Selection of typical wet desulfurization system and economic analysis of variable load operation for industrial coal-fired boilers

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Abstract. In this paper, the operation costs of wet flue gas desulfurization based on MgO, CaO and CaCO₃ under basic, special and ultra-low emission limits are analyzed from the unit price of desulfurizer and electricity price. Guidance about desulfurizer selection in Liaoning Province under different electricity prices and different loads is given. The results show that the desulfurization cost of MgO is greatly affected by the desulfurizer price, while the CaCO₃ is more sensitive to the fluctuation of electricity price, and the CaO is between the two. In Liaoning Province, the overall economy of CaCO₃ is relatively poor in the whole range of electricity price, while CaO and MgO perform better. The former has obvious advantages at low electricity price, while the latter is preferred at high. With the emission standard becoming stricter, the dominant range of CaO is expanded. When the boiler load changes, the power consumption cost and desulfurizer cost also change accordingly under different emission requirements. When the electricity price of Liaoning Province is 0.8 RMB/kWh, no matter under which emission limit, the operation cost of MgO is always the lowest under the considered loads, followed by CaO, and the economy of CaCO₃ is the worst.

1. Introduction

As energy conversion equipment, industrial boilers have been playing an important role in industrial manufacturing and society development. Different from power plant boilers, industrial boilers are used in a large number of areas and widely distributed throughout the country. At present, about 600,000 industrial boilers have been put into operation in China, which can be divided into coal-fired, oil-gas-fired, electric heating and biomass industrial boilers according to the different fuels. Among them, the number of coal-fired boilers is the largest, about 500,000, accounting for about 80% of the total [1].

The widespread use of coal-fired industrial boilers and the consequential SO₂ emission from coal combustion have contributed to the serious environmental contamination [2, 3], which are also some of the main reasons for the serious haze that has continued to occur in recent years in China [4]. Moreover, industrial boilers are mostly located in the city or suburb with usually low chimneys, so the impact on the environment and human health should not be overlooked [5]. Faced with this situation, China has become more stringent in the formulation of pollutant emission standards for coal-fired boilers, and the ultra-low emission has been proposed as the strictest emission standard currently. It is
required by the ultra-low emission standard that after processing, the concentration of SO\textsubscript{2} produced from coal-fired boilers should be less than 35 mg/m\textsuperscript{3}, for NO\textsubscript{x}, it’s 50 mg/m\textsuperscript{3}, and PM is 5 mg/m\textsuperscript{3} [6].

For its low operation cost, high desulfurization efficiency and almost no water consumption, wet flue gas desulfurization is the most universal and mature desulfurization technology [7], which accounts for about 85\% of the desulfurization units built in the world [8]. However, as a complex system bringing huge environmental benefits, the wet flue gas desulfurization unit is also a high energy consumption system. Therefore, for the existing wet flue gas desulfurization system, the energy-saving operation is of great significance to improve its economic performance. At present, there are many studies on energy consumption and economic analysis of wet flue gas desulfurization, and the influence of desulfurization materials, operation of equipment, coal quality and etc. on energy consumption and cost are discussed in depth. Zhou et al. [9] carried out the on-the-spot investigation on more than ten power plants, summarized the common problems of energy consumption and operation of desulfurization system, and gave the optimum feasible scheme according to the actual operation of the power plant. Xue et al. [10] analyzed the energy consumption of desulfurization system from three aspects: energy consumption of desulfurization equipment, selection of coal types and chemical technology, and gave suggestions on optimization of energy consumption. Xu et al. [11] investigated the operation characteristics of various equipment in desulfurization system, and established mathematical models such as fitting curve to study their characteristics, and provided guidance for reducing the energy consumption of desulfurization system from quantitative analysis. Lu [12] established the energy consumption model of the main equipment used in the wet flue gas desulfurization system and optimized the operation of the main energy-consuming equipment such as oxidation fan and circulating slurry pump. Zhang [13] focused on the cost and benefit of the wet flue gas desulfurization system and discussed the influence of generation hours, electricity price and raw material cost on the economy. Wang [14] put forward a weighted model of desulfurization cost by analyzing the factors affecting the cost of desulfurization. Shi [15] took unit capacity, sulfur content, desulfurization efficiency, annual utilization time, fumace type, coal quality, and regional difference into consideration, and established a cost-benefit calculation model of the limestone-gypsum method. Wang [16] of Shandong University proposed a calculation method of energy consumption based on power consumption and studied the influence of operation parameters, flue gas parameters and technical parameters on the energy efficiency of desulfurization tower under ultra-low emission condition.

