Study on economic operating mode for combined desulfurization system of circulating fluidized bed unit

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Abstract. With the stricter emission regulation taking effect, most of circulating fluidized bed (CFB) power generation units operate with conventional desulfurization in CFB furnace and flue gas desulfurization (FGD) technology to meet the requirements of ultralow SO₂ emission. Therefore, it is urgent to analyse operating cost of the combined desulfurization system and explore the low-cost operating mode for CFB units. In this paper, the operating cost model of combined desulfurization system was established, in which the influence of desulfurization in furnace on thermal efficiency of the CFB boiler was considered. Then, the operating cost of combined desulfurization system under different load conditions for a 300MW subcritical CFB unit was analysed, combined with measured data. The operating cost optimization result shows that, under different loads, when Ca/S is in the range of 0.4 to 0.5, the operating cost of combined desulfurization system reaches the minimum. In addition, as the unit load increases, the higher proportion of SO₂ removal in FGD is required to achieve low-cost operating mode for CFB units.

1. Introduction
The rapid development of circulating fluidized bed technology is obvious due to its wide fuel applicability, low temperature combustion, high efficiency and low pollution emission, etc. [1, 2, 3]. There are more than 8000 CFB boiler units around the world have been put into operation, which are used for power generation, dyeing, metallurgy and other industrial manufacture. For the SO₂ emission reduction, the desulfurization by limestone during the combustion process in CFB furnaces is widely used due to its low investment and simple system [4]. However, with the environmental concerns grow, the SO₂ emission standards for CFB boilers have been tightened. The ultralow emission standard in China requires SO₂ emission cannot be higher than 35 mg/Nm³ [5, 6]. Unfortunately, it is difficult to realize the ultralow SO₂ emission by desulfurization in furnace for most CFB boilers, so the FGD systems are installed [7]. Wet flue gas desulfurization (WFGD) technology is usually selected for flue gas desulfurization systems. Compared with a single desulfurization in CFB furnace, combined desulfurization system can achieve higher desulfurization efficiency, but the operating cost of the system also increases [8].

Cai Y [9] established a cost model of material and equipment energy consumption for a combined desulfurization system. By converting coal quality and sulfur content, the coal is divided into six categories, and the optimal operating mode of various coal systems is given subsequently. Besides, the sensitivity analysis of limestone unit price, industrial water unit price, and on-grid electricity price to various coals is analyzed. The above study is a simple model that discussed the...
operating cost under full load only, lacking the effect of Ca/S on desulfurization efficiency under different loads.

In this paper, the combined desulfurization system of a subcritical 300MW CFB power generation unit is selected to explore the low-cost operating mode. The Ca/S of desulfurization in furnace with the lowest operating cost under different load conditions are obtained. The economic operating mode can be concluded that, as the unit load increases, the higher proportion of SO$_2$ removed in WFGD is helpful to minimize the operating cost of the combined desulfurization system and improve the operating economy for CFB units.

2. Modeling of economic index for combined desulfurization system

\[ m_{\text{CFB, limestone}} = m_{\text{coal}} \frac{M_{\text{CaCO}_3}}{M_S} \frac{S_{\alpha}}{R_{\text{CFB}}} \]  

Where $m_{\text{CFB, limestone}}$ is the consumption of limestone in the CFB boiler furnace, t/h; $m_{\text{coal}}$ is the coal-feed rate, t/h; $R_{\text{CFB}}$ is the molar ratio of calcium to sulfur; $M_{\text{CaCO}_3}$ and $M_S$ are the molar masses of

![Figure 1. Main process flow chart of CFB boiler combined desulfurization system.](image-url)
CaCO₃ and S respectively, g/mol; \( S_{\text{ar}} \) is the sulfur content of received base, %; \( \alpha \) is the purity of limestone in furnace, %.

