Article

Economic Analysis of Atomization Drying of Concentrated Solution Based on Zero Discharge of Desulphurization Wastewater

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Abstract: With the improvement of environmental protection requirements, more and more attention has been given to desulphurization wastewater with zero discharge in coal power plants. Atomization drying is part of the main zero discharge technologies at present. Economic analysis of the atomization drying of desulphurization wastewater is beneficial to the formulation of an appropriate operation scheme and to the reduction of operation costs. The economic analysis and sensitivity analysis of different operating conditions such as unit load, the handling capacity of concentrates, and the temperature of the extracted flue gas in the atomization drying process of concentrated desulfurized wastewater were carried out in this paper. The main cost of the drying process came from the influence of flue gas extraction on the overall heat transfer in the boiler, resulting in the decrease in power generation revenue, which can reach more than 80%. The operating cost of auxiliary machinery was relatively low. The cost of treatment for per ton of concentrates increased first and then decreased with the increase in temperature of the extracted flue gas, and it decreased with the increase in the handling capacity of the concentrates. The effect of a unit load on the treatment cost was also related to the temperature of the extracted flue gas, and the optimal flue gas temperature increase to higher temperatures as the unit load decreased. The minimum treatment costs per ton of concentrate ranged from CNY 143.54/t to CNY 158.77/t under different unit loads. Sensitivity analysis showed that the temperature of the extracted flue gas had the greatest impact on treatment cost, and its sensitivity coefficient was 0.0834. The ways in which to improve economic benefits were discussed.

Keywords: desulphurization wastewater; atomization drying; economic analysis

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1. Introduction

In order to meet the environmental protection requirements, coal power plants need to desulfurize flue gas. The most widely used desulfurization technology in coal power plants is limestone–gypsum wet flue gas desulfurization (WFGD) technology [1,2]. To ensure the desulfurization efficiency and equipment safety, the fluorine and chlorine content in the desulfurization liquid slurry should be controlled within a certain range, so it is necessary to regularly discharge desulfurization wastewater to maintain the chlorine balance of the system [3,4]. There are a lot of pollutants in desulfurization wastewater [5,6], meaning that desulfurized wastewater cannot be directly discharged or directly reused and needs to be treated [7].

The main traditional desulfurization wastewater treatment process is chemical precipitation [8], and the suspended matter in the desulfurization wastewater is precipitated by adding chemical agents. Advanced treatment processes include membrane separation technology [9], the biological treatment method [10], and so on. Nanoporous materials are also commonly used to remove contaminants from wastewater [11–13]. With the improvement

of environmental protection requirements, the concept of zero liquid discharge has also been encouraged for several saline wastewater sources, such as desalination brine and textile wastewater [14,15]. Evaporation is mostly used to evaporate pretreated desulfurization wastewater concentrate to achieve wastewater with zero discharge.

Flue evaporation technology has become one of the main technical means for the desulfurization wastewater with zero discharge due to its many advantages, such as its simple process operation system, low modification difficulty, and low operating costs [16]. However, since desulfurization wastewater contains complex substances and has corrosive components such as chlorine, it will corrode the flue and equipment if the evaporation process is not complete. The use of independent equipment for atomization drying is conducive to its maintenance and does not affect the operation of the main equipment [17].

As people pay more attention to desulfurization wastewater with zero discharge, researchers have begun to study the drying of wastewater by means of atomization. Ye [18] studied the effects of injection velocity, liquid film angle, flue gas velocity on the evaporation process through numerical simulation. They found that increasing the injection velocity and the liquid film thickness and reducing the flue gas velocity was beneficial to evaporation. Liang [19] studied the effect of solid particles on evaporation and crystallization process. The results showed that solid particles had no effect on evaporation, but the solid particles in desulfurization wastewater, such as SiO_2 , CaCO_3 , Fe_2O_3 , and Fe_3O_4 , sped up the crystallization. Chen used the single droplet drying method [20] and pilot-scale spray drying system [21] to study the HCl migration characteristics during the evaporation of desulfurization wastewater and proposed that the release of chloride ions went through three phases. Ma [22] also studied the characteristics of HCl volatilization during wastewater evaporation and pointed out that using $\text{Ca}(\text{OH})_2$ to adjust the pH value of desulfurization wastewater to be between 9.0 and 10.0 can inhibit the volatilization of chlorides during high-temperature evaporation. Sun [17] conducted flue gas evaporation and drying on the desulfurization wastewater of a 330 MW coal power plant and found that the moisture content of the bottom ash was below 1.1% under different unit loads, proving that the evaporation system could meet the needs of different loads.

