Study on selection and optimization of slag cooler system for a ultra-supercritical CFB boiler

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Abstract. The construction of large scale CFB units with high steam parameters is the best way to make large-scale clean use of low calorific value coal such as slime and gangue. The ash and slag heat loss of CFB units burning low calorific value coal is large. Roller slag coolers widely used in in-service CFB units have a low efficiency in terms of heat recovery and utilization of ash and slag for CFB boiler, while air-water combined slag cooler can effectively recover heat from ash and slag. By analyzing and studying the influence of air-water combined slag cooler and roller slag cooler on boiler efficiency and power consumption, the coal consumption of ultra-supercritical CFB units with different slag coolers was calculated, and the technical economy of different types of slag coolers was also compared. The results indicate that the air-water combined slag cooler should be selected for the CFB unit with high price of standard coal and large amount of bottom slag, and better economy of the unit could be obtained. In order to take into account the economy and operational reliability of slag cooler system, the scheme of mixing air-water slag cooler with roller slag cooler can be adopted to optimize the selection of slag cooler system for a ultra-supercritical CFB unit. These results can provide referential materials for the selection and optimization of slag cooler system of large-scale CFB boiler.

1. Introduction
Circulating fluidized bed (CFB) combustion technology can be used for burning low calorific value fuels such as gangue, washed coal and slime. It is the best way for large-scale clean utilization of low calorific value coal such as slime and gangue to construct supercritical CFB units with large capacity and high steam parameter in the mining area to realize in-situ conversion of low calorific value coal [1]. By September 2019, 36 supercritical CFB units have been put into operation in China, including a 600 MW unit and thirty-five 350 MW units. The total installed capacity of China's supercritical CFB units has reached 12850 MW.

Table 1. Comparison of ash and slag heat loss between pulverized coal boiler and CFB boiler.

| Item               | Unit | Pulverized coal boiler | CFB boiler |
|--------------------|------|------------------------|------------|
|                    |      | Test condition 1 | Test condition 2 | Test condition 3 | Design value |
| Boiler load        | MW   | 597.33               | 449.23      | 299.58           | 600          |
| Ash and slag heat loss | %   | 0.21                  | 0.20        | 0.19             | 2.25         |
With the decline of coal quality and the utilization of low calorific value coal, the amount of bottom slag discharged from CFB boiler is larger, as well as the heat loss of bottom slag, which results in the boiler efficiency of CFB unit is lower than that of pulverized coal boiler with the same capacity, as shown in Table 1. It is seen that for a 600MW coal fired unit, ash and slag heat loss of pulverized coal boiler is 0.2%, while that of CFB boiler is 2.25%. Difference between the two type boiler is very significant [2].

Roller slag cooler or air-water combined slag cooler is usually used for bottom slag cooling of large CFB boilers. When the air-water combined slag cooler was used in the early CFB boilers, due to the poor control of coal particle size and the complex structure of the air-water combined slag cooler, problems such as fluctuation of slag feeding volume, internal coking and slag discharging were happened all the time in operation, which failed to give full play to the advantages of the air-water combined slag cooler [3-5]. Roller slag cooler is widely used in existing supercritical CFB boilers which has higher stability [6-7]. However, its ability of effectively recovering and utilizing heat from bottom slag is low. The heat recovered by the slag cooler is not utilized effectively, which reduces the efficiency of the steam turbine system [8-10].

The operation and application of the air-water combined slag cooler in many power plants show that the stability of the air-water combined slag cooler can be guaranteed as long as the coal particle size is effectively controlled [11-14]. With the continuous development of large-scale CFB technology and the improvement of unit operation technology, the requirement of coal particle size control in power plants is increasingly stringent. The particle size of coal has been improved obviously. Therefore, the air-water combined slag cooler has the conditions for its application in supercritical CFB units. Based on the successful operation of a large number of 350 MW and 600 MW supercritical CFB boilers, 660 MW supercritical CFB units are expected to be built and put into operation in 2021. By fully considering the influence of various factors of using roller slag cooler and air-water combined slag cooler on boiler efficiency, power consumption and standard coal consumption of power supply, the optimization of slag cooler system selection for 660 MW ultra-supercritical CFB units is studied.

