Selection of ultra-low emission transformation scheme for 300MW CFB unit desulphurization system

Lei Zhang1,2,3, Guangcun Yuan1 and Shuyuan Li1

1 Shenhua Guoneng Shandong Construction Group Co.,Ltd;
2 School of Energy, Power and Manchanical Engineering, North China Electric Power University.
3 Email: 17055974@chnenergy.com.cn

Abstract. Mature outside-desulfurization technology is supplied as an ultra-low emission transformation for meeting present emission standard. In order to explore a reasonable method to select the most economical transformation scheme of desulfurization system, a CFB boiler of 300MW class unit was taken as the research object. According to actual operation data and characteristics of different technical routes, a numerical model was set up, in which the cost caused by material consumption in desulfurization and denitrification and change of boiler efficiency was considered. The model was transformed into a single value function of ratio of calcium to sulfur in furnace. Through derivation, optimum proportion of joint desulfurization in and out furnace and comprehensive annual cost including initial investment, operation and maintenance of different schemes were obtained. The results show that for semi-dry desulphurization system outside furnace, the change of ratio of calcium to sulfur outside furnace has little influence on optimum ratio of desulfurization in furnace. When the ratio of calcium to sulfur outside furnace is 1.2~2.0, optimum ratio of desulfurization in furnace is about 76%~88%. According to this ratio, the ultra-low emission transformation scheme combining semi-dry desulphurization outside furnace and limestone injection in furnace is the most economical.

1. Introduction

In order to cope with increasingly severe pressure of environmental protection, the Ministry of Environmental Protection of China issued the Work Program for Fully Implementing Ultra-low Emission and Energy-saving Reform Project of Coal-fired Power Plants in 2015, requiring the eastern, central and western coal-fired power plants to achieve ultra-low emission by the end of 2017, the end of 2018 and the end of 2020 respectively. Emission concentrations of soot, sulfur dioxide and nitrogen oxide are not higher than 10mg·m⁻³, 35mg·m⁻³ and 50mg·m⁻³ correspondingly under the condition of 6% oxygen content.

CFB boilers can effectively remove SO₂ generated by fuel combustion relying on adding a suitable amount of desulfurizer in furnace, but SO₂ emission concentration at furnace outlet is about 200 mg·m⁻³[1]. Numerous experimental and theoretical studies about the sulphur retention in CFB boilers are present, there are many model proposed for predicting the SO₂ emission under different operational parameters[2-8]. Gungor et al.[9-11] developed a 2D model to study the influence of bed operational velocity, excess air ratio, gas inlet and coal particle size on the overall SO₂ emission and combustion efficiency from a small-scale CFBC. Krzywanski et al.[12-14] utilized the artificial neural network (ANN) approach to predict SO₂ emissions from large-and small-scale CFB boilers, which can be easily
applied for simulations ans optimizations of CFB units. Although through those approach of parameter adjustment SO2 emissions can be reduced to a lower level, but it is also difficult to meet the emission targets only by desulfurization in furnace. Therefore, taking mature outside-desulfurization technology as a supplement has become the main way of ultra-low emission transformation of desulfurization system. One route is limestone injection in furnace+wet desulfurization outside furnace+high efficiency demister+chimney anticorrosion, and another is limestone injection in furnace+pre-duster+semi-dry desulfurization outside furnace+high efficiency bag filter [15].

According to the actual emission situation of reformed power plants in China, no matter which technology route is adopted, it can meet the national emission requirements, but how to choose is mostly focused on initial investment [16]. One CFB boiler desulfurization system of a 300 MW unit in a power plant was taken as the research object. According to actual operation data and characteristics of different technical routes, a numerical model was established and one method to select the optimal scheme for ultra-low emission transformation of desulfurization system based on comprehensive cost of investment, operation and maintenance was explored.