How to ensure that desulfurization wastewater generates zero discharge has been given a great deal of attention; however, all of the existing research on desulfurization wastewater with zero discharge has all been technical research, and there are no research reports on its economic analysis. Without the guidance of economic research, although the environmental protection requirements for wastewater with zero discharge can be met, the operating conditions are often not optimal, which will cause energy to be wasted. Studying the economics of different operating conditions is conducive to formulating a suitable operating plan on the basis of meeting the evaporation requirements and reducing operating costs. This is conducive to reducing energy consumption, which, in turn, contributes to the reduction of carbon emissions. However, there is no relevant research yet, and it is necessary to conduct economic research on different operation schemes that take place during the processes for desulfurization wastewater with zero discharge. Sensitivity analysis is one of the methods that can be used to analyze the uncertainty in the operation process, which can analyze the degree of influence of different parameters on the economics of the project [23,24]. Unit load, the handling capacity of concentrates, and the temperature of the extracted flue gas will all have an impact on the economics of system operation. It is necessary to conduct a sensitivity analysis on the economics of atomization drying.

This paper conducted a comprehensive economic analysis of the atomization drying of a concentrated solution based on desulfurization wastewater with zero discharge and compared economic performance under the different operation conditions of unit loads, wastewater treatment capacity, and the temperature of the extracted flue gas. Sensitivity analysis was conducted and sensitive factors were pointed out. Suggestions to improve economic benefits were put forward.

2. Unit Situation and Calculation Model

2.1. Unit Situation

The prototype of this paper was a coal thermal power plant in Guangdong Province. There were three coal-fired generating units in operation with a total capacity of 1130 MW, namely Unit 5 (200 MW), Unit 6 (330 MW), and Unit 7 (600 MW). The desulfurization wastewater generated during the operation of the unit was first concentrated by MVR evaporation, and the remaining concentrated liquid was sprayed into the drying tower through a centrifugal atomizing disk, and the boiler flue gas was extracted and sent to the drying tower to evaporate the concentrated liquid, generating wastewater with zero discharge. Since the concentration process used the waste heat in the low-temperature flue gas for heating, it had no effect on the efficiency of the unit; therefore, only the cost of the atomization drying system was discussed. Unit 7 was used as the prototype.

2.2. Calculation Model

A flowchart of the cost calculation for the atomization drying system is shown in Figure 1. By setting the load of the unit, the temperature of the flue gas at the inlet of the dryer, and the handling capacity of concentrates, the heat exchange calculation was performed on the drying of the wastewater, and the required flue gas flow rate for drying the concentrated liquid was obtained. Then, the reduction in power generation due to the decrease in boiler efficiency caused by the exhaust flue gas was calculated, as was the energy consumption of the exhaust fan. The energy consumption of the mistorizer was determined by the flow of the concentrates.

Figure 1. Flowchart of the cost calculation of the atomization drying system.

2.2.1. Calculation Model of Heat Exchange Calculation

The heat required to dry the concentrates consisted of three components:

Sensible heat required to evaporate water Q_1 :

$$Q_1 = c_1 q_m \Delta T \quad (1)$$

where c_1 is the specific heat capacity of water, 4.19 kJ/(kg·K); q_m is the flow rate of evaporated water, kg/h, calculated as 80% of the flow rate of the concentrates; ΔT is the temperature increase of the evaporating water, which was calculated according to the difference between the exhaust gas temperature of the evaporator and the ambient temperature, and the ambient temperature was 20 °C.

Latent heat required to evaporate water Q_2 :

$$Q_2 = q_m \gamma \quad (2)$$

where γ is the specific latent heat of water, 2256.40 KJ/Kg.

Heat required to increase the temperature of the impurities in the concentrates Q_3 :

$$Q_3 = c_3 q_{m3} \Delta T_3 \quad (3)$$

where c_3 is the specific heat capacity of the impurities in the concentrates, $1.05 \text{ kJ}/(\text{kg}\cdot\text{K})$ [25]; q_{m3} is the mass of the impurities, kg/h , calculated as 20% of the flow rate of the concentrates; ΔT_3 is the temperature increase of the impurities, 80°C .

The heat balance of atomization drying system:

$$Q_1 + Q_2 + Q_3 = (h_1 - h_2)G\varphi \quad (4)$$

where h_1 is the specific enthalpy of the flue gas entering the atomization drying system, kJ/Nm^3 , which was the same as that of flue gas extracted from the boiler. h_2 is the specific enthalpy of the flue gas leaving the atomization drying system, kJ/Nm^3 . h_1 and h_2 were calculated from the flue gas temperature and flue gas composition. The inlet temperature was variable, and the outlet temperature was 155°C . G is the flue gas flow rate, Nm^3/h ; φ is the heat exchange efficiency, which changed with the heat exchange temperature difference. When the exhaust temperature was 300°C , φ was 90%, and φ decreased by 1% for every 50 increase in the temperature of the flue gas entering the atomization drying system.

2.2.2. Calculation Model of Reduction in Power Generation

The residual heat of that part of the flue gas extracted by the atomization drying system was not used in the boiler, resulting in energy loss Q_{loss} :

$$Q_{\text{loss}} = G(h_1 - h_0) \quad (5)$$

where Q_{loss} is the energy loss caused by flue gas extraction, kJ/h , and h_0 is the enthalpy of the exhaust flue gas from the boiler, kJ/Nm^3 , calculated by the exhaust temperature and flue gas components.