2. Calculation model description

2.1. Calculation of slag quantity and heat loss
The total ash content of CFB boiler consists of ash in coal and limestone added into furnace for desulfurization.

\[ G_{ash} = B A_{ar} + 3.12 B R S_{ar} \]

In the formula, \( G_{ash} \) is the ash and slag quantity of the boiler, t·h\(^{-1}\). \( B \) is the total coal quantity of the boiler, t·h\(^{-1}\). \( R \) is the Ca/S ratio of desulfurization in the boiler, and design value of the Ca/S ratio in this project is about 2. \( A_{ar} \) and \( S_{ar} \) are 35.4% and 0.99%, respectively. The design coal quantity of 660 MW ultra supercritical CFB unit is 380.4 t·h\(^{-1}\), and the calculated ash quantity of boiler is 139.6 t·h\(^{-1}\). The design proportion of bottom slag to total ash and slag \( \lambda_{sl} \) is 40%. The bottom slag \( B_{sl} \) of the boiler is 55.86 t·h\(^{-1}\).

The calculation method for heat loss of bottom slag \( \eta_{sl} \) is:

\[ \eta_{sl} = \frac{B_{sl} (h_1 - h_2)}{BQ_{net,ar}} \]

In the formula, \( h_1 \) and \( h_2 \) are hot slag enthalpy and cold slag enthalpy, respectively. The temperature of hot slag is 890 °C, and the temperature of cold slag is 150 °C. \( Q_{net,ar} \) is the received base low calorific value of design coal, MJ/kg.

2.2. Calculation method of boiler efficiency and coal consumption of power supply
After using air water combined slag cooler to recover the heat from bottom slag, the heat absorbed by fluidizing air of slag cooler is sent back to the furnace, which reduces the heat loss of bottom slag of the boiler, and the boiler efficiency changes accordingly.
The effect of heat absorbed by fluidizing air on boiler efficiency $\eta_{b1}$ is

$$\eta_{b1} = \lambda B_{sl} (h_1 - h_2) / BQ_{net, ar}$$

In the formula, $\lambda$ is the ratio coefficient of air cooling in the slag cooler. The water-cooling part is calculated as follows: after using the air-water combined slag cooler, the condensate water is used as cooling medium to absorb heat, and part of the steam volume is push aside from the low-pressure heater, which can increase the output power of the turbine. In order to unify the calculation, this part of steam energy is converted to calculate its equivalent boiler efficiency improvement value $\eta_{b2}$. The effect of carbon content of fly ash and bottom slag on boiler efficiency is $\eta_{b3}$. The correction value of boiler efficiency after considering various factors $\eta_{b}$ is

$$\eta_b = \eta_{b0} + \sum \eta_{bi}$$

In the formula, $\eta_{b0}$ is the benchmark boiler efficiency, which is calculated by design value 93%.

The standard coal consumption rate $b_s$ of the whole power supply is the general thermal economy index of the thermal power plant [15], which is calculated as follows

$$b_s = \frac{3600Q_b}{P_e(1-\eta_e) \times \eta_b \times q_L}$$

In the formula, $Q_b$ is the boiler load, MW, which can be obtained from the boiler design data. $P_e$ is the generating power of 660 MW, $q_L$ is the calorific value of standard coal, 29 307 kJ/kg. $\eta_e$ is the auxiliary power consumption rate of the unit. This item is based on the design value of the auxiliary power of the project, which is 5.12%. Based on it, the influence of using different types of slag coolers on the auxiliary power consumption rate is considered and then substituted into the calculation.

### 2.3. Calculation and test of heat recovery efficiency of roller slag cooler

Roller slag coolers are widely used in CFB power plants for bottom slag cooling. Although the running stability of roller slag cooler is higher, its ability to effectively utilize the heat of bottom slag is relatively low. Generally, the cooling water of roller slag cooler uses condensed water, which will reduce the amount of water entering into each low pressure heater in the main circuit of condensed water, as well as the corresponding final stage extraction of steam turbine, which leads to the cold source loss of steam turbine increase and the efficiency of steam turbine reduce, and the heat recovered by slag cooler is not fully utilized effectively. Through the field test on 600MW supercritical CFB Unit, the equivalent enthalpy drop method is used to calculate the heat recovery efficiency of the roller slag cooler.