The research object power plant has a circulating fluidized bed boiler with subcritical parameter, natural circulation, primary reheat. Its type is HG-1065/17.6-L.MG44. The main design parameters are shown in Table 1.

| Parameter                               | Unit        | Data in BMCR |
|-----------------------------------------|-------------|--------------|
| Evaporation                             | t·h⁻¹       | 1,065        |
| Steam pressure at superheater outlet    | MPa         | 17.5         |
| Steam temperature at superheater outlet | ℃           | 541          |
| Steam pressure at reheater inlet        | MPa         | 4.046        |
| Steam temperature at reheater inlet     | ℃           | 334          |
| Bed temperature                         | ℃           | 904          |
| Flue gas quantity                       | Nm³·h⁻¹     | 1,027,130    |
| Efficiency                              | %           | 91.502       |
| Desulfurization efficiency              | %           | ≥85          |

2. Mathematical model and calculation method

2.1. Mathematical model

On the premise that space of power plant is enough for different transformation routes, the comprehensive annual cost is taken as the main criterion for the selection of schemes, which includes initial investment, annual operation cost and annual maintenance cost.

2.1.1. Initial investment and annual maintenance cost. From May 2017 to September, the average sulphur content of coal entered the power plant was 0.58%, which has little influence on initial investment and annual maintenance cost under the same route when choosing ultra-low emission transformation scheme. Therefore, the initial investment and annual maintenance cost of desulfurization system outside furnace could be considered according to removal of all sulfur content.

2.1.2. Joint operation cost. Whether wet or semi-dry desulfurization technology is used outside furnace, there is a problem of desulfurization capacity distribution. Different ratio of desulfurization inside and outside furnace not only determines consumption of desulfurizer, but also indirectly affects boiler efficiency and consumption of SNCR denitrification urea. According to different operation conditions and material prices, there must be an optimum desulfurization ratio inside and outside furnace, so that the joint operation cost consisting of material consumption in desulfurization and denitrification and boiler efficiency is the lowest under the premise of emission standard. The model formula is,
In the form, $E$ - joint operation cost, yuan/(kW·h)$^{-1}$

\[ E = \frac{q_{\text{des.in}} P_{\text{des.in}}}{P} + \frac{q_{\text{den}} P_{\text{den}}}{P} + \frac{q_{\text{des.out}} P_{\text{des.out}}}{P} + \frac{\Delta \eta_t}{\eta_t - \Delta \eta_t} p_b g \]  

(1)

In design of desulfurization system outside furnace, it is usually based on selected inlet SO$_2$ concentration and desulfurization efficiency needed to meet ultra-low emission. The standard of ultra-low emission is determined, so the key parameter of desulfurization capacity allocation is SO$_2$ concentration at the inlet of outside-desulfurization system. Considering the calculation of effect on boiler efficiency and denitrification, all the sub-items are related to ratio of calcium to sulfur in furnace, so the joint operation cost can be reduced to a single value function of the ratio of calcium to sulfur.

2.1.3. Relationship between ratio of calcium to sulfur and joint operation cost. The definition of ratio of calcium to sulfur in furnace is as follows[17],

\[ r_{Ca/S} = \frac{32.066 \alpha_{\text{CaCO}_3\text{des}} q_{\text{des.in}}}{100.086 \alpha_{S,\text{air}} q_c} \]  

(2)

the consumption of desulfurizer in furnace in unit time can be expressed by transposition.

Research[18] show that the heat loss of limestone desulfurization has the greatest influence which account for more than 90 percent on boiler efficiency when adding limestone to furnace. Therefore, the influence of desulfurizer on boiler efficiency can be approximately expressed as the heat loss of limestone desulfurization. The formula is,

\[ \Delta \eta_t = \frac{Q_s}{100} (57.19 r_{Ca/S} \eta_{\text{CaCO}_3} - 151.59 \eta_{SO_2}) \]  

(3)

in the form, $\eta_{\text{CaCO}_3}$ is decomposition rate of CaCO$_3$, $\eta_{SO_2}$ is desulfurization efficiency in furnace. The formula for calculating consumption of desulfurizer outside furnace in unit time is,

\[ q_{\text{des.out}} = \frac{56 V m_{\text{out}} r_{\text{out}}}{64 \omega_{\text{des.out}}} \]  

(4)

in the form, $V$ is flue gas volume at inlet of desulfurization tower, $r_{\text{out}}$ is ratio of calcium to sulfur outside furnace, $\omega_{\text{des.out}}$ is mass fraction of CaO in desulfurizer outside furnace, $m_{\text{out}}$ is the amount of SO$_2$ removed by outside desulfurization system.