2.1.2. Desulfurization efficiency in furnace. The formula for calculating the desulfurization efficiency in furnace is:

\[
\eta_{\text{CFB}} = \frac{c_{\text{SO}_2,\text{produce}} - c_{\text{SO}_2,\text{in}}}{c_{\text{SO}_2,\text{produce}}} \tag{2}
\]

Where \( \eta_{\text{CFB}} \) is the desulfurization efficiency in furnace; \( c_{\text{SO}_2,\text{produce}} \) is the \( \text{SO}_2 \) concentration generated from the combustion, mg/m³; \( c_{\text{SO}_2,\text{in}} \) is the \( \text{SO}_2 \) concentration at the entrance of the absorption tower the WFGD, mg/m³.

\[
c_{\text{SO}_2,\text{produce}} = m_{\text{coal}} \frac{S_{\text{ar}}}{100} \frac{M_{\text{SO}_2}}{M_{\text{S}}} \frac{1}{V_{\text{air}}} \times 10^6 \tag{3}
\]

Where \( V_{\text{air}} \) is the flow rate of air in furnace, m³/h.

Given that the desulfurization efficiency of CFB boiler is closely related to the Ca/S and bed temperature in the combustion process, Cai Y [9] chose the desulfurization efficiency of CFB boiler based on the regression calculation of combustion experiment data. In this paper, these parameters related to the bed temperature and the performance of limestone are selected, and then the efficiency formula of desulfurization in furnace considering the self-desulfurization is obtained. The calculating formula selected is as follows:

\[
\eta_{\text{CFB}} = 1 - A \cdot e^{-B \cdot R_{\text{CFB}}} \tag{4}
\]

In this formula, \( A \) and \( B \) are corrected coefficients, which are mainly related to boiler model, coal type, bed temperature, limestone characteristics and load.

2.1.3. Power consumption in furnace. The power consumption equipment in CFB boiler mainly includes primary fan, secondary fan, induced fan, high pressure fluidization fan, return fan, air compressor, limestone conveying fan, etc. This paper considers the power consumption of primary and secondary air and limestone conveying fan.

\[
W_{\text{CFB}} = W_1 + W_2 + W_3 \tag{5}
\]

Where \( W_1, W_2 \) and \( W_3 \) stand for the power consumption of primary and secondary air and limestone conveying fan respectively, and \( W_{\text{CFB}} \) represents the sum of power consumption in furnace, yuan/h.

2.1.4. Heat loss of CFB boiler. The desulfurization in CFB furnace by limestone will change the combustion conditions and result in a decrease in the thermal efficiency of boiler. The limestone fed into furnace will undergoes calcination decomposition reaction and sulfation reaction in CFB boiler [11, 12], which are expressed as

\[
\text{CaCO}_3 = \text{CaO} + \text{CO}_2; \Delta H = +178.3 \text{kJ/mol} \tag{6}
\]

\[
\text{CaO} + \frac{1}{2} \text{O}_2 + \text{SO}_2 = \text{CaSO}_4; \Delta H = -486 \text{kJ/mol} \tag{7}
\]

In the process of the desulfurization reaction, the chemical reactions occurring in the CFB boiler furnace need to absorb or release heat, and the ash and flue gas generated from the desulfurization will also absorb a part of the heat, which results in heat loss. In this paper, exhaust heat loss \( Q_2 \), mechanical incomplete combustion heat loss \( Q_4 \) and desulfurization heat loss \( Q_7 \) are considered, and heat loss can be converted into coal loss for calculation.

\[
m_{\text{coal, loss}} = m_{\text{coal}} \left( \frac{\eta}{\eta - \Delta \eta} - 1 \right) \tag{8}
\]

Where \( \eta \) is the design value of the thermal efficiency, %; \( \Delta \eta \) is the heat loss of the boiler, %; \( m_{\text{coal, loss}} \) is the coal loss converted from heat loss, t/h.
\[ \Delta \eta = \frac{Q_r + Q_\Delta + Q_s}{Q_r} \]  

Where \( Q_r \) is the input heat of CFB boiler, kJ/h.

