Performance Evaluation and Optimization Analysis of Zero Discharge Device for Desulfurization Wastewater Based on Spray Drying Technology

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Abstract. The original desulfurization wastewater treatment system was reformed by spray drying technology in a thermal power plant, and the performance of the modified system was evaluated. The results show that the treatment capacity of the system is above 5m3/h. It can meet the requirements of zero discharge of desulfurization wastewater in power plant, and has many characteristics, such as simple process, reliable technology, stable operation, convenient operation and so on. At the same time, some suggestions for further optimization and improvement are put forward in view of the existing problems.

1. General situation of reconstruction project
There are two 330MW coal-fired units in a thermal power plant. Each unit is equipped with two-chamber five-electric field electrostatic precipitator and wet limestone-gypsum desulfurization system. The wastewater from the desulfurization process comes from the cyclone discharge water. Desulfurization wastewater contains a large number of suspended matter, sulfite, chloride and heavy metals, which have the characteristics of "high hardness, high salt, high suspended matter, high corrosion and heavy metal". It is the most difficult wastewater to be treated in coal-fired power plants at present [1-2]. The spray drying technology was selected by power plant to carry out the zero discharge transformation project of desulfurization wastewater in response to the national environmental protection policy [3-4].

2. The principle of revamping process.
In this project, spray drying technology was used to treat desulfurization wastewater produced by two 330 MW units, reclaimed water from chemical water workshop and reclaimed water from fine treatment, etc. The technical principle is that the hot flue gas between the boiler SCR denitrification reactor and the air perheater is used as the heat source to vaporize the wastewater after atomization by a high-speed rotating atomizer in the spray drying tower. When the moisture enters the flue gas, the large particle solid material produced by drying is discharged from the bottom of the spray drying tower, and the small particle solid material is returned to the electrostatic precipitator inlet for collection with the tail gas after drying [5-6]. The process flow chart is shown in figure 1.
3. Designed water quality and quantity

The desulphurization wastewater produced by each unit under full load is about 4.5 m$^3$/h, and the total amount of desulphurization wastewater produced by two units is 9.0 m$^3$/h. The total amount of reclaimed water and refined reclaimed water in chemical water workshop is about 1.0 m$^3$/h. The total amount of waste water is about 10 m$^3$/h. The design water quality of desulphurization wastewater is shown in Table 1. The designed wastewater treatment capacity and unit flue gas parameters under different loads are shown in Table 2.

Table 1. Design water quality of desulphurization wastewater

| Order number | Water quality project   | Unit | Numerical data |
|--------------|------------------------|------|----------------|
| 1            | Solid content          | %    | 3~5%           |
| 2            | Cl$^-$                 | mg/L | 20000          |
| 3            | pH                     | -    | 5.5~6.0        |

Table 2. Design wastewater treatment capacity and unit flue gas volume under different loads

| Order number | Project                          | Unit | Working condition 1 | Working condition 2 | Working condition 3 |
|--------------|----------------------------------|------|---------------------|---------------------|---------------------|
| 1            | Unit load                        | MW   | 165                 | 250                 | 325                 |
| 2            | Boiler flue gas volume           | Nm$^3$/h | 530000         | 740000              | 960000              |
| 3            | Denitrification outlet flue gas temperature | ℃ | 298                | 330                 | 355                 |
| 4            | Air preheater differential pressure | kPa | 0.7                | 1.0                 | 1.5                 |
| 5            | Air preheater outlet smoke temperature | ℃ | 114                | 133                 | 141                 |
| 6            | Wastewater treatment capacity    | m$^3$/h | 3.0             | 4.1                 | 5.0                 |
| 7            | Drying tower outlet temperature  | ℃ | 142                | 150                 | 150                 |
4. Process system and main equipment parameters
The spray drying process system of desulphurization wastewater mainly includes three parts: wastewater feeding system, flue gas system and spray drying tower system.

4.1. Wastewater feeding system
The wastewater feeding system mainly includes new waste water tank, wastewater lifting pump, and wastewater buffer tank. The waste water tank has a volume of 20m$^3$, a diameter of 3m, a height of 3m, lined with glass scales, and is equipped with a mixing device (power 3kW). Each unit is equipped with a wastewater tank. The output of wastewater lifting pump is 15m$^3$/h; lift 50m, power 7.5kW, one shipment and one preparation. The equipment in the original desulphurization wastewater treatment system is as follows: 1) the original clarifier is used as the water storage tank for the reclaimed water in the water treatment workshop and the reclaimed water in the condensate treatment system; 2) the original clean water tank is used as the storage tank of the wastewater to be treated; 3) the original triad box is used as the waste water conditioning reaction box. The wastewater produced by desulphurization system is adjusted and tempered by lime slurry in triple box and then flows into clean water tank for storage. The reclaimed water of the chemical water workshop and the reclaimed water of the fine treatment are transported through the pipeline to the clarification tank for storage, and after the conditioning of the triple box, it flows into the cleaning tank for storage, and the wastewater in the cleaning tank is transported to the wastewater tank of the spray drying tower through the wastewater transport pump, Then through the wastewater lifting pump into the drying tower of the wastewater buffer tank, self-flow into the spray drying tower. The volume of the wastewater buffer tank is 6m$^3$, the diameter is 2m, the height is 2.2m, the glass scale is lined, and equipped with a mixing device (power is 1.1kW). Each unit is equipped with a wastewater buffer tank.