Although there have been many studies on the energy consumption and economy of wet flue gas desulfurization, greater challenges for its economic operation have been brought by ultra-low emission standard [17]. The discharge concentration of pollutants are greatly reduced by ultra-low emission, however, the energy consumption of the unit is also increased in the process of transformation and emission reduction. Nowadays, the implementation of the ultra-low emission standard is mainly realized by upgrading the existing technology and equipment or optimizing the system, and the specific implementation process is also related to the coal quality, boiler units and the region where it’s located [18]. In this situation, there are few energy efficiency studies and economic optimization for wet flue gas desulfurization of coal-fired industrial boilers. At the same time, due to the difference of electricity cost, original pollutant emission concentration, and treatment methods of products between industrial boilers and utility boilers, the research results of coal-fired boilers in thermal power plants can’t be directly applied to industrial ones. Thus, it is necessary to establish energy consumption and economic evaluation of wet flue gas desulfurization system for coal-fired industrial boilers.

In this paper, the economic analysis of three typical desulfurizers for wet flue gas desulfurization of coal-fired industrial boilers will be carried out, and the effects of desulfurizer price, electricity price and load variation on operation cost under different emission standards will be discussed, so as to provide guidance for energy saving and emission reduction of industrial coal-fired boiler enterprises.
2. Typical wet flue gas desulfurization system for industrial boilers

Typical wet flue gas desulfurization system for industrial boilers usually consists of flue gas subsystem, SO$_2$ absorption subsystem, absorbent reserve and supply subsystem, product treatment subsystem, feed water subsystem, and wastewater treatment subsystem.

Flue gas is introduced into the wet desulfurization system by the flue gas subsystem so that SO$_2$ can react with desulfurizer in the system. A booster fan or induced draft fan is usually used to boost pressure of the flue gas before it enters absorber. Then the liquid drops in the flue gas after SO$_2$ removal are eliminated by demister and discharged through the chimney.

SO$_2$ absorption subsystem including absorber, demister, circulating slurry pump and oxidation fan is the main place of SO$_2$ reacting with desulfurizer. Different liquid-gas ratio (L/G) are adopted according to the different desulfurization efficiencies, and 2-4 spray layers are usually used for a certain circulating slurry. Because the flow rate through the nozzle and atomization pressure are fixed values, one pump is usually used to correspond to one spray layer, or one pump is used to control two layers by combining frequency conversion and throttling adjustment. In this paper, the first method is adopted.

Typical wet flue gas desulfurization processes used in industrial boilers generally do not have a pulverizing system, and desulfurizers are purchased in powder. Desulfurizers are usually alkaline compounds used in SO$_2$ and SO$_3$ removal, including lime (the main component is CaO), slaked lime (the basis is Ca(OH)$_2$), limestone (the base is CaCO$_3$), magnesium oxide (MgO), magnesium hydroxide (Mg(OH)$_2$), soda ash (Na$_2$CO$_3$), carbide slag (the basis is Ca(OH)$_2$) and so on. In this paper, three different desulfurizers of CaO, CaCO$_3$ and MgO will be studied.

The solid content of slurry discharged from the outlet of desulfurization circulating pump is about 10%–15%. The slurry flows through the slurry pipe to the sedimentation tank, where slurry clarified liquid after sedimentation is pumped back to the circulating pool, and the precipitated product is discharged. If the desulfurization products are to be used, further dehydration can be carried out. The product dehydration subsystem generally includes first and second vacuum dehydration. After treatment, the desulfurization products with water content less than 10% are generally stored in the storage room, which is convenient for transportation. But not all industrial boilers dehydrate and reuse the desulfurization products, and some by-products which are difficult to be used may be discarded.

The feed water subsystem is mainly responsible for the water supply during the operation of the wet flue gas desulfurization system. Generally, the water is introduced from the original water supply system of the boiler and then sent to users through pumps, such as the flushing water of the demister during operation, and start-up and replenishment water of the slurry pond. The flushing water for all slurry conveying and storage equipment is provided by the feed water subsystem.