The reduction in boiler efficiency due to flue gas extraction:

$$\Delta\eta_{\text{boiler}} = Q_{\text{loss}}/Q_{\text{input}} \quad (6)$$

where Q_{input} is the total energy input to the boiler, kJ/h .

Boiler efficiency after the atomization drying system was put into use:

$$\eta'_{\text{boiler}} = \eta_{\text{boiler}} - \Delta\eta_{\text{boiler}} \quad (7)$$

where η_{boiler} is the boiler efficiency before the atomization drying system was put into use, %.

The total efficiency of the unit after the atomization drying system was put into use:

$$\eta'_{\text{total}} = \eta'_{\text{boiler}} \times \eta_{\text{else}} \quad (8)$$

where η_{else} is the total product of the other efficiencies, including pipeline efficiency, steam turbine efficiency, mechanical efficiency, and generator efficiency. It was considered that η_{else} remained unchanged before and after the atomization drying system was put into use, and it can be obtained by dividing the total efficiency before flue gas extraction by the boiler efficiency before flue gas extraction.

Power generation of the unit after the atomization drying system was put into use, MW:

$$P' = \frac{Q_{\text{input}}}{3.6 \times 10^6} \eta'_{\text{total}} \quad (9)$$

The reduction in power generation after the atomization drying system was put into use, kWh/h :

$$\Delta P = (P - P') \times 1000 \quad (10)$$

The decrease in power generation revenue C_1 , CNY/h :

$$C_1 = 0.39\Delta P \quad (11)$$

where 0.39 was the unit price of electricity, 0.39 CNY/kWh.

The unit parameters under different loads before flue gas extraction are shown in Table 1.

Table 1. Unit parameters under different loads before flue gas extraction.

	THA	75%THA	50%THA	40%THA	30%THA
Unit load MW	600	450	300	240	180
Exhaust temperature °C	124	110	105	90	91
Total energy input to the boiler GJ/h	4844.19	3699.58	2584.36	2124.82	1695.93
Boiler efficiency %	94.14	94.49	94.4	94.96	94.59
Total efficiency %	44.59	43.79	41.79	40.66	38.21
η_{else} %	47.37	46.34	44.27	42.82	40.39

2.2.3. Calculation Model of Energy Consumed by the Exhaust Fan

The power consumption factor of flue gas extraction was 0.005 kWh/Nm³ flue gas, that is, the power consumption of flue gas extraction 1 Nm³ was 0.005 kWh [26].

Cost from the operation of exhaust fan C_2 , CNY/h:

$$C_2 = 0.39 \times 0.005G \quad (12)$$

2.2.4. Calculation Model of Energy Consumed by the Mistorizer

According to the on-site operating data, the relationship between the current of mistorizer and the handling capacity of the concentrates was fitted, as shown in Figure 2. The relationship was obtained as:

$$y = 25.07 - 12.56x + 8.97x^2 - 1.39x^3 \quad (13)$$

where y is the current of mistorizer, A, and x is the handling capacity of the concentrates, t/h.

Figure 2. Diagram of the relationship between the current of mistorizer and the handling capacity of the concentrates.

Power of the mistorizer, W:

$$P_{mistorizer} = UI \quad (14)$$

where U is the voltages of the mistorizer, 380 V, and I is the current of the mistorizer, A, calculated according to Formula (13).

Cost from the operation of mistorizer C_3 , CNY/h:

$$C_3 = 0.39 \times P_{\text{mistorizer}} / 1000 \quad (15)$$

The cost of treatment for per ton of concentrates C_{per} , CNY/t:

$$C_{\text{per}} = C / M = (C_1 + C_2 + C_3) / M \quad (16)$$

where C is the sum of all of the costs of different items, CNY/h, and M is the handling capacity of the concentrates, t/h.

2.3. Sensitivity Analysis

The economic benefit index was C_{per} . Indeterminacy factors included unit load, the handling capacity of the concentrates, and the temperature of the extracted flue gas. Single factor analysis was used to analyze the influence degree of unit load, the handling capacity of the concentrates, and the temperature of the extracted flue gas on C_{per} [27]:

$$E_A = \frac{\Delta C_{\text{per}}}{\Delta A} \quad (17)$$

where E_A is the sensitivity coefficient of factor A to C_{per} ; ΔC_{per} is the relative change of C_{per} relative to fiducial value; and ΔA is the relative change of factor A relative to fiducial value.