After limestone is added into the furnace, the desulfurization heat loss caused by calcining decomposition reaction and sulfation reaction can be calculated as:

\[ Q_r = 1783 m_{\text{CFB,limestone}} \cdot \frac{\alpha}{100} - 15631 \eta_{\text{CFB}} \cdot m_{\text{coal}} \cdot \frac{S_u}{100} \]  

Assuming that all limestone is decomposed in the furnace, it can be inferred that the increased flue gas volume for 1 kg of coal is:

\[ V_{\text{flue}} = 0.007 R_{\text{CFB}} \cdot S_u - 1.866 \times 0.375 \frac{S_u}{100} \cdot \eta_{\text{CFB}} \]  

The main component of limestone used for desulfurization is CaCO\(_3\), and it also contains impurities such as MgCO\(_3\), SiO\(_2\), Fe\(_2\)O\(_3\), and water. Therefore, the ash generated from desulfurization in furnace also contains products of impurity reaction and unreacted CaO, etc., which will affect the combustion condition. As a result of the addition of desulfurizer, the quality of ash and slag produced by 1 kg of coal can be calculated by the following formula:

\[ m_{\text{ash}} = 0.0425 \eta_{\text{CFB}} \cdot S_u + 0.01749 S_u \cdot (R_{\text{CFB}} - \eta_{\text{CFB}}) + \frac{0.03125 R_{\text{CFB}} \cdot S_u}{\alpha} \cdot (100 - \alpha - \theta) \]  

Where \( \theta \) is the moisture content of CFB limestone, %.

2.2. Economic index modeling of WFGD system

2.2.1. Limestone consumption of WFGD. In the WFGD system, limestone slurry is sent from slurry pool of absorption tower to spray system in tower by slurry circulating pump. Limestone slurry contacts with flue gas from top to bottom to absorb SO\(_2\) in flue gas [13]. In the slurry pool of absorption tower, air is blown by oxidation fan, so that calcium sulfite in slurry is oxidized into calcium sulfate, namely gypsum.

\[ m_{\text{limestone}} = Q_{\text{flue}} \cdot c_{SO_2,\text{in}} \cdot \eta_{\text{WFGD}} \cdot M_{CaCO_3} \cdot R_{\text{FGD}} \frac{100}{\beta} \times 10^{-3} \]  

Where \( m_{\text{limestone}} \) is the limestone consumption mass of the desulfurization slurry, t/h; \( Q_{\text{flue}} \) refers to the flow rate of original flue gas, m\(^3\)/h; \( \eta_{\text{WFGD}} \) means the WFGD efficiency; \( M_{SO_2} \) represents the molar mass of SO\(_2\), g/mol; \( R_{\text{FGD}} \) is the molar ratio of calcium to sulfur for WFGD; \( \beta \) stands for the purity of limestone in WFGD, %.

2.2.2. The efficiency of WFGD system. The calculating formula of WFGD efficiency is:

\[ \eta_{\text{WFGD}} = \frac{c_{SO_2,\text{in}} - c_{SO_2,\text{out}}}{c_{SO_2,\text{in}}} \]  

Where \( c_{SO_2,\text{out}} \) is the SO\(_2\) concentration at the outlet of the absorption tower of WFGD, mg/m\(^3\).

It is generally accepted that the efficiency of WFGD is related to SO\(_2\) concentration of original flue gas, liquid flow and gas flow rate. In the paper [14], the model of WFGD system efficiency was established, in which liquid and gas flow rate are considered. In this section, it is assumed that slurry flow rate depends on the number of slurry circulating pumps put into operation, and the flow rate of the flue gas is related to unit load. The calculating formula of WFGD efficiency is:

\[ \eta_{\text{WFGD}} = 1 - e^{c_{SO_2,\text{in}} \cdot (N_e)^{C \cdot D \cdot E}} \]  

Where \( N_e \) is the load of the unit, MW; \( C, D \) and \( E \) are the corrected coefficients, which are mainly related to the number of operating slurry circulation pumps and the temperature, etc.
2.2.3. Operating power consumption of WFGD. The main power consumption equipment for WFGD includes absorber agitator, slurry circulating pump, oxidation fan, booster fan, gypsum discharge pump, limestone slurry pump, etc. The power consumption of slurry circulating pump and oxidation fan is involved.

\[ W_{\text{FGD}} = W_4 + W_5 \]  
(16)

Where \( W_4 \) and \( W_5 \) stand for the power consumption of slurry circulating pump and oxidation fan respectively, and \( W_{\text{FGD}} \) represents the sum of power consumption in WFGD, yuan/h.