Normally, the wastewater produced in the operation of the system is lower in pH value and contains many heavy metals, which don't meet the environmental protection requirements of discharge. It must be treated to reduce environmental hazards. Wastewater can be mixed with alkaline ash slurry in the ash removal system, or directly introduced into professional wastewater treatment equipment. After professional physical sedimentation, chemical neutralization and other processes, the wastewater whose pH value and element content reach certain standard can be reused in the process water subsystem.

3. Test conditions

In this paper, the basic, special and ultra-low emission standards are considered, and the limits for SO$_2$ under the three standards are 400 mg/m$^3$, 200 mg/m$^3$, and 35 mg/m$^3$, respectively.

The following information got from a heating industrial coal-fired boiler located in Shenyang City are used in the next investigation. The boiler capacity is 70 MW with 0.29% sulfur content of the designed coal. And the flue gas volume is 63.89 m$^3$/s and the original SO$_2$ emission concentration is 644.96 mg/m$^3$ as the exhaust temperature is 150 °C at the 100% boiler load. When the basic, special and ultra-low emission standards are considered respectively, the SO$_2$ removal amounts are correspondingly 56.34 kg/h, 102.34 kg/h, and 140.29 kg/h. Due to the different consumption and unit
price of desulfurizers and the electricity cost fluctuation caused by the change of flow rate and circulating pump’s power, the total cost of desulfurization will change subsequently. Therefore, the economy of the system under different desulfurizer price, electricity price and changing load is analyzed.

4. Result and discussion

4.1 The effect of desulfurizer price on the cost
The influence of different desulfurizers on the technical parameters of desulfurization is shown in table1. It’s can be seen from table1 that when the desulfurization efficiency is assumed as 90%, the L/G of different desulfurization methods are quite different. Because the dissolving alkalinity of magnesium ion is stronger than that of calcium ion, the reaction ability of which can be more than ten times of that of calcium ion, the reaction intensity of MgO with SO₂ is higher. The molecular mass of MgO is 40 g/mol, CaO and CaCO₃ are 56 g/mol and 100 g/mol, respectively. Therefore, the amount of MgO is 73% of CaO and 40% of CaCO₃ when reacting with the same amount of SO₂.

Table 1 Technical indicators of desulfurization methods under different emission standards

| Emission standard | Desulfurization efficiency | Desulfurization method | L/G (L/m³) | Ca(Mg)/S | The pH of circulating slurry |
|-------------------|---------------------------|-------------------------|------------|----------|----------------------------|
| Basic             | >90%                      | Lime                    | >5         | <1.10    | 5.0~7.0                    |
|                   |                           | Magnesium               | >2         | <1.05    | 5.0~7.0                    |
|                   |                           | Limestone               | >10        | <1.05    | 5.0~6.0                    |
|                   |                           | Lime                    | >6         | <1.10    | 5.0~7.0                    |
| Special           | >90%                      | Magnesium               | >2.5       | <1.05    | 5.0~7.0                    |
|                   |                           | Limestone               | >12        | <1.05    | 5.0~6.0                    |
|                   |                           | Lime                    | >8         | <1.10    | 5.0~7.0                    |
| Ultra-low         | >90%                      | Magnesium               | >4         | <1.05    | 5.0~7.0                    |
|                   |                           | Limestone               | >16        | <1.05    | 5.0~6.0                    |

The desulfurizer price is highly related to the desulfurizer storage and transportation cost caused by geographical location. The prices of desulfurizers in different regions are shown in table 2. And according to table2, the price range of MgO, CaO and CaCO₃ is 650~1350 RMB/t, 500~600 RMB/t and 200~300 RMB/t, respectively.

Table 2 Unit price of desulfurizers in different provinces

| Desulfurizer | Heilongjiang (RMB/t) | Jilin (RMB/t) | Liaoning (RMB/t) | Shandong (RMB/t) |
|--------------|----------------------|---------------|------------------|-----------------|
| MgO          | 850                  | 780           | 1350             | 650             |
| CaO          | 600                  | 580           | 500              | 550             |
| CaCO₃        | 300                  | 300           | 250              | 200             |

The desulfurizer costs are calculated under the basic, special and ultra-low emission limits and the results are shown in figure 1, figure2 and figure3.
As can be seen from the figures, the desulfurizer costs of different desulfurizers increase with the stringent emission standards, but the slope of the same desulfurizer is the same under different emission standards. Because the quality of desulfurizer reacting with the same quality of SO$_2$ is CaCO$_3$ > CaO > MgO, the slope of CaCO$_3$ is the largest, followed by CaO, and MgO is the smallest. Under the three emission standards, the desulfurizer costs of the three desulfurizers all increase. But because of the highest unit price of MgO, its desulfurizer cost is relatively high, ranging from 22.89–47.54 RMB/h under the basic emission standard to 41.58–86.35 RMB/h under the special, until 56.99–118.37 RMB/h under the ultra-low. The unit price of CaCO$_3$ is the cheapest, so its desulfurizer cost of 17.61–65.76 RMB/h is relatively low and that of calcium oxide of 24.65–73.65 RMB/h is medium.