3. Results

3.1. Different Temperature of the Extracted Flue Gas

The economic parameters under different extracted flue gas temperature operating conditions are showed as Table 2. As the flue gas temperature increased, the required flue gas volume showed an obvious decrease. This was because with the temperature of the inlet flue gas increased, and the heat energy that was carried in the per unit volume of flue gas became so large that the amount of flue gas required to evaporate the same quality of concentrates decreased. With the decrease in the flue gas volume, the energy consumed by the exhaust fan also decreased, while the relationship between the decrease in power generation revenue and flue gas temperature was not monotonous. It can be seen that with the increase in the flue gas temperature, the decrease in power generation revenue first decreased and then increased. The flue gas temperature affected the energy consumption of the exhaust fan through the change of flue gas flow but had no direct correlation with the flue gas temperature itself. However, as for the decrease in power generation revenue, it was mainly reflected by the change in boiler efficiency. In addition to the flue gas flow, the flue gas temperature itself had a great influence on the decrease in power generation revenue. When the temperature rose, if the flue gas flow remained unchanged, it meant that more heat was extracted and that the boiler efficiency would decrease. When the flue gas flow decreased, if the flue gas temperature was unchanged, it meant that the heat extracted was reduced and that the boiler efficiency would increase. In the operation process, the flue gas flow was not independent of the flue gas temperature. As the exhaust gas temperature increased, the required flue gas flow decreased. The effect of the two changes on the boiler efficiency was exactly the opposite. Therefore, under the action of flue gas flow and flue gas temperature, there was an optimal temperature for the extracted flue gas, which made the boiler efficiency drop the least; that is, the decrease in power generation revenue was the lowest. At the beginning, with the increase in the flue gas temperature, the degree of reduction in the boiler efficiency gradually decreased. When the flue gas temperature was 300 °C, the boiler efficiency decreased by 0.0629%, and when the flue gas temperature was 500 °C, the boiler efficiency only decreased by 0.0594%. At this time, the reduction in the flue gas flow played a major role in increasing boiler efficiency. As the flue gas temperature continued to rise, the reduction in the boiler efficiency gradually increased. When the flue gas temperature was 800 °C, boiler efficiency decreased by 0.0613%. It can be seen that when the flue gas temperature was 500 °C, the

boiler efficiency was the highest, and the decrease in power generation revenue was the lowest, reaching values of 147.5925 CNY/h. The costs of operating the mistorizer was only related to the handling capacity of the concentrates, and the cost remained unchanged when the flue gas temperature changed.

Table 2. Economic parameters under different extracted flue gas temperature operating conditions.

Flue Gas Temperature (°C)	300	350	400	450	500	550	600	650	700	750	800
Unit Load (MW)	600	600	600	600	600	600	600	600	600	600	600
Concentrates Flow (t/h)	1	1	1	1	1	1	1	1	1	1	1
Flue gas flow (Nm ³ /h)	10924.06	8148.75	6475.21	5396.33	4641.73	4070.97	3635.35	3283.69	3001.15	2764.33	2567.44
Boiler efficiency (%)	94.0771	94.0792	94.0800	94.0805	94.0806	94.0806	94.0804	94.0800	94.0796	94.0792	94.0787
C ₁ (CNY/h)	156.4202	151.0822	149.2037	147.9651	147.5925	147.7274	148.2463	149.0197	150.0109	151.1615	152.4583
C ₂ (CNY/h)	21.3019	15.8901	12.6267	10.5228	9.0514	7.9384	7.0889	6.4032	5.8522	5.3904	5.0065
C ₃ (CNY/h)	2.9773	2.9773	2.9773	2.9773	2.9773	2.9773	2.9773	2.9773	2.9773	2.9773	2.9773
C (CNY/h)	180.6995	169.9496	164.8076	161.4653	159.6212	158.6431	158.3126	158.4002	158.8405	159.5293	160.4421
C _{per} (CNY/t)	180.6995	169.9496	164.8076	161.4653	159.6212	158.6431	158.3126	158.4002	158.8405	159.5293	160.4421

Comparing the costs of the three items, as shown in Figure 3, it can be seen that the decrease in the power generation revenue accounted for the highest proportion, accounting for more than 86%. Furthermore, as the temperature of the flue gas rose, the proportion of the decrease in power generation revenue increased. The second was that of the energy consumption cost of the exhaust fan, which accounted for 11.79%. Combining the costs of the three items, the total cost first decreased and then rose as the flue gas temperature rose, reaching its lowest value at 600 °C, which was 158.3126 CNY/h.

Figure 3. The proportion of costs in different items.

3.2. Different Handling Capacity of Concentrates

The economic parameters under operating conditions where the concentrates had different handling capacities are showed in Table 3. As the handling capacity of the concentrates, the energy consumption of the exhaust fan, the decrease in power generation revenue, and the operation costs of the mistorizer increased to varying degrees, the total cost also increased. However, when comparing the C_{per} value in conditions where the concentrates had different handling capacities, it can be seen that with the increase in the handling capacity, the C_{per} value continued to decrease. When the handling capacity was

low, the degree of decline was greater, and the degree of decline tended to be flat when the handling capacity increased further, as shown in Figure 4. After the handling capacity reached 2.2 t/h, the relative change in the C_{per} value was small and basically unchanged. That is, in order to reduce the C_{per} value, the handling capacity of the concentrates should be kept above 2.2 t/h as much as possible.

Table 3. Economic parameters under conditions where the concentrates had different handling capacities.

