged combustion in the furnace, the removal of sulfur dioxide is carried out by spraying limestone, the dust is removed by electric bag composite dust collector.

The performance test results of the 600MW supercritical CFB boiler unit after the production show that the service power rate and net coal consumption are slightly better than the design value, but still a large room for improvement. Therefore, an energy-saving upgrade transformation was carried out. The equipment transformations of the boiler comprise the body transformation of primary and secondary air fan with installing frequency convertor, body transformation of high-pressure fluidized fan, rotary air preheater seal transformation, installing a low temperature economizer. Table 1 shows the effects of energy-saving for CFB boiler.

| Transformation object            | Evaluation index       | value before transformation | value after transformation | transformation effecta |
|----------------------------------|------------------------|----------------------------|----------------------------|------------------------|
| Primary air Fan                  | Current(A)             | 480.4                      | 298                        | +182.4                 |
| Secondary air fan                | Current(A)             | 270.8                      | 153.6                      | +117.2                 |
| High-pressure fluidized fan      | Current(A)             | 46                         | 42                         | +4                     |
| Rotary air preheater             | Air leakage rate(%)    | 6.95                       | 5.73                       | +1.22                  |
| Low temperature economizer       | Temperature (℃)        | 125.7                      | 86.5                       | +39.2                  |

a The value before the transformation minus the value after the transformation.

The primary and secondary air fan have been modified by the body with a frequency convertor. After the transformation, the parameter selection of air fan is reduced, and the convertor is configured to reduce the running current. The data from the same load are compared before and after the transformation, and the energy saving transformation effects are evaluated. It can be seen from Table 1 that the current of the primary or secondary air fan is significantly reduced. According to the calculated average value, the total current value of the primary and secondary air fan is reduced by 299A, and the service plant rate is reduced by about 0.89% (estimated by the average load of 70%). There are 5 high-pressure fluidized fans, 4 ships and 1 reserve. After the transformation, the operating current under the same working condition is reduced from 46A to 42A, and the total current is reduced by 16A, which reduced the service power rate by 0.05%.

The rotary air preheater was modified for the sealing structure. The air preheater seal was originally a three-prong type seal. After running for indicate exactly time, the sealing piece is worn and the air
leakage rate is increased. The air leakage rate of the A side air preheater is 7.94%, The air leakage rate of the B side is 5.95%, the average is 6.95%. After the transformation, the air preheater is a flexible contact seal, performance test values show A side is 6.37%, B side is 5.09%, and the average is 5.73%, which is better than the design value of 6.0%.

A low temperature economizer is installed between the outlet of the draft fan and the stack. The part of the waste heat from exhaust of the boiler is introduced into the steam turbine heat recovery system, that is, the condensed water is led from the condensate system to the rear of the boiler flue and after absorbing heat, it is sent back to the regenerative system to reduce the exhaust gas temperature. After the transformation, the average exhaust temperature of the low temperature economizer inlet was 125.7 °C, and outlet 86.5 °C, which was reduced by 39.2 °C.

To further compare the effects of energy-saving technology transformation, the main economic indicators of the unit are shown in Table 2. After the transformation, the boiler efficiency is improved by 0.12%, and the service plant rate is decreased by 1.428%, the net coal consumption is reduced by 7.86 g/kw·h. The effects of energy-saving technology transformation have achieved remarkable results.

| Economic Indicator               | Unit | Guarantee value | Value before transformation | Value after transformation | Contrast | Remark          |
|---------------------------------|------|-----------------|-----------------------------|----------------------------|----------|-----------------|
| Boiler efficiency               | %    | 91.01           | 91.52                       | 91.64                      | -0.12    | ASME standard   |
| Service plant rate              | %    | 6.863           | 6.998                       | 5.57                       | +1.428   |                 |
| Net coal consumption            | g/kw · h | 303.1     | 309.46                      | 301.6                      | +7.86    |                 |
| Air leakage rate of air preheater| %    | 6               | 6.95                        | 5.73                       | +1.22    |                 |

The value before the transformation minus the value after the transformation.

2.2. Energy-saving technology of 350MW supercritical CFB boiler
Shendonghequ 350MW supercritical CFB boiler is single-legged, single-furnace, M-shaped arrangement, and 6 drum type slag coolers are arranged on the rear wall of the boiler furnace. The tail flue air preheater is a tubular air preheater. The removal of nitrogen oxide from boilers is carried out by staged combustion in the furnace and SNCR denitration system, the removal of sulfur dioxide is carried out by spraying limestone and semidry flue gas desulfurization process\[10\], the dust is removed by electrostatic precipitator and bag filter.