2.2.4. Industrial water consumption. In the process of WFGD, water consumption mainly includes four parts: evaporated water of flue gas, carried water in flue gas discharge, water in by-product gypsum and discharged wastewater.

\[ m_{\text{water}} = m_1 + m_2 + m_3 + m_4 \]  
(17)

Where \( m_1, m_2, m_3 \) and \( m_4 \) stand for the mass of evaporated water of flue gas, carried water in flue gas discharge, water in by-product gypsum and discharged wastewater, and \( m_{\text{water}} \) means the sum of industrial water consumption, t/h.

2.2.5. Gypsum production. The main product of limestone-gypsum WFGD process is gypsum with certain purity and water content, whose chemical formula is \( \text{CaSO}_4 \cdot 2\text{H}_2\text{O} \).

\[
m_{\text{gypsum}} = Q_{\text{flue}} \cdot c_{\text{in},m} \cdot \frac{M_{\text{CaSO}_4 \cdot 2\text{H}_2\text{O}}}{M_{\text{gypsum}}} \cdot \frac{R_{\text{FGD}}}{(100 - \omega)} \times 10^9 \]  
(18)

Where \( m_{\text{gypsum}} \) is the gypsum production, t/h; \( \omega \) is the moisture content of gypsum.

2.3. Economic cost modeling of combined desulfurization system

For power plants that have determined to choose combined desulfurization, the initial construction costs and depreciation expenses of corresponding equipment and facilities required by different operating strategies are the same, so these costs do not affect the choice of operating strategies. The total operating cost of the CFB combined desulfurization system is divided into two parts: desulfurization in furnace and WFGD, including material consumption and energy consumption. In addition, the sale of by-product gypsum can also obtain certain benefits.

The formula for cost calculation is:

\[
f_{\text{total}} = f_{\text{in}} + f_{\text{out}} \]  
(19)

\[
f_{\text{in}} = m_{\text{CFB,limestone}} \cdot p_{\text{CFB,limestone}} + W_{\text{CFB}} \cdot p_{\text{power}} + m_{\text{coal,loss}} \cdot p_{\text{coal}} \]  
(20)

\[
f_{\text{out}} = m_{\text{FGD,limestone}} \cdot p_{\text{FGD,limestone}} + W_{\text{FGD}} \cdot p_{\text{power}} + m_{\text{water}} \cdot p_{\text{water}} + m_{\text{gypsum}} \cdot p_{\text{gypsum}} \]  
(21)

Where \( f_{\text{total}} \) is the total cost of CFB boiler unit combined desulfurization system running for one hour, yuan/h; \( f_{\text{in}} \) and \( f_{\text{out}} \) are the costs of CFB boiler unit desulfurization system in furnace and WFGD running for one hour respectively, yuan/h.

3. Results and analysis

According to the quality test report and operating procedures of the power plant, some of the parameters required for economic calculation mentioned in this paper have been listed in the below table.

Table 1. Parameters for economic calculation.
In this paper, the average value that measured from Distributed Control System (DCS) of coal feed rate, the flow rate of original flue gas and net flue gas of the 300MW subcritical CFB unit under steady operating condition are substituted into the model for calculation, which are shown as follows:

Table 2. Average data under stable operating condition.

| Load /MW | Coal feed rate /t/h | Flow rate of original flue gas /m³/h | Flow rate of Net flue gas /m³/h |
|----------|---------------------|-------------------------------------|--------------------------------|
| 300      | 186.35              | 1087675.22                         | 1113170.81                     |
| 260      | 133.11              | 778919.90                          | 866933.06                      |
| 220      | 106.89              | 700374.48                          | 804782.54                      |
| 180      | 87.30               | 532610.59                          | 674446.55                      |

Figure 2 shows the relationship between the operating cost of the combined desulfurization system and the Ca/S in the furnace respectively under different load conditions. Meanwhile, the optimal cost of combined desulfurization and the corresponding Ca/S in the furnace are obtained.