4.2 The effect of electricity price on the cost

For improving the utilization rate of equipment and energy efficiency and reducing electricity consumption, many factories and enterprises choose to make use of the peak-valley tariff. When different SO$_2$ emission standards are taken into consideration, the value of L/G will change and the power consumption of the desulfurization system may be variable. The power consumptions of different desulfurizers under the three emission limits are shown in table3, table4 and table5.

| Desulfurizer | Circulating slurry volume (m$^3$/s) | Pump power (kW) | The resistance of flue gas side (Pa) | Fan power (kW) | Total power (kW) |
|--------------|--------------------------------------|----------------|-------------------------------------|---------------|-----------------|

Figure 1 Desulfurizer cost under basic emission standard

Figure 2 Desulfurizer cost under special emission standard

Figure 3 Desulfurizer cost under ultra-low emission standard
Table 4: Electricity consumption under special emission limits

| Desulfurizer | Circulating slurry volume (m³/s) | Pump power (kW) | The resistance of flue gas side (Pa) | Fan power (kW) | Total power (kW) |
|--------------|----------------------------------|-----------------|--------------------------------------|----------------|-----------------|
| MgO          | 159.72                           | 45.04           |                                      |                | 140.88          |
| CaO          | 383.34                           | 108.10          | 1500                                 | 95.84          | 203.94          |
| CaCO₃        | 766.68                           | 216.20          |                                      |                | 312.04          |

Table 5: Electricity consumption under ultra-low emission limits

| Desulfurizer | Circulating slurry volume (m³/s) | Pump power (kW) | The resistance of flue gas side (Pa) | Fan power (kW) | Total power (kW) |
|--------------|----------------------------------|-----------------|--------------------------------------|----------------|-----------------|
| MgO          | 255.56                           | 72.07           |                                      | 115.02         | 187.09          |
| CaO          | 511.12                           | 144.13          | 1800                                 | 259.15         | 403.29          |
| CaCO₃        | 1022.24                          | 288.27          |                                      |                |                 |

Considering the large range of electricity price in factories and enterprises, the electricity costs of different desulfurizers are calculated in the scope of 0.2–1 RMB/kWh, and the results are shown in figure 4, figure 5 and figure 6.
Figure 5 Electricity cost under special emission standard

Figure 6 Electricity cost under ultra-low emission standard

Figure 4, figure 5 and figure 6 demonstrate that with the strictness of emission standards, the electricity costs of MgO, CaO and CaCO3 all increase substantially. Among them, the electricity cost of MgO increases the most with the strictness of emission standards, the increasing rate of which from the basic to the special is 25.01%, and 32.80% from the special to the ultra-low, and the total growth rate was 66.01%. The electricity cost for CaO increases by 55.41% from the basic to the ultra-low, and for CaCO3, it’s 57.02%. Under the basic, special and ultra-low emission limits of SO2, the electricity costs of the three desulfurization methods grow with the electricity price climbing, and the range of the CaCO3 is the largest, which indicates that the electricity cost of the limestone method is the most sensitive to the change of electricity price. And the electricity cost of MgO has a minimum increase with the rise in electricity price, showing that the magnesium method is the least sensitive to electricity price and has better adaptability. With the fluctuation of electricity price, the electricity cost of MgO is always the lowest among the three methods no matter which standard is carried out for its smallest circulating slurry volume and the least power consumption.

4.3 The operation cost of the desulfurization system

The desulfurizer cost and the electricity cost constitute the total operation cost of the desulfurization system. For the ultra-low emission standard, the total cost of the desulfurization system is given according to the change of desulfurizer cost and electricity cost, and the total costs of the three desulfurizers are shown in Figure 7.