Flue Gas Temperature (°C) Unit Load (MW) Concentrates Flow (t/h)	600 600 1	600 600 1.2	600 600 1.4	600 600 1.6	600 600 1.8	600 600 2	600 600 2.2	600 600 2.4	600 600 2.6	600 600 2.8	600 600 3
Flue gas flow (Nm ³ /h)	3635.35	4362.42	5089.49	5816.56	6543.63	7270.70	7997.77	8724.84	9451.91	10,178.98	10,906.05
C_1 (CNY/h)	148.2463	177.8956	207.5448	237.1941	266.8434	296.4926	326.1419	355.7911	385.4404	415.0897	444.7389
C_2 (CNY/h)	7.0889	8.5067	9.9245	11.3423	12.7601	14.1779	15.5956	17.0134	18.4312	19.8490	21.2668
C_3 (CNY/h)	2.9773	3.0400	3.1497	3.2965	3.4706	3.6620	3.8609	4.0574	4.2416	4.4035	4.5334
C (CNY/h)	158.3126	189.4423	220.6190	251.8329	283.0740	314.3325	345.5984	376.8620	408.1132	439.3422	470.5392
C_{per} (CNY/t)	158.3126	157.8686	157.5850	157.3956	157.2633	157.1663	157.0902	157.0258	156.9666	156.9079	156.8464

Figure 4. Relative change value of C_{per} .

3.3. Different Unit Loads

Table 4 shows the economic parameters in operating conditions under different unit loads. As the load of the unit decreased, the operating cost of the exhaust fan increased. Obviously, this was caused by the increase in the amount of flue gas that was extracted. Although the temperature of the extracted flue gas was the same, the decrease in the load caused the flue gas composition to change, which caused the energy contained in the unit flue gas volume to be different, and, in turn, led to the increase in the amount of the required flue gas. The impact of the load on the decrease in the power generation revenue was also related to the temperature of the extracted flue gas. When the extracted temperature was low, there was no obvious relationship between the unit load and the decrease in the power generation revenue. When the extracted temperature became higher, the decrease in the power generation revenue decreased as the unit load decreased. With the decrease in the unit load, the energy that was contained in the unit flue gas volume decreased, resulting

in an increase in the amount of required flue gas. Meanwhile, the exhaust temperature of the unit decreased as the unit load increased. That is, when the load decreased, the extracted part of the flue gas should have had more energy available for the unit. However, as the flue gas was extracted, this part of the energy was not used by the boiler. Because of the two reasons mentioned above, as the load decreased, the boiler efficiency decreased more due to flue gas extraction. However, the decrease in power generation revenue was not only determined by efficiency, it was proportional to the product of the unit load and the drop in the boiler efficiency. Therefore, although the low load had a large drop in boiler efficiency, the decrease in power generation revenue was not simply a monotonous change because the unit load value was small. In cases where the flue gas was extracted at a high temperature, when the load decreased, the decrease in power generation revenue decreased. That is, although the decrease in the boiler efficiency under a low load was relatively large, it was not enough to offset the impact of the load base on the decrease in power generation revenue, and the decrease in power generation revenue generally showed a downward trend. The operating costs for the mistorizer were only related to the handling capacity of the concentrates, so it did not change with the unit load. There was a certain relationship between the amount of desulfurization wastewater generated and the unit load; however, desulphurization wastewater with zero discharge refers to not being discharged to the outside rather than real-time elimination. The concentrates of wastewater storage method can be combined with strategic treatment, so it was considered that the handling capacity of the concentrates did not change with the change in the load.

Table 4. Economic parameters under different unit load operating conditions.