The 350MW supercritical CFB boiler was designed with advanced energy-saving technology measures, including the State Specification Design theory technology, selection optimization of the air fan parameter, and boiler system process optimization, etc. The use of the State Specification Design theory technology achieves the low bed pressure operation to reduce electrical energy consumption of air fan. Combined with the State Specification Design theory technology and frequency converter adjustment of air fan, it can reduce the service plant rate by about 1%. Optimizing the selection of air fan parameter, reasonably selecting the auxiliary machine richness factor and motor capacity can avoid the waste phenomenon of the big horse with a small carriage. The wind pressure coefficient of the primary air fan is reduced by 5% in the design technical specification, and the service plant rate is reduced by about 0.8%. According to the relevant regulations and the operating experience of CFB boilers after production, the output margin coefficient of air fan is reasonably selected. The main and reheating steam pipelines use the Y-type three-way technology and the large-bend technology adopted Preferentially, which reduces the coal consumption by about 0.43 g/kw·h. The performance test of
350MW supercritical CFB boiler unit shows that the boiler efficiency is 91.76%, which is higher than the guarantee value requirement of 91.20%. The service plant rate of the whole unit is 6.335%, better than the guarantee value of 6.415%. The air leakage rate of the air preheater is 0.89%, which is lower than the guarantee value under the rated load, shown in Table 3.

| Economic Indicator                      | Guarantee value | Test value | Remarks                  |
|-----------------------------------------|-----------------|------------|--------------------------|
| Boiler efficiency                        | %               | 91.20      | 91.76                    | ASME standard                           |
| Service power rate                      | %               | 6.415      | 6.335                    |                                            |
| Net coal consumption                    | g/kw·h          | 325.31     | 321.0                    |                                            |
| Air leakage rate of air preheater       | %               | 1          | 0.89                     |                                            |

2.3. Energy saving technology for (ultra-)supercritical CFB boilers

Reference to practical applications of energy-saving technology from two typical supercritical CFB boiler, the low energy Consumption CFB technology in design or transformation that can be used for (super) supercritical CFB boilers is shown below:

For the first application in the State Specification Design theory technology for supercritical CFB boiler, the bed pressure can be guaranteed to be around 5kpa after long-term full-load operation of the CFB boiler, which provides valuable data for the foundation and support for considering the State Specification Design theory technology in the design of CFB boilers in the future.

When the air fan parameters are selected during the design, the richness factor isn't too big, and the Specified margin factor can be broken. It is recommended to select a lower air fan richness factor.

Combined with the transformation effect of supercritical CFB boiler, it is recommended to use the frequency convertor to effectively reduce the service plant rate between the medium and low load.

For the boiler system process optimization, the main and reheat steam pipelines can use the Y-type three-way technology and large-bend technology, which can reduce system process resistance and coal consumption.

For the addition of the low temperature economizer to recover flue gas waste heat, in design of CFB boiler, lower-design exhaust gas temperature can be considered, or the low temperature economizer can be used to recover flue gas waste heat, and optimize the mode of flue gas waste heat utilization.

The tubular air preheater can guarantee low air leakage rate, while the rotary air preheater can adopt mature flexible contact sealing technology to effectively reduce air leakage rate.

3. Energy distribution characteristics of Supercritical CFB boilers

Through the energy distribution test, several production indexes related to the energy consumption distribution under the stable operation load of the H-type 600MW supercritical CFB boiler unit after the modification and the M-type 350MW supercritical CFB boiler unit were collected respectively, and the structure diagram of the power supply for station of CFB boiler unit was made.

3.1. Comparison of energy consumption indicators in supercritical CFB boiler units

It can be seen from Table 4 that compared to the energy consumption indicators of 600MW supercritical CFB boiler after energy-saving technology transformation, 350MW supercritical CFB boiler has slightly improved the boiler efficiency due to advanced energy saving technology, but the service power rate is relatively higher, the main reason is that 350MW supercritical CFB boiler unit includes a desulfurization and denitration device outside the furnace. The net coal consumption of 350MW unit is is higher than the 19.4 g/kw·h of 600MW unit, which is mainly the difference
between boiler capacity and the thermal efficiency of steam turbine system. And the air leakage rate of the tubular air preheater is significantly lower than that of the rotary air preheater.

| Economic Indicator          | unit 600MW | unit 350MW | Contrast¹ | Remarks          |
|----------------------------|------------|------------|-----------|------------------|
| Boiler efficiency          | %          | 91.64      | 91.76     | -0.12            |
| Service power rate         | %          | 5.57       | 6.35      | -0.765           |
| Net coal consumption       | g/kw • h   | 301.6      | 321.0     | -19.4            |
| Air leakage rate of air    | %          | 5.73       | 0.89      | +4.84            |
| preheater                  |            |            |           |                  |

¹ The value of 600MW unit minus the value of 350MW unit.