According to experimental data, the relationship between flow rate of denitrified urea solution and ratio of calcium to sulfur in furnace is shown in Figure 1. Initial concentration of NOx is taken into account according to the design value of 280mg·m$^{-3}$ when no desulfurizer is added. The fitting formula is,

\[ V_{\text{den}} = 0.0015 r^4 - 0.0251 r^3 + 0.145 r^2 - 0.2882 r + 0.3663 \]  

(5)

Experimental data illustrates that under rated load condition, bed temperature is 880℃, and sulfur content is 0.6%, the relationship between desulfurization efficiency and ratio of calcium to sulfur in furnace is shown in Figure 2. The fitting formula is,

\[ \eta_{SO_2} = -0.0182 r^6 + 0.5157 r^5 - 5.8568 r^4 + 33.767 r^3 - 103.49 r^2 + 158.84 r - 0.0019 \]  

(6)
2.2. Boundary condition
The boundary condition are as follows: sulfur content is 0.58%, utilization hours are 3636h, coal quantity is 200 t-h⁻¹, flue gas quantity is 1,278,000 Nm⁻³-h⁻¹ (all above are average value of statistics); ratio of calcium to sulfur of wet desulfurization system is 1.1, and semi-dry desulfurization system is 1.4.

The price of desulfurization related materials are as below: limestone is 140 yuan-t⁻¹, quicklime is 400 yuan-t⁻¹, water is 1.1 yuan-t⁻¹, electricity is 0.2829 yuan-(kW-h)⁻¹, urea is 1,920 yuan-t⁻¹, standard coal is 450 yuan-t⁻¹.
3. Results and discussion

According to the price of materials and boundary conditions of wet and semi-dry desulfurization system outside furnace, the joint operation cost calculation model was transformed into a single value function of ratio of calcium to sulfur in furnace. The function was derived, the ratio of calcium to sulfur and the desulfurization efficiency at the lowest joint operation cost were obtained. The related parameters are shown in Table 2.

| Parameter                                      | Unit  | wet  | semi-dry |
|------------------------------------------------|-------|------|----------|
| Ratio of calcium to sulfur in furnace          | /     | 0.14 | 0.88     |
| Desulfurization efficiency in furnace          | %     | 19.81| 79.59    |
| Ratio of calcium to sulfur outside furnace     | /     | 1.1  | 1.4      |
| Desulfurization efficiency outside furnace     | %     | 97.60| 90.55    |
| Ratio of desulfurization in furnace            | %     | 20.20| 81.15    |
| SO₂ concentration at inlet of outside          |       |      |          |
| desulfurization system                         | mg·Nm⁻³| 1,455| 370      |

Under the given boundary conditions, optimum ratio of desulfurization in furnace is 20.20% for wet desulfurization system and 81.15% for semi-dry desulfurization system. The difference between them is mainly determined by the price of desulfurization materials.

Four ultra-low emission transformation schemes including single wet desulfurization system outside furnace, single semi-dry desulfurization system outside furnace, limestone injection in furnace+wet desulfurization outside furnace, and limestone injection in furnace+semi-dry desulfurization outside furnace were compared for economical efficiency. The optimal ratio of desulfurization distribution inside and outside furnace was calculated by the lowest joint operation cost model. Details are listed below.