Flue Gas Temperature	Unit Load	300 °C	350 °C	400 °C	450 °C	500 °C	550 °C	600 °C	650 °C	700 °C	750 °C	800 °C
C_1 (CNY/h)	600 MW	156.420	151.082	149.204	147.965	147.593	147.727	148.246	149.020	150.011	151.161	152.458
	450 MW	164.624	157.186	152.902	150.543	149.374	148.898	148.941	149.322	149.991	150.864	151.922
	300 MW	162.082	153.078	148.412	145.773	144.385	143.725	143.608	143.846	144.382	145.130	146.070
	240 MW	168.145	156.563	150.369	146.686	144.553	143.315	142.745	142.606	142.827	143.303	144.005
	180 MW	157.890	147.157	141.424	138.023	136.062	134.932	134.424	134.315	134.543	135.007	135.682
C_2 (CNY/h)	600 MW	21.302	15.890	12.627	10.523	9.051	7.938	7.089	6.403	5.852	5.390	5.007
	450 MW	21.506	15.919	12.755	10.633	9.148	8.025	7.167	6.475	5.918	5.452	5.064
	300 MW	21.506	16.053	12.867	10.729	9.232	8.100	7.235	6.537	5.976	5.505	5.114
	240 MW	21.582	16.114	12.917	10.772	9.270	8.133	7.265	6.565	6.002	5.530	5.137
	180 MW	21.653	16.171	12.964	10.813	9.306	8.165	7.294	6.591	6.026	5.552	5.158
C_3 (CNY/h)		2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977
C (CNY/h)	600 MW	180.699	169.950	164.808	161.465	159.621	158.643	158.313	158.400	158.840	159.529	160.442
	450 MW	189.107	176.082	168.634	164.153	161.500	159.900	159.085	158.774	158.886	159.293	159.964
	300 MW	186.565	172.108	164.256	159.479	156.594	154.801	153.820	153.360	153.335	153.613	154.162
	240 MW	192.704	175.654	166.263	160.436	156.800	154.426	152.988	152.148	151.806	151.809	152.119
	180 MW	182.520	166.305	157.366	151.813	148.345	146.075	144.695	143.884	143.546	143.537	143.818
C_{per} (CNY/t)	600 MW	180.699	169.950	164.808	161.465	159.621	158.643	158.313	158.400	158.840	159.529	160.442
	450 MW	189.107	176.082	168.634	164.153	161.500	159.900	159.085	158.774	158.886	159.293	159.964
	300 MW	186.565	172.108	164.256	159.479	156.594	154.801	153.820	153.360	153.335	153.613	154.162
	240 MW	192.704	175.654	166.263	160.436	156.800	154.426	152.988	152.148	151.806	151.809	152.119
	180 MW	182.520	166.305	157.366	151.813	148.345	146.075	144.695	143.884	143.546	143.537	143.818

The C_{per} values under different operating conditions with different unit loads are showed in Figure 5. It can be seen that under different loads, all of the C_{per} values first decreased and then rose as the flue gas temperature rose, and there was an optimal flue gas temperature. The optimal flue gas temperature corresponding to different loads was different. As the load decreased, the optimal flue gas temperature shifted to higher temperatures. During the operation process, the load was able to change at any time; however, the port through which the flue gas could be distracted was not able to change real-time and was fixed. Therefore, it was necessary to accurately select the position of the port through which the gas was extracted to ensure that the total cost was at a lower value most of the time. This will be further analyzed in later chapters.

Figure 5. The C_{per} value under operating conditions with different unit loads.

3.4. Sensitivity Analysis

A sensitivity analysis of the handling capacities of concentrates and the temperature of the extracted flue gas under the rated load (600 MW) is showed in Table 5. The fiducial value of the flue gas temperature was 600 °C, and it was calculated to be from 300 °C to 800 °C, with a step size of 50 °C. The fiducial value of the handling capacity of the concentrates was 1 t/h, and it was calculated from 1 t/h to 3 t/h, with a step size of 0.2 t/h. When performing a sensitivity analysis of a factor, the other factors maintained their fiducial value.

Table 5. Sensitivity analysis of the handling capacities of the concentrates and the temperature of the extracted flue gas.

Flue gas Temperature (°C)	300	350	400	450	500	550	600	650	700	750	800
C_{per} (CNY/t)	180.6995	169.9496	164.8076	161.4653	159.6212	158.6431	158.3126	158.4002	158.8405	159.5293	160.4421
E_A	−0.2828	−0.1764	−0.1231	−0.0797	−0.0496	−0.0251	/	0.0066	0.0200	0.0307	0.0404
Concentrates flow (t/h)	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6	2.8	3
C_{per} (CNY/t)	158.3126	157.8686	157.585	157.3956	157.2633	157.1663	157.0902	157.0258	156.9666	156.9079	156.8464
E_A	/	−0.0140	−0.0115	−0.0097	−0.0083	−0.0072	−0.0064	−0.0058	−0.0053	−0.0049	−0.0046

The sign for the sensitivity coefficient represented the direction of the impact that the indeterminacy factors had on the economic benefit index. A sensitivity coefficient with a positive value meant that the economic benefit index increased as the indeterminacy factors increased; the negative signs represent how the economic benefit index decreased as the indeterminacy factors increased. The absolute value of the sensitivity coefficient represented the degree of influence that the indeterminacy factors had on the economic benefit index; the greater the absolute value, the greater the degree of influence [28].

When the flue gas temperature was lower than 600 °C, the sensitivity coefficient of the flue gas temperature had a negative value; that is, as the temperature increased, the cost of treatment for per ton of concentrates decreased. When the flue gas temperature was higher than 600 °C, the sensitivity coefficient of the flue gas temperature had a positive value; that is, as the temperature increased, the cost of treatment for per ton of concentrates increased. This proves that when the flue gas temperature was 600 °C, the cost of treatment for per ton of concentrates was the lowest, which was consistent with the results of a previous analysis. As for the absolute value of the sensitivity coefficient, it can be seen that when the flue gas temperature was lower than 600 °C, the absolute value of the sensitivity coefficient of the flue gas temperature decreased as the temperature increased. When the flue gas temperature was higher than 600 °C, the absolute value of the sensitivity coefficient of the flue gas temperature increased as the temperature increased. The sensitivity coefficient of the flue gas temperature obtained the smallest absolute value at 600 °C; that is, when the flue gas temperature changed at around 600 °C, the degree of change in the economic benefit index was the smallest. The lower the absolute value of the sensitivity coefficient, the lower economic risk of resistance to the change of a specific indeterminacy factor. Therefore, the flue gas temperature at 600 °C not only achieved the lowest cost, but also had the best risk resistance, showing that it was the optimal flue gas extraction temperature the under rated load.