3.2. Distribution characteristics of service plant rate

3.2.1. Distribution characteristics of service plant rate of 600MW unit

![Figure 1](image1.png)

**Figure 1.** Structure of the service plant rate of 600MW unit.

![Figure 2](image2.png)

**Figure 2.** Structural subdivision of the service plant rate of 600MW unit.

(Use this modified Figure 1 to Figure 4. Please attention the previously typeset Figure not show all the content)
It can be seen from Figure 1 and Figure 2 that the 600MW supercritical CFB boiler unit has various types of converters that consume the power structure of the plant. The power consumption of the air fan is the first, and the power consumption of the air compressors is ranked second, and the power consumption of the water pumps is the third. So, the key to reducing the power supply for station is still to reduce the power consumption of the three types of load. Further subdividing various types of loads, the top ranked is the primary air fan, induced induced-draft fan, high-pressure fluidized fan, circulating water pump, screw air compressor, secondary air fan and condensate pump.

3.2.2. Distribution characteristics of service plant rate of 350MW unit

Through the analysis of date of energy consumption distribution test, it can be seen from Figure 3 and Figure 4 that the 350MW supercritical CFB boiler unit is used in the power consumption of various types of converters. The power consumption of the air fan is the first, the power consumption of the pump is the second, and the power consumption of the air compressor is the third. Therefore, the key to reducing the power consumption of the plant is to reduce the power consumption of the three types of load. Further subdividing various types of loads, the top ranked is the induced draft fan, circulating water pump, primary air fan, air compressor, coal handling system, high-pressure fluidized fan, secondary air fan, desulfurization and dust removal transformer.
3.3. **Optimization direction of service plant rate for (ultra-)supercritical CFB boilers**

It can be seen from Table 5 that based on the comparison of the distribution of the service plant rate for the H-type 600MW and M-type 350MW supercritical CFB boiler unit, the key to reducing the service plant rate should be considered the optimization of the air fan system, in addition to air compressor and its system. It is still necessary to consider the optimization of circulating water pump, condensate pump and its system. Compared with the distribution of 600MW unit, the proportion of various types of load in the 350MW unit is significantly changed. The reason why the proportion of primary or secondary air fan is significantly reduced is that the 350MW unit adopts the technology of the State Specification Design theory and lower air fan margin coefficients, and the energy consumption of the primary or secondary fan is lower. The main reason for the reduction of energy consumption of high-pressure fluidized fans is that the 600MW unit has external heat exchangers, and the external circulation system is more than 350MW unit, and the high-pressure fluidized fan provides fluidized air for the external bed and the external circulation system. The increase in energy consumption of the induced draft fan is that the arrangement of ultra-low emission equipment leads to an increase in the resistance of the tail flue gas process resistance, which indicates that the ultra-low emission equipment and its system have a certain impact on the energy consumption of the unit, and the potential for energy saving is big.

Therefore, to achieve the lower energy Consumption CFB technology of (ultra-)supercritical CFB boiler unit, it is still a need to research the equipment and its system process optimization of primary air fan, secondary air fan, high-pressure fluidized fan, induced-draft fan and ultra-low emissions in the future.

4. **Conclusions**

By analyzing the application of energy-saving technology of typical supercritical CFB boiler units and their energy consumption indicators, this work proposes the lower energy Consumption CFB technology that can be transplanted into (ultra-)supercritical CFB boilers, adopting"State Specification Design theory" technology, selecting low air fan richness coefficient and the use of air fan frequency converter can significantly reduce the service plant rate by about 1%. For the process optimization, the main and reheat steam pipelines can be considered to use Y-type three-way, preferential use of large...
pipe bending technology, which can reduce process resistance and coal consumption. The low exhaust gas temperature can be considered in design, or the waste heat can be recovered by using the low-temperature economizer and the waste heat utilization mode can be optimized. The tubular air preheater can ensure a low air leakage rate(<1%), and the rotary air preheater can adopt the mature flexible contact sealing technology, which can ensure a low air leakage rate(<6%).

The energy distribution characteristics of supercritical CFB boiler units is studied through experiments. It is concluded that the key technology for reducing the service plant rate of CFB boiler units is to achieve the equipment and its system process optimization of primary air fan, secondary air fan, high-pressure fluidized fan, induced draft fan and air compressor. The system process optimization of circulation water pump, ultra-low emission equipment and its system have an impact on the energy consumption, and certain optimization space.

Acknowledgement
This work was supported by The National Key R & D Program of China (No. 2016YFB0600203).

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