| Serial number | Cost name                                      | Simple system                        | Combined system                       |
|---------------|-----------------------------------------------|--------------------------------------|---------------------------------------|
|               | Cost name                                     | Simple system wet | Simple system semi-dry | Combined system wet | Combined system semi-dry |
| 1             | Additional investment in desulphurization      | 6,330 | 6,880 | 6,330 | 6,880 |
|               | system outside furnace                         |                      |                         |                      |                         |
| 2             | land clearing                                  | 100 | 50 | 100 | 50 |
| 3             | Annual cost of operation                       | 675.90 | 664.48 | 622.26 | 351.74 |
| 3.1           | Annual consumption of desulfurizer             | 221.14 | 506.62 | 182.00 | 239.82 |
| 3.1.1         | In furnace                                     | / | / | 5.54 | 144.32 |
| 3.1.2         | Outside furnace                                | 221.14 | 506.62 | 176.47 | 95.50 |
| 3.2           | Annual consumption of water                    | 16.00 | 28.00 | 16.00 | 28.00 |
| 3.3           | Annual consumption of electric                 | 365.47 | 56.57 | 365.47 | 56.57 |
| 3.4           | Annual consumption of urea                     | 73.29 | 73.29 | 73.29 | 73.29 |
| 3.5           | Annual cost of increase for boiler efficiency  | / | / | -14.51 | -45.94 |
| 4             | Annual cost of wastewater treatment            | 90.9 | / | 72.72 | / |
| 5             | Annual cost of maintenance                     | 200 | 140 | 200 | 140 |
| 6             | Annual cost of replacement for filter bag      | 64.5 | 94.5 | 64.5 | 94.5 |
| 7             | Annual cost in sum                             | 1,553.30 | 1,407.65 | 1,481.48 | 1,094.91 |

It can be confirmed that in the four transformation schemes, limestone injection in furnace+semi-dry desulfurization outside furnace is the most economical.
The Table 4 shows the optimum proportion of desulfurization in furnace when the ratio of calcium to sulfur assumed in boundary condition changes.

**Table 4. Optimum proportion of desulfurization in furnace under different ratio of calcium to sulfur.**

| Mode   | Ratio of calcium to sulfur | Ratio of desulfurization in furnace |
|--------|----------------------------|-------------------------------------|
| Wet    | 1.1                        | 20.20%                              |
|        | 1.2                        | 33.72%                              |
|        | 1.3                        | 43.56%                              |
|        | 1.4                        | 51.02%                              |
| semi-dry | 1.2                        | 76.34%                              |
|         | 1.4                        | 81.15%                              |
|         | 1.6                        | 84.34%                              |
|         | 2.0                        | 88.27%                              |

The results imply that for semi-dry desulfurization system outside furnace, the change of ratio of calcium to sulfur has little influence on optimum proportion of desulfurization in furnace. When the ratio of calcium to sulfur outside furnace is 1.2 ~ 2.0, the optimum proportion of desulfurization in furnace is about 76% ~ 88%. While, for wet desulfurization system outside furnace, the change of the ratio of calcium to sulfur has obvious influence on the optimum proportion of desulfurization. When the ratio of calcium to sulfur outside furnace is 1.1 ~ 1.4, the optimum proportion of desulfurization inside furnace is about 20% ~ 50%.

Because of the lowest comprehensive annual cost belongs to semi-dry desulfurization, and lower value of ratio of calcium to sulfur was chosen in the boundary condition, deviation between actualities and hypothesis will not cause substantial changes in the results.

**4. Conclusions**

1. Under the reasonable and controllable ratio of calcium to sulfur in furnace, combined desulfurization system inside and outside furnace is more economical than single desulfurization system outside furnace for ultra-low emission.
2. For semi-dry desulfurization system outside furnace, the change of ratio of calcium to sulfur outside furnace has little influence on optimum proportion of desulfurization in furnace, while the change has more obvious influence on optimum proportion of desulfurization for wet desulfurization system.
3. The comprehensive annual cost of ultra-low emission transformation scheme is the lowest by combining semi-dry desulfurization outside furnace and limestone injection in furnace, which is distributed according to the most economical ratio of desulfurization inside and outside furnace.