According to the test data of 600MW supercritical CFB unit, the reduction of each low pressure heater's steam extraction volume caused by the heat absorption of condensate water in the roller slag cooler and the sum of the steam's work income in the turbine's low pressure cylinder are calculated, and the results are shown in Table 2. The cooling water of slag cooler is taken from the inlet of No. 8 low pressure heater, and the hot water returns to the inlet of No. 6 low pressure heater. The connection mode of this system will affect the extraction capacity of No. 6, 7 and 8 low pressure heaters. The heat balance equation is established for each low pressure heater, and the change of the steam extraction quantity of each low pressure heater before and after the roller slag cooler is put into operation is calculated. The sum of the enthalpy drop of each extraction section after the corresponding extraction position is the effective heat recovery of the roller slag cooler.

### Table 2. Effective heat recovery of slag cooler.

| Low pressure heater | Test extraction capacity | Change of extraction capacity | Enthalpy of steam kJ/kg | Equivalent enthalpy drop kJ/kg | Turbine power increase | Heat recovery from slag cooler |
|---------------------|--------------------------|-------------------------------|-------------------------|-------------------------------|-----------------------|-------------------------------|
| No. 6               | 51.6t·h⁻¹                | 12.04t·h⁻¹                   | 2854.58                 | -1619.59                      | 942.8kW               | 14476.1kW                     |
| No. 7               | 36.8t·h⁻¹                | -12.77t·h⁻¹                  | 2730.98                 | 1279.73                       |                       |                               |
| No. 8               | 50.7t·h⁻¹                | -21.59t·h⁻¹                  | 2584.23                 | 1282.64                       |                       |                               |
The utilization efficiency of the bottom slag heat of the drum slag cooler calculated under different load conditions is shown in Table 3 as below.

Table 3. Effective utilization rate of ash heat of roller slag cooler under different load conditions.

| Item                              | Unit | Condition 1 | Condition 2 | Condition 3 |
|-----------------------------------|------|-------------|-------------|-------------|
| Load MW                           |      | 360         | 450         | 600         |
| Effective utilization rate of heat from bottom slag % |      | 6.06        | 8.10        | 6.51        |

3. Results and discussion
Proximate and ultimate analysis of coal used in 660 MW ultra supercritical CFB unit are given in Table 4.

Table 4. The coal properties.

| Coal sample | Proximate analysis/% | Ultimate analysis/% | $Q_{net,ar}$/MJ/kg |
|-------------|----------------------|---------------------|--------------------|
|             | $M_i$ | $M_d$ | $A_{ar}$ | $V_{daf}$ | $C_{ar}$ | $H_{ar}$ | $N_{ar}$ | $O_{ar}$ | $S_{ar}$ |                |
| design coal | 24.48 | 2.49  | 31.03   | 36.86     | 28.5    | 38.7    | 2.14     | 0.58     | 2.18     | 0.91      | 14.35       |
| check coal  | 23.36 | 2.25  | 35.43   | 39.95     | 25.6    | 35.2    | 1.98     | 0.61     | 2.45     | 0.99      | 12.99       |

3.1. Calculation results of heat loss of bottom slag
According to the design coal of the project, the sensible heat recovery of bottom slag is 54304.11MJ/h, the theoretical value of improving boiler efficiency is 0.751% in the case of the use of air water combined slag cooler. However, there are some other factors to affect the heat recovery effect when using the air-water combined slag cooler, such as the change of carbon content in the bottom slag, the limitation of air cooling ratio by the total air volume, and so on.

3.2. Effect of different types of slag coolers on boiler efficiency
Taking various factors into account, the influence of different types of slag coolers on boiler efficiency is calculated, and the conversion rate of sensible heat of boiler bottom slag by roller slag cooler and air-water combined slag cooler is quantified.

The influence of various factors on boiler efficiency by using air water combined slag cooler is calculated as follows.