The sensitivity coefficient of the handling capacity of the concentrates always maintained a negative value; that is, as the handling capacity increased, the cost of treatment for per ton of concentrates decreased. The absolute value of the sensitivity coefficient for the handling capacity of the concentrates decreased as the handling capacity increased. That is, under the high handling capacity, the cost of treatment for per ton of concentrates was less affected by the change in the handling capacity, showing a stronger ability to resist economic risks. That is, regardless of the cost or the ability to resist economic risks, the handling capacity of concentrates should be increased as much as possible within the processing capacity.

As for the sensitivity coefficient of the unit load, it can be seen from Table 6 that it was also closely related to the flue gas temperature, and it was not a monotonous negative value or a monotonous positive value. This was mainly due to the complicated influence of the unit load on the cost. Regarding the absolute value of the sensitivity coefficient, the absolute value of the sensitivity coefficient was determined, and then the average value was taken. These were compared with the effect of the handling capacity of concentrates and the flue gas temperature, as shown in Figure 6. It can be seen that the unit load and especially flue gas temperature were the main sensitivity factors. The impact of the handling capacity of concentrates was relatively small.

Table 6. Sensitivity analysis of unit load.

E_A	600 MW	450 MW	300 MW	240 MW	180 MW
300 °C	/	−0.1861	−0.0649	−0.1107	−0.0144
350 °C	/	−0.1443	−0.0254	−0.0559	0.0306
400 °C	/	−0.0929	0.0067	−0.0147	0.0645
450 °C	/	−0.0666	0.0246	0.0106	0.0854
500 °C	/	−0.0471	0.0379	0.0295	0.1009
550 °C	/	−0.0317	0.0484	0.0443	0.1132
600 °C	/	−0.0195	0.0568	0.0561	0.1229
650 °C	/	−0.0094	0.0636	0.0658	0.1309
700 °C	/	−0.0011	0.0693	0.0738	0.1376
750 °C	/	0.0059	0.0742	0.0807	0.1432
800 °C	/	0.0119	0.0783	0.0865	0.1480

Figure 6. The absolute value of the sensitivity coefficient of factor A to C_{per} .

4. Discussion

According to the above results, some measures to improve the economy are put forward:

1. Selection of the position of the gas extraction port:

It can be seen from the above analysis that the effects of flue gas temperature and the unit load on treatment cost were interactive rather than separate. The temperature of the extracted flue gas was mainly determined by the location of the extracted port. As mentioned above, the flue gas port cannot change with the change of the load; it was in a fixed position. Then, for a unit whose load changed in real-time, the selection of the position of the gas extraction port should fully consider the influence of flue gas temperature and load change.

The relationship between C_{per} and the flue gas temperature under different loads was fitted, as showed in Table 7. In this case, y represented C_{per} , and x represented the flue gas temperature.

Table 7. The fitting formula of C_{per} with flue gas temperature under different loads.

Unit Load	Fitting Formula	R ²
THA	$y = 348.13 - 1.04x + 0.002x^2 - 1.86 \times 10^{-6}x^3 + 6.20 \times 10^{-10}x^4$ ^a	0.9948
75%THA	$y = 412.59 - 1.40x + 0.003x^2 - 2.65 \times 10^{-6}x^3 + 9.17 \times 10^{-10}x^4$	0.9982
50%THA	$y = 470.75 - 1.86x + 0.004x^2 - 4.10 \times 10^{-6}x^3 + 1.54 \times 10^{-9}x^4$	0.9988
40%THA	$y = 555.36 - 2.43x + 0.006x^2 - 5.81 \times 10^{-6}x^3 + 2.28 \times 10^{-9}x^4$	0.9993
30%THA	$y = 527.16 - 2.30x + 0.005x^2 - 5.52 \times 10^{-6}x^3 + 2.16 \times 10^{-9}x^4$	0.9993

^a: y was C_{per} , and x was flue gas temperature.

The fitting formula of C_{per} with flue gas temperature under different loads was shown in Table 7. Substituting the flue gas temperature at different positions, as shown in Table 8, into the fitting relationship in Table 7, the C_{per} value at different flue positions was obtained, as shown in Table 9.

Table 8. Flue gas temperature at different load positions and probabilities.