**Acknowledgment**

This work was supported by Shenhua Group Co., Ltd. Science and Technology Innovation Project (SHJT-17-27).

**References**

[1] Qing Li, Youmin Li 2015 Energy saving and emission reduction manual for thermal power plants [M] China Electric Power Press 110-115

[2] Adanez J, Gayan P, Grasa G, de Diego L F, Armesto L, Cabanillas A 2001 Circulating fluidized bed combustion in the turbulent regime: modeling of carbon combustion efficiency and sulfur retention *Fuel* **80** 1405-1414

[3] Zhao Y, Xu P Y, Fu D 2006 Experimental study on simultaneous desulfurization and denitrification based on highly active absorbent *Journal of Environmental Sciences-China*
18(2) 281-286

[4] Barletta D, Marzocchella A, Salatino P 2002 Modelling the SO$_2$-limestone reaction under periodically changing oxidizing/reducing conditions: the influence of cycle time on reaction rate Chemical Engineering Science 57 631-641

[5] Tarelho L A C, Matos M A A, Pereira F J M A 2005 The influence of operational parameters on SO$_2$ removal by limestone during fluidized bed coal combustion Fuel Processing Technology 86 1385-1401

[6] Manovica V, Gruborb B, Loncarevic D 2006 Modelling of inherent SO$_2$ capture in coal particles during combustion in fluidized bed Chemical Engineering Science 61 1676-1685

[7] Liu H, Gibbs B M 1998 The influence of limestone addition at different positions on gaseous emissions from a coal-fired circulating fluidized bed combustor Fuel 77 1569-1577

[8] Lyngfelt A, Aamand L E, Leckner B 1995 Obtaining low N$_2$O, NO$_x$, and SO$_2$ emissions from circulating fluidized bed boilers by reversing the air staging conditions Energy Fuel 9 386-387

[9] Gungor A 2009 Prediction of SO$_2$ and NO$_x$ emissions for low-grade Turkish lignites in CFB combustors Chem.Eng.J. 146 388-400

[10] Gungor A, Eskin N 2008 Two-dimensional coal combustion modelling of CFB, Int.J.Therm.Sci. 47 157-174

[11] Gungor A, Eskin N 2008 Effects of operational parameters on emission performance and combustion efficiency in small-scale CFBCs J.Chin.Inst.Chem.Eng. 39 541-556

[12] Krzywanski J, Nowak W 2015 Artificial intelligence treatment of SO$_2$ emissions from CFBC in air and oxygen-enriched conditions J.Energy Eng. 142(1) Article number 04015017

[13] Krzywanski J, Czakiert T, Błaszczuk A, Rajczyk R, Muskala W, Nowak W 2015 A generalized model of SO$_2$ emissions from large- and small-scale CFB boilers by artificial neural network approach, Part 1. The mathematical model of SO$_2$ emissions in air-firing, oxygen-enriched and oxycombustion CFB conditions Fuel Processing Technology 137 66-74

[14] Krzywanski J, Czakiert T, Błaszczuk A, Rajczyk R, Muskala W, Nowak W 2015 A generalized model of SO$_2$ emissions from large- and small-scale CFB boilers by artificial neural network approach, Part 2. SO$_2$ emissions from large- and pilot-scale CFB boilers in O$_2$/N$_2$, O$_2$/CO$_2$ and O$_2$/RFG combustion atmospheres Fuel Processing Technology 137 73-85

[15] Shoubao Duan 2016 Technical route of air pollutants ultra low emission modification for 300MW CFB boilers[J] Clean Coal Technology Press 22(06) 88-94

[16] Yunfei Zhu, Weiping Yan, Yupeng Wang, et al. 2015 Technical economic analysis and optimization of two-stage desulfurization system for CFB boiler[J] Electric Power Construction. 33(06) 109-113

[17] Performance test code for utility boiler GB/T 10184-2015.

[18] Shengwei Xin 2017 Study on modification of SO$_2$ ultra-low emission in CFB boiler[J] Electric Power Technology and Environmental Protection 33(4) 10-14