Figure 7 Total cost under ultra-low emission standard
Figure 7 illustrates that it’s CaCO₃ that has the highest minimum electricity cost and electricity cost variation, which is related to the maximum pump power of the limestone method. Because of the low power consumption of MgO, the minimum electricity cost and the electricity cost variation of MgO are the lowest, and CaO is between the two. However, the minimum desulfurizer cost is not completely arranged according to the unit price of desulfurizer. Because the desulfurizer cost equals the unit price of desulfurizer times the consumption of desulfurizer, it is obvious that the inhibition of the unit price of CaCO₃ on the desulfurizer cost exceeds the influence of the desulfurizer consumption, thus, the minimum of desulfurizer cost of CaCO₃ is the lowest. While the consumption of desulfurizer of CaO and the unit price of CaO are both relatively higher, which results in its highest minimum value of desulfurizer cost. The variation of desulfurizer cost is equal to the unit price change of desulfurizer times the consumption change of desulfurizer. Therefore, the variation of desulfurizer cost in MgO is maximum should be contributed to its highest unit price change. And it should be the most relevant to the change of consumption that the desulfurizer cost variation in CaCO₃ ranks the next. Because the unit price change and the consumption change of desulfurizer in CaO are both smaller, its desulfurizer cost variation is the lowest.

4.4 The operation cost of desulfurization under different electricity prices
Based on the provinces referred in section 4.1, when the electricity price is 0.2 RMB/kWh, the unit prices of MgO, CaO and CaCO₃ are 650 RMB/t, 500 RMB/t and 200 RMB/t, the total cost of desulfurization system is the smallest. The desulfurizer cost and electricity cost are shown in table 6.

When the electricity price is 0.8 RMB/kWh, the unit prices of MgO, CaO and CaCO₃ are 650 RMB/t, 500 RMB/t and 200 RMB/t, the desulfurizer cost and electricity cost are shown in table 7.

When the electricity price is 0.8 RMB/kWh, the unit prices of MgO, CaO and CaCO₃ are 1350 RMB/t, 600 RMB/t and 300 RMB/t, the desulfurizer cost and electricity cost are shown in table 8.

| Desulfurizer | Desulfurizer cost (RMB/h) | Electricity cost (RMB/h) | The proportion of desulfurizer cost (%) | The proportion of Electricity cost (%) |
|--------------|---------------------------|--------------------------|----------------------------------------|--------------------------------------|
| MgO          | 56.99                     | 37.42                    | 60.37                                  | 39.63                                |
| CaO          | 61.37                     | 51.83                    | 54.22                                  | 45.78                                |
| CaCO₃        | 43.84                     | 80.66                    | 35.21                                  | 64.79                                |

| Desulfurizer | Desulfurizer cost (RMB/h) | Electricity cost (RMB/h) | The proportion of desulfurizer cost (%) | The proportion of Electricity cost (%) |
|--------------|---------------------------|--------------------------|----------------------------------------|--------------------------------------|
| MgO          | 56.99                     | 149.67                   | 27.58                                  | 72.42                                |
| CaO          | 61.37                     | 207.32                   | 22.84                                  | 77.16                                |
| CaCO₃        | 43.84                     | 322.63                   | 11.96                                  | 88.04                                |

| Desulfurizer | Desulfurizer cost (RMB/h) | Electricity cost (RMB/h) | The proportion of desulfurizer cost (%) | The proportion of Electricity cost (%) |
|--------------|---------------------------|--------------------------|----------------------------------------|--------------------------------------|
| MgO          | 118.37                    | 149.67                   | 44.16                                  | 55.84                                |
| CaO          | 73.65                     | 207.32                   | 26.21                                  | 73.79                                |
| CaCO₃        | 65.76                     | 322.63                   | 16.93                                  | 83.07                                |

According to the results, when the unit prices of desulfurizers are the same, if the electricity cost is 0.2RMB/kWh, the desulfurizer cost is more than the electricity cost, and if the electricity price is 0.8 RMB/kWh, the opposite has occurred. When the electricity price is fixed, the proportions of
desulfurizer costs are also changed when the unit prices of desulfurizers are the most expensive and the cheapest. Therefore, when the electricity price and desulfurizer price fluctuate, there exists a balanced electricity price which makes the total costs of different desulfurizers equal.