3.2.1. Improvement of boiler efficiency by heat recovery from fluidizing air of air-water combined slag cooler.
Ignore the heat dissipation of slag cooler, and all the heat of bottom slag recovered by cooling air will enter the boiler. If the slag cooler of the existing unit is reformed, the fluidizing air of the slag cooler may generate hot extrusion to the flue gas system, which will increase the flue gas temperature of the boiler. However, considering that the project is a new one, the slag cooler system and the boiler air pre-heater system should be integrated in the design stage, and the flue gas volume and exhaust gas temperature will remain unchanged after the slag cooler is used. According to the calculation of air-water combined slag cooler with the heat absorption ratio of fluidizing air and cooling water of 2:1, the heat recovery ratio of bottom slag by cooling air is 66.6% [16].

3.2.2. The conversion value of the heat recovered from the cooling water of the air water combined slag cooler to the improvement of the boiler efficiency.
The cooling water of slag cooler is condensed water, the heat of water-cooling part can not directly improve the boiler efficiency, only reduce the heat consumption of steam turbine. The actual operation parameters of 600 MW supercritical CFB boiler show that the effective utilization rate of steam turbine for this part of heat only accounts for about 6.5% of the heat recovered from the water-cooled part. In order to make a unified comparison, the heat effectively used by the steam turbine recovered from the water-cooled part is converted into
the boiler efficiency. When the effective recovery heat is converted to the boiler efficiency, the efficiency of steam turbine and auxiliary system is 47%.

3.2.3. The effect of incomplete combustion loss. After using the air-water combined slag cooler, as the fluidizing air of the slag cooler returns to the furnace as the secondary air, it has certain influence on the original combustion structure in the furnace, and the carbon content of the fly ash increases about 0.2%. However, due to the increase of combustion retention time, the carbon content of bottom ash decreased. Combined with the two effects, the change of incomplete combustion loss can remain unchanged after combustion optimization.

The influence of the above factors on boiler efficiency is given in Table 5.

### Table 5. Influence of various factors on boiler efficiency by using air water combined slag cooler.

| Influence factor | Unit Factor | Influence | Calculation | Increment |
|------------------|-------------|-----------|-------------|-----------|
| $\eta_{b1}$ | % Air cooled part | Air-cooled ratio 66.6% | $\eta \times 0.666$ | 0.500 |
| $\eta_{b2}$ | % Water-cooled part | Water cooling ratio 33.4% | $(\eta \times 0.334 \times 0.065) / 0.47$ | 0.035 |
| $\eta_{b3}$ | % Incomplete combustion loss | Carbon content of fly ash increased while carbon content of bottom ash decreased. | The effect on heat loss of incomplete combustion is 0. | 0.000 |

The correction value of boiler efficiency after considering various factors is

$$\eta_b = \eta_{b0} + \sum \eta_{bi}$$

In the formula, $\eta_{b0}$ is the reference boiler efficiency provided by the boiler plant, 93%, and the correction value of boiler efficiency using air water combined slag cooler $\eta_b$ is 93.535%.

When roller slag cooler is used, condensate water is used as cooling medium, and the steam consumption reduction of steam turbine accounts for 6.5% of the total recovered heat, and its effect on boiler efficiency gains are as follows: $\eta_{b1} = \eta \times 0.065 / 0.47 = 0.104\%$. Therefore, the correction value of boiler efficiency is 93.104%.

When using the air-water combined slag cooler, the heat of the water-cooled part is not recycled into the boiler. However, when ASME standard is used to calculate the boiler efficiency, the water-cooled heat absorption benefit is also included in the thermal system, and the theoretical value of boiler efficiency can be increased to 0.751%.

3.3. Influence of using air water combined slag cooler on service power consumption

In order to ensure the operation stability and slag removal uniformity of the unit, six slag coolers are proposed to be selected for the unit, and the design output of each slag cooler is 25 t·h$^{-1}$. The fluidizing air volume of each slag cooler is calculated as 26.2km$^3$. The primary air is used as fluidizing air in the air-water combined slag cooler. Compared with the roller slag cooler, the primary air volume of the boiler needs another 157.2km$^3$, but the secondary air volume correspondingly reduces. With reference to the supercritical CFB unit put into operation, the current of the primary fan increases by 80.1A, the current of the secondary fan decreases by 41.7A, and the power of each roller slag cooler is 25 kW. When air-water combined slag cooler is used, the auxiliary power of the unit increases by 208.7 kW, so the auxiliary power rate of air-water slag cooler is 0.032% higher than that of roller slag cooler.
3.4. Influence of different types of slag coolers on standard coal consumption of power supply