Flue Gas Temperature (°C)	THA	75%THA	50%THA	40%THA	30%THA
Leaving Furnace	965	915	817	772	723
Leaving SH2 ^a	1139	1049	930	874	811
Entering SH3	1139	1049	930	874	811
Leaving SH3	965	915	817	772	723
Entering SH1	744	691	616	576	533
Leaving SH1	559	519	463	447	432
Entering RH2 ^b	969	896	799	754	706
Leaving RH2	869	808	730	686	641
Entering RH1	829	770	691	643	598
Leaving RH1	378	365	367	350	352
Entering ECO ^c	559	519	461	445	429
Leaving ECO	344	318	278	268	248
Probability of the load (%)	0.00	21.46	31.71	19.70	27.13

^a: SH, superheater; ^b: RH, reheater; ^c: ECO, economizer.

Table 9. The C_{per} value at different positions and the average cost.

$C_{per\ i}$	THA	75%THA	50%THA	40%THA	30%THA	$\overline{C_{per}}$
Leaving Furnace	159.8413	161.2278	156.1253	150.6330	142.1978	152.3601
Leaving SH2 ^a	173.7831	171.4794	163.7696	156.3855	143.1121	158.3656
Entering SH3	173.7831	171.4794	163.7696	156.3855	143.1121	158.3656
Leaving SH3	159.8413	161.2278	156.1253	150.6330	142.1978	152.3601
Entering SH1	157.1432	158.8013	155.0615	153.2787	146.1721	153.1014
Leaving SH1	156.7897	160.1580	158.8184	159.9803	152.8160	157.7066
Entering RH2 ^b	159.9673	160.6666	155.7047	150.4981	142.3714	152.1268
Leaving RH2	158.0472	159.3470	154.9958	151.0276	143.4315	152.0107
Entering RH1	157.6985	159.1125	154.9270	151.7821	144.3294	152.3308
Leaving RH1	166.6354	173.9733	169.8800	176.1394	166.2362	171.0032
Entering ECO ^c	156.7897	160.1580	158.9463	160.1756	153.1473	157.8755
Leaving ECO	171.3747	183.7952	194.2078	206.6030	206.0846	197.6374

^a: SH, superheater; ^b: RH, reheater; ^c: ECO, economizer.

The probability of the unit being under different loads in October 2021 is shown in Table 8. The load rate of 0~35% belonged to 30% THA, the load rate of 35~45% belonged to 40% THA, the load rate of 45~60% belonged to 50% THA, the load rate of 60~80% belonged to 75% THA, and the load rate of 80~100% belonged to 100% THA. To determine the value for a specific extraction port, the treatment cost for each ton of concentrates under different loads should be multiplied with the probability of the corresponding load; when all of the loads are superimposed, then the average cost at the location can be obtained:

$$\overline{C_{per}} = \sum C_{per\ i} * P_i. \quad (18)$$

where $\overline{C_{per}}$ is the average cost of the concentrate treatment for one specific extracted port, CNY/t; $C_{per\ i}$ is the cost of treatment for per ton of concentrates under a specific load, CNY/t, as shown in Table 9; and P_i is the probability of the corresponding load, %, as shown in Table 8.

The average cost of concentrate treatment at different extraction port locations is shown in Table 9. It can be seen that the average cost varied greatly by extraction port location, with the lowest average costs being achieved when the extraction port location is the position leaving RH2. Therefore, in order to improve the economy, the extraction port should be arranged at the position behind Reheater 2.

2. A concentrate storage container should be set up to adjust the handling capacity of the concentrates

The handling capacity of the concentrates had less impact on the treatment cost than the flue gas and the unit load did; however, as the handling capacity of the concentrates increased, the cost of treatment for per ton of concentrates also decreased to a certain extent. A concentrates storage container should be set up. When the desulfurization wastewater output is low, then the atomization drying system of concentrates can be suspended. When the output of desulfurization wastewater increases or has accumulated a certain amount, the drying system can be restarted to ensure that the handling capacity of the concentrates increases as much as possible while the drying system is running, and the unit processing cost can be reduced.

5. Conclusions

An economic analysis for the atomization drying of concentrated solutions based on desulphurization wastewater with zero discharge was analyzed. Extracting flue gas to dry the wastewater concentrate reduced the efficiency of the boiler. Under the rated load conditions, extracting flue gas can reduce the boiler efficiency by 0.0594% to 0.0639%, and the boiler efficiency can be reduced by more than 0.1% under low loads. The cost of treatment for per ton of concentrates decreased first and then rose with the increase in the temperature of the extracted flue gas. An optimal extracted temperature was determined. As the load decreased, the optimal flue gas temperature migrated to higher temperature. The increase in the handling capacity of the concentrates was conducive to reducing the cost. The temperature of the extracted flue gas was a sensitive factor for the cost of treatment per ton of concentrate and had the greatest impact on its processing costs. In order to reduce the cost, the effects of flue gas temperature and the unit load should be considered comprehensively, and the extraction port should be arranged behind the Reheater 2.

This paper provided a guide for the economical zero-discharge treatment of desulfurization wastewater from units with a rated load of about 600 MW and provided calculation methods for other units. In future research, researchers can use the calculation method determined in this paper to conduct an economic analysis of desulfurization wastewater with zero discharge from power plants with different rated loads in order to summarize the general law and to extend it to units of differently rated loads.

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