For Liaoning Province, the unit price of MgO is 1350 RMB/t, CaO is 500 RMB/t, and CaCO$_3$ is 250 RMB/t. The balanced point of the electricity price affecting the total cost is found and shown in table 9.

| Electricity price RMB/h | MgO  | CaO   | CaCO$_3$ | MgO  | CaO   | CaCO$_3$ | MgO  | CaO   | CaCO$_3$ |
|-------------------------|------|-------|----------|------|-------|----------|------|-------|----------|
| 0.2                     | 70.08| 58.00 | 73.38    | 114.53| 85.56 | 102.39   | 155.79| 113.21| 135.46   |
| 0.3                     | 81.35| 74.64 | 99.06    | 128.62| 105.96| 133.59   | 174.50| 139.12| 175.79   |
| 0.4                     | 92.62| 91.35 | 124.74   | 142.70| 126.35| 164.79   | 193.21| 165.04| 216.12   |
| 0.5                     | 103.89| 108.02| 150.43   | 156.79| 146.74| 196.00   | 211.92| 190.95| 256.45   |
| 0.6                     | 115.16| 124.70| 176.11   | 170.88| 167.14| 227.20   | 230.63| 216.87| 296.78   |
| 0.7                     | 126.43| 141.37| 201.80   | 184.97| 187.53| 258.41   | 249.34| 242.78| 337.11   |
| 0.8                     | 137.70| 158.05| 227.48   | 199.06| 207.93| 289.61   | 268.04| 268.70| 377.43   |
| 0.9                     | 148.97| 174.72| 253.16   | 213.14| 228.32| 320.81   | 286.75| 294.61| 417.76   |
| 1.0                     | 160.24| 191.40| 278.85   | 227.23| 248.71| 352.02   | 305.46| 320.53| 458.09   |

Under the basic, special and ultra-low emission limits, the total costs of different desulfurizers are shown in figure 8, figure 9 and figure 10.
It can be seen from figure 8 that when the basic emission limit is implemented in Liaoning Province, the total cost of CaO is the lowest at the scope of lower than 0.42 RMB/kWh, and beyond this value, using MgO is more economical. Within the range of 0.2 RMB/kWh to 1.0 RMB/kWh, the total cost of CaCO$_3$ is always the highest. As figure 9 shows, under the special emission limit, CaO is optimal when the electricity price is lower than 0.66 RMB/kWh, and MgO is more favorable as it exceeds 0.66 RMB/kWh. When the electricity price is beyond 0.27 RMB/kWh, CaCO$_3$ performs worst economically. Figure 10 depicts the total costs of ultra-low emission and it illustrates that 0.79 RMB/kWh is the demarcation point between CaO and MgO and the less costly region lower than 0.79 RMB/kWh is dominated by CaO and otherwise is MgO. The CaCO$_3$ shows obvious disadvantage compared with the other two desulfurizers at the range of 0.29 RMB/kWh to 1 RMB/kWh.

Generally speaking, although the cost of CaCO$_3$ is lowest, its electricity cost is relatively high, especially when the electricity price rises, as it needs a larger circulating slurry volume and a higher pump power. Compared with CaCO$_3$, both CaO and MgO perform better economically. The former has an obvious advantage at low electricity price, while the latter is preferred at high. As the emission limit gets lower, the electricity price level with the same total cost of both increases gradually, from 0.42 RMB/kWh at basic emission to 0.66 RMB/kWh at special, and until 0.79 RMB/kWh of ultra-low, and the range where CaO shows better economy is becoming wider.

4.5 The operation cost of desulfurization under variable load conditions

Under basic, special and ultra-low emission limits, there will be two, three and four spray layers respectively, so the spray flow rate of circulating slurry volume under basic emission limit can be assigned as 50% or 100%, while under the special it can be set as 33.3%, 66.7% or 100%, and under the ultra-low it can be 25%, 50%, 75% or 100%. Taking Liaoning Province into consideration, the unit price of MgO is 1350 RMB/t, CaO is 500 RMB/t and CaCO$_3$ is 250 RMB/t. The total costs under the three emission limits are discussed at four changing loads (100%, 70%, 50% and 25%) when the electricity price is 0.8 RMB/kWh.