After comprehensive consideration of the above factors, the calculation results of the influence of different types of slag coolers on the standard coal consumption of power supply unit are shown in Table 6. The datum data is the design value.

| Type of slag cooler                              | Boiler efficiency/% | Auxiliary power ratio/% | Standard coal consumption of power supply/g | Reduction of standard coal consumption/ g |
|------------------------------------------------|--------------------|-------------------------|---------------------------------------------|-------------------------------------------|
| reference value                                | 93.000             | 5.120                   | 292.050                                     | 0                                         |
| roller slag cooler                             | 93.104             | 5.120                   | 291.724                                     | 0.326                                     |
| air water combined slag cooler                 | 93.535             | 5.152                   | 290.477                                     | 1.573                                     |
| theoretical value of air-water cooling         | 93.751             | 5.152                   | 289.807                                     | 2.243                                     |

To sum up, when the air water combined slag cooler is used in the project, the final coal consumption of power supply is 1.573 g/kWh lower than the reference value after considering the adverse factors such as the increase of auxiliary power consumption.

When roller slag cooler is used, boiler efficiency cannot be improved directly. Most of the recovered heat is taken away by the loss of cold source. Through calculation, the standard coal consumption of power supply can be reduced by 0.326 g/kWh by using the roller slag cooler.

3.5. Effect of different ratio of bottom slag on unit economy

In order to compare the effect of different slag ratio on boiler efficiency and standard coal consumption of power supply. The bottom slag ratio is calculated and analyzed as 25%, 30%, 35%, 40% and 45% respectively. The benchmark boiler efficiency is still taken as 93%, and the calculation results are shown in Figures 1 and 2.

![Figure 1. Change of boiler efficiency.](image)

![Figure 2. Change of standard coal consumption of power supply.](image)

It can be seen from the figures 1 and 2 that the larger the proportion of bottom slag is, the more significant the boiler efficiency is improved and the more the reduction value of standard coal consumption of power supply is when the air-water combined slag cooler is used. Therefore, in the project with a large proportion of bottom slag, the economy of using air-water combined slag cooler is better.
3.6. Technical and economic comparison of different types of slag coolers

There are three schemes for the slag cooler of 660 MW ultra-supercritical CFB Unit. Scheme 1 uses 6 roller slag coolers (reference scheme), scheme 2 uses 6 air-water slag coolers, scheme 3 uses 4 air-water slag coolers and 2 roller slag coolers. The technical economy of each scheme is calculated when the price of standard coal is 198 yuan/t and the proportion of bottom slag is 40%. When the present value of cost method is used to calculate the 20-year income of each scheme, the annual interest rate of loan interest is 4.9%. The calculation results are given in Table 7.

| Table 7. The calculation results of different types of slag coolers. |
|------------------|------------------|------------------|------------------|
| Item             | Scheme 1         | Scheme 2         | Scheme 3         |
| General situation| number of slag coolers | 6               | 6               | 4+2              |
|                  | type of slag cooler | roller slag cooler | air water combined slag cooler | air water combined / roller slag cooler |
|                  | cooling capacity of single slag cooler/(t/h) | 25              | 25              | 25              |
| Investment cost  | unit price of slag cooler/10^4yuan | 90              | 210             | 210/90           |
|                  | total price of slag cooler/10^4yuan | 540             | 1260            | 1020            |
|                  | total price of primary fan/10^4yuan | reference value | 60              | 60              |
|                  | total price of secondary fan/10^4yuan | reference value | -40             | -40             |
|                  | initial investment difference/10^4yuan | reference value | 740             | 500             |
| Operation and maintenance cost | maintenance cost/(10^4yuan/a) | reference value | 18.00           | 12.00           |
|                  | reduction of standard coal cost(10^4yuan/a) | reference value | -50.82          | -60.20          |
|                  | total income(10^4yuan/a) | reference value | -32.82          | -48.20          |
|                  | present value of cost/10^4yuan | reference value | -412.51         | -605.79         |
| Total cost       | sum of Investment cost & present value of cost/10^4yuan | reference value | 327.49          | -105.79         |

From the analysis of the above calculation results, it can be seen that the total cost of scheme 3 using 4 air water combined slag coolers and 2 roller slag coolers is 1.0579 million yuan lower than that of scheme 1. So scheme 3 is more economical.