Figure 2. Relationship between operating cost and Ca/S in furnace under different load conditions.

By observing Figure 2, it can be seen that as the load increases, the operating cost of the combined desulfurization system increases correspondingly. The operating cost shows a trend of first decreasing
and then increasing with the gradual increase of the Ca/S in furnace. When the Ca/S in furnace is in the range of 0.4 to 0.5, there exists an optimal in-furnace Ca/S, which makes the operating cost of the combined desulfurization system the lowest. The optimized results are listed in Table 3.

Table 3. Optimal results of combined desulfurization system of the CFB unit.

| Load (MW) | Concentration of SO₂ generated (mg/m³) | Concentration of SO₂ in the original flue gas (mg/m³) | Optimal Ca/S | Limestone consumption in furnace (t/h) | Limestone consumption in WFGD (t/h) | Optimal cost (yuan/h) |
|-----------|---------------------------------------|-------------------------------------------------|--------------|----------------------------------------|------------------------------------|-----------------------|
| 300       | 3186.71                               | 1782.90                                         | 0.49         | 2.9720                                 | 3.6129                             | 2863.63               |
| 260       | 3178.56                               | 1579.92                                         | 0.42         | 1.8196                                 | 2.2854                             | 2421.81               |
| 220       | 2838.70                               | 1342.68                                         | 0.42         | 1.4612                                 | 0.9740                             | 2285.92               |
| 180       | 3048.72                               | 984.99                                          | 0.51         | 1.4492                                 | 0.9656                             | 2080.02               |

After optimization, the corresponding optimal limestone consumption can be obtained, which can provide guidance for operating workers to adjust the supply of limestone powder and limestone slurry. On the basis of the above research, further analysis shows that the proportion of SO₂ concentration removed in furnace and WFGD of the CFB combined desulfurization system can be obtained, as shown in Figure 3.

Figure 3. Proportion of SO₂ concentration removed desulfurization in furnace and WFGD.

According to Figure 3, with the decrease of unit load, the desulfurization share in furnace gradually increases and the WFGD share gradually decreases. It provides theoretical guidance for crew operators on the macro-control of the proportion of SO₂ removal of the combined desulfurization system.

4. Conclusion

In this paper, based on the relevant theoretical knowledge of the combined desulfurization system of CFB boiler unit and measured operating data from DCS of a 300MW subcritical CFB unit, economic model of combined desulfurization system is set up, in which the production of gypsum, heat loss of the boiler owing to desulfurization and so forth are included. The solution obtained in the environmental constraint conditions meets economic performance and the technical performance index of main parameters of combined desulfurization system. After optimization, the corresponding optimal
limestone consumption can be obtained, which can provide guidance for operating workers to adjust the supply of limestone powder and limestone slurry. With the decrease of the load, the concentration of SO$_2$ in the original flue gas is controlled lower, and so is the operating cost, while the optimal Ca/S decreased first and increased subsequently. In general, the optimal Ca/S is in the range of 0.4 to 0.5.

At the same time, the proportion of desulfurization in furnace and WFGD of the combined desulfurization system under different load conditions is also obtained, where we can apparently see that the higher the unit load is, the more the proportion of SO$_2$ removal in WFGD is needed to bring about a economic operating mode for the combined desulfurization system of CFB. This paper provides operating guidance and theoretical basis for the operational personnel to adjust the processing parameters of the desulfurization system. Besides, method guidance for the realization of energy saving and consumption reduction of the same type of CFB unit are provided.

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