When the load is 70%, three layers are opened under the ultra-low emission standard, and all of the layers should be fully opened under both basic and special emission limits. Assuming the load to be 50%, two spray layers should be opened under the special and ultra-low emission standards and one under the basic. Then it comes to 25% load, there should be only one layer to be opened no matter under which limits. The calculation results of electricity cost and desulfurizer cost under different loads are shown in table10, table11, table12 and table13.
### Table 10 Desulfurizer cost and electricity cost at 100% load

| Emission standard | Desulfurizer | Pump power (kW) | Fan power (kW) | Total power (kW) | Electricity cost (RMB/h) | Desulfurizer cost (RMB/h) | Total cost (RMB/h) |
|-------------------|--------------|----------------|---------------|-----------------|-------------------------|--------------------------|------------------|
| Basic             | MgO          | 36.03          | 76.67         | 112.70          | 90.16                   | 47.54                    | 137.70           |
|                   | CaO          | 90.08          | 76.67         | 166.75          | 133.40                  | 29.58                    | 162.98           |
|                   | CaCO$_3$     | 180.17         | 76.67         | 256.84          | 205.47                  | 22.01                    | 227.48           |
|                   | MgO          | 45.04          | 95.84         | 140.88          | 112.70                  | 86.35                    | 199.06           |
| Special           | CaO          | 108.10         | 95.84         | 203.94          | 163.15                  | 53.73                    | 216.88           |
|                   | CaCO$_3$     | 216.20         | 95.84         | 312.04          | 249.63                  | 39.98                    | 289.61           |
|                   | MgO          | 72.07          | 115.02        | 187.09          | 149.67                  | 118.37                   | 268.04           |
| Ultra-low         | CaO          | 144.13         | 115.02        | 259.15          | 207.32                  | 73.65                    | 280.97           |
|                   | CaCO$_3$     | 288.27         | 115.02        | 403.29          | 322.63                  | 54.80                    | 377.43           |

### Table 11 Desulfurizer cost and electricity cost at 70% load

| Emission standard | Desulfurizer | Pump power (kW) | Fan power (kW) | Total power (kW) | Electricity cost (RMB/h) | Desulfurizer cost (RMB/h) | Total cost (RMB/h) |
|-------------------|--------------|----------------|---------------|-----------------|-------------------------|--------------------------|------------------|
| Basic             | MgO          | 36.03          | 53.67         | 89.70           | 71.76                   | 33.28                    | 105.04           |
|                   | CaO          | 90.08          | 53.67         | 143.75          | 115.00                  | 20.71                    | 135.71           |
|                   | CaCO$_3$     | 180.17         | 53.67         | 233.84          | 187.07                  | 15.41                    | 202.48           |
|                   | MgO          | 45.04          | 67.09         | 112.13          | 89.70                   | 60.45                    | 150.15           |
| Special           | CaO          | 108.10         | 67.09         | 175.19          | 140.15                  | 37.61                    | 177.76           |
|                   | CaCO$_3$     | 216.20         | 67.09         | 283.29          | 226.63                  | 27.98                    | 254.62           |
|                   | MgO          | 54.05          | 80.51         | 134.56          | 107.65                  | 82.86                    | 190.51           |
| Ultra-low         | CaO          | 108.10         | 80.51         | 188.61          | 150.89                  | 51.56                    | 202.45           |
|                   | CaCO$_3$     | 216.20         | 80.51         | 296.71          | 237.37                  | 38.36                    | 275.73           |

### Table 12 Desulfurizer cost and electricity cost at 50% load

| Emission standard | Desulfurizer | Pump power (kW) | Fan power (kW) | Total power (kW) | Electricity cost (RMB/h) | Desulfurizer cost (RMB/h) | Total cost (RMB/h) |
|-------------------|--------------|----------------|---------------|-----------------|-------------------------|--------------------------|------------------|
| Basic             | MgO          | 18.02          | 38.34         | 56.36           | 45.09                   | 23.77                    | 68.86            |
|                   | CaO          | 45.04          | 38.34         | 83.38           | 66.70                   | 14.79                    | 81.49            |
|                   | CaCO$_3$     | 90.08          | 38.34         | 128.42          | 102.74                  | 11.00                    | 113.74           |
|                   | MgO          | 30.18          | 47.92         | 78.10           | 62.48                   | 43.18                    | 105.66           |
| Special           | CaO          | 72.43          | 47.92         | 120.35          | 96.28                   | 26.86                    | 123.14           |
|                   | CaCO$_3$     | 144.85         | 47.92         | 192.77          | 154.22                  | 19.99                    | 174.20           |
|                   | MgO          | 36.04          | 57.51         | 93.55           | 74.84                   | 59.19                    | 134.03           |
| Ultra-low         | CaO          | 72.07          | 57.51         | 129.58          | 103.66                  | 36.83                    | 140.49           |
|                   | CaCO$_3$     | 144.14         | 57.51         | 201.65          | 161.32                  | 27.40                    | 188.72           |