It can be seen in Figure 3 that with the increase of standard coal price and the increase of bottom slag ratio, the total cost of scheme 2 and scheme 3 is lower than that of the reference scheme. That is to say, the higher the price of standard coal and the larger the proportion of bottom slag, the better the economy of using air water combined slag cooler.

The research and development of the technology of the air water combined slag cooler is innovated to further improve its operation stability. With the combination of roller slag cooler and air-water slag cooler, the advantages of slag cooler system are complementary, and the reliability is better, as well as the operation effect.
Figure 3. Difference from total cost of reference scheme.

4. Conclusions
1) When the designed coal is used, the proportion of bottom slag is relatively small, which to a certain extent affects the improvement of boiler efficiency by air-water combined slag cooler. When the ratio of bottom slag is 40%, the theoretical value of boiler efficiency improvement with air-water combined slag cooler is 0.751%. Taking into account the adverse factors such as the increase of auxiliary power brought by the air slag cooler, the boiler efficiency is increased by 0.535%, and the standard coal consumption of power supply can be reduced by 1.573 g/kWh.

2) When roller slag cooler is used, boiler efficiency cannot be directly improved. Most of the recovered heat is taken away by the cold source loss after entering the turbine. The standard coal consumption of power supply can be reduced by 0.326 g/kWh.

3) There are three alternatives for the slag cooler of 660 MW ultra supercritical CFB unit. The first scheme uses 6 roller slag coolers, the second scheme uses 6 air-water slag coolers, the last one uses 4 air-water slag coolers and 2 roller slag coolers. When the price of standard coal is 198 yuan/t and the proportion of bottom slag is 40%, the economy of scheme 3 is better.

4) With the increase of standard coal price and the proportion of bottom slag, the difference between the present value of total cost of scheme 2 and scheme 3 is lower than that of scheme 1. That is to say, the higher price of standard coal and the larger the proportion of bottom slag are, the better the economy of using air-water combined slag cooler is.

5) Considering the economy and operation stability of each scheme, the slag cooler system of 660 MW ultra supercritical CFB unit can be combined with 4 air water combined slag coolers and 2 roller slag coolers.

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Nomenclature

| Symbol | Description |
|--------|-------------|
| $G_{ash}$ | total ash and slag quantity (t·h$^{-1}$) |
| $B$ | total coal quantity of the boiler (t·h$^{-1}$) |
| $R$ | Ca/S ratio |
| $A_{ar}$ | ash content as received basis (%) |
| $S_{ar}$ | sulfur content as received basis (%) |
| $B_{sl}$ | bottom slag quality (t·h$^{-1}$) |
| $h_1$ | hot slag enthalpy (kJ/kg) |
| $h_2$ | cold slag enthalpy (kJ/kg) |
| $Q_{net}$ | low calorific value (MJ/kg) |
| $b_s$ | standard coal consumption rate (g/kWh) |
| $Q_b$ | boiler load (MW) |
| $P_e$ | generating power (MW) |
| $q_{L}$ | calorific value of standard coal (kJ/kg) |

Greek Letters

| Symbol | Description |
|--------|-------------|
| $\lambda$ | proportion of air cooling (%) |
| $\lambda_{sl}$ | proportion of slag to total ash (%) |
| $\eta_0$ | benchmark boiler efficiency (%) |
| $\eta_{b1}$ | boiler efficiency affected by fluidizing air (%) |
| $\eta_{b2}$ | boiler efficiency affected by cooling water (%) |
| $\eta_{b3}$ | boiler efficiency affected by incomplete combustion (%) |
| $\eta_e$ | auxiliary power consumption rate (%) |
| $\eta_b$ | correction value of boiler efficiency (%) |

Subscripts and Superscripts

| Symbol | Description |
|--------|-------------|
| ar | as received basis |
| sl | slag |
| b | boiler |