### Table 13 Desulfurizer cost and electricity cost at 25% load

| Emission standard | Desulfurizer | Pump power (kW) | Fan power (kW) | Total power (kW) | Electricity cost (RMB/h) | Desulfurizer cost (RMB/h) | Total cost (RMB/h) |
|-------------------|--------------|----------------|---------------|-----------------|-------------------------|--------------------------|------------------|
| Basic             | MgO          | 18.02          | 19.17         | 37.19           | 29.75                   | 11.88                    | 41.64            |
|                   | CaO          | 45.04          | 19.17         | 64.21           | 51.37                   | 7.39                     | 58.76            |
|                   | CaCO$_3$     | 90.08          | 19.17         | 109.25          | 87.40                   | 5.50                     | 92.90            |
|                   | MgO          | 14.86          | 23.96         | 38.82           | 31.06                   | 21.59                    | 52.64            |
| Special           | CaO          | 35.67          | 23.96         | 59.63           | 47.70                   | 13.43                    | 61.14            |
|                   | CaCO$_3$     | 71.35          | 23.96         | 95.31           | 76.25                   | 9.99                     | 86.24            |
As shown in figure 11, the total costs under 100%, 70%, 50% and 25% of loads are compared.

Under the three standards, with the decrease of load, the consumption of desulfurizer and power both decrease, and the total cost decreases gradually. For MgO and CaO, the total cost increases with the strictness of emission standards under any load, but for CaCO₃, the total cost under special emission standards is lower than that under the basic at 25% load. When the load is 25%, the flow rate of the spray layer can only be assigned as 50% under the basic limit, and 33.3% under the special, so the power consumption of the pump decreases by a much greater extent than that of the fan, resulting in the reduction of the total power consumption and a significant decrease of the power consumption cost, offsetting the increase in the desulfurizer cost, thus reducing the total cost. For the three desulfurizers, no matter under which discharge standard and which load, the operation cost of MgO is always the lowest, followed by CaO, and the economy of CaCO₃ is the worst.

When the boiler load is 70%, the spray layer of the absorber can only be set to 100% for meeting the basic and special emission limits, while the spray layer can be set to 75% for ultra-low emission, which plays an important role in energy conservation. The situation is similar when the boiler load is 25%. Therefore, when the boiler load changes, there will be some dynamic changes in the cost of electricity and desulfurizer under different emission requirements. For industrial enterprises, desulfurizer should be selected reasonably according to desulfurizer price, electricity price, emission standard and load range.

5. Result and discussion
According to the actual situation of the Northeast Three Provinces and Shandong Province, this paper analyses the influence of the unit price of desulfurizer and electricity price on the operation cost of three typical wet desulfurization systems under different emission limits. Taking Liaoning Province as an example, guidance is given for the selection of desulfurizer under different electricity prices and boiler loads. Because of the high unit price of MgO, the operation cost of magnesium method is greatly affected by unit price compared with electricity price. The higher circulating slurry volume of limestone method determines that it is more sensitive to the fluctuation of electricity price, and the
lime method is between the two. When electricity price fluctuates, the overall economy of CaCO₃ in Liaoning Province is relatively poor, while the CaO and MgO are more economical. The former has obvious advantages in lower electricity price, while the latter is preferred at higher electricity price. With the strictness of emission standards, the electricity price level with the same total cost of the two methods gradually increases, from 0.42 RMB/kWh at the basic emission to 0.66 RMB/kWh at the special and until 0.79 RMB/kWh at the ultra-low, the range where the operation cost of CaO is lowest becomes much wider. As the boiler load changes, there will be some dynamic changes in the electricity cost and desulfurizer cost under different emission requirements. When the electricity price of Liaoning Province is 0.8 RMB/kWh, under the four load conditions discussed, the operation cost of MgO is always the lowest, followed by CaO, and CaCO₃ is the most costly. When the boiler load is 70%, the spray amount can only be set to 100% for basic and special emission limits, while it can be set to 75% for ultra-low emission, thus realizing energy conservation. The situation is similar when the boiler load is 25%. Therefore, under ultra-low emission, the electricity cost can be reduced by flexibly adjusting the spray amount to meet the desulfurization requirements under different loads.

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