4.2. Flue gas systems
The flue gas system mainly includes baffle, expansion joint and flue. The flue gas is drawn from the main flue in front of the air preheater and enters the spray drying tower, and the treated flue gas is discharged into the main flue before the dust collector. The inlet baffle is arranged on the main flue outlet pipe in front of the air preheater, and the outlet baffle is arranged on the outlet flue at the lower part of the spray drying tower. The purpose of the inlet baffle is to direct the hot flue gas to the spray drying wastewater treatment system or to isolate it from the original flue gas system. The flue gas baffle is electric uniaxial double baffle (design temperature $400 \, ^\circ C$, flange connection, blade Q345, seal 316L), in which the inlet baffle adopts adjusting type and the size is $800 \times 1600$mm, which can adjust the amount of flue gas entering the system according to the actual operation condition. The outlet baffle adopts switch type executive structure and the size is $\Phi 1500$mm. Each drying system consists of two inlet electric regulating baffle, two inlet manual baffle and one outlet electric switch baffle. The sealed air of the baffle adopts the air transported by the boiler fan.

4.3. Spray drying system
Spray tower system is mainly spray drying tower and its ancillary equipment. After the flue gas enters the spray drying tower, it is in full contact with the fine droplets of desulphurization wastewater (average droplet diameter 10~60 microns) after atomization of atomizing nozzles. The moisture in the droplets evaporates rapidly and the salt in the waste water is dried and precipitated. Most of the salt is mixed into the dust of the imported flue gas, and a small part flows into the bottom of the drying tower, and the ash at the bottom of the drying tower is pneumatic transported to the ash depot of the power plant. Through the accurate control of flue gas distribution, desulphurization wastewater flow rate, droplet size and outlet temperature, the droplets have been fully dried before reaching the inner wall of the drying tower, that is to say, desulphurization wastewater can be completely dried and water vapor enters the flue gas. The salt in the waste water is dried and precipitated.
4.3.1. **Spray drying tower.** Each boiler in this project is equipped with a spray drying tower. The inner diameter of the drying tower is 8.5 m, the height of the cylinder is 16 m, and the total height is about 36.5 m. The spray drying tower is composed of cylinder and cone. Hot flue gas and wastewater enter the drying tower from the top of the tower, the dried flue gas leaves the drying tower from the upper part of the cone, and the large particle solid enters the silo pump from the bottom of the tower. The material of the drying tower is carbon steel, the tower is supported by the whole steel frame, the interior is the empty tower structure, the maintenance room is set up at the top of the tower, and the maintenance hoisting device is set up.

4.3.2. **Rotating atomizer.** Rotating atomizer is the core component of the whole process. Its basic principle is that when the desulphurization wastewater after regulating pH is pumped to the high speed rotating atomization disk, due to the action of centrifugal force, The wastewater extends into a thin film or is drawn into a filaments (depending on the speed and amount of wastewater), breaking and dispersing into droplets at the edge of the atomization disk, and the size of the droplets depends on the speed of rotation and the amount of wastewater. The atomizer can ensure that the particle size distribution of atomized droplets does not change significantly when the liquid flow rate does not change greatly. The schematic diagram of the rotating atomizer is shown in figure 2. Each rotating atomizer in this project is equipped with 45kW dual-frequency motor and frequency converter, the speed of atomizer is 10000~13000rpm, which can be adjusted according to the frequency converter, and the average diameter of spray droplets is 10~60 microns. In order to make the liquid intake smoothly and evenly distributed from the liquid supply pipe to the atomization disk, special parts for liquid distribution are installed near the atomization disk at the lower end of the spindle. The atomization disk is disk type and the diameter of the disk is 250mm. The atomizer is made of hastelloy alloy, the shield is 304 stainless steel, the inlet pipe is titanium tube, and the atomizer is equipped with oil circuit cooling and circulating water cooling system.

**Figure 2.** Schematic diagram of rotating atomizer

4.3.3. **Flue gas distributor.** The flue gas distributor is arranged at the top of the spray drying tower. Its function is to make the hot flue gas for drying enter the drying tower evenly, mix effectively with the atomized droplets, make the moisture evaporate rapidly, and avoid the condensation of water on the wall of the drying tower. The flue gas distributor is equipped with a guide plate with a certain angle, which is used to control the flow direction of hot flue gas, make the mixing of droplets and hot flue gas meet the appropriate requirements, and improve the drying and atomization efficiency. The flue gas distributor is in the form of volute and 304 stainless steel.

5. **Performance after revamping**

The performance test of the desulphurization wastewater spray drying device was carried out in March
The average water quality of desulphurization wastewater during the test period is shown in Table 3. From Table 3, it can be seen that the pH value of desulphurization wastewater is about 8, and the Cl\(^-\) is about 12000 mg/L. The suspended matter is about 7000 mg/L and the salt content (dissolved solid) is about 40,000 mg/L. The main results of performance test are shown in Table 4. It can be seen from Table 4 that the imported flue gas volume of desulphurization wastewater spray drying device is about 60340 Nm\(^3\)/h and the imported flue gas temperature is about 334°C under the full load condition of the unit. The wastewater treatment capacity of the system is above 5.2 m\(^3\)/h (the maximum treatment capacity is 6.2 m\(^3\)/h), the moisture content of drying products is 0.15%, the chlorine content in fly ash is 0.26%, and the influence value of boiler efficiency is about 0.55%. The flue gas temperature at the outlet of the device is about 180°C. All the performance indexes of the device meet the design requirements, and there is no obvious wall hanging, corrosion and scaling. At the same time, after this part of the flue gas enters the electrostatic precipitator, due to the evaporation of the waste water, the humidity of the flue gas increases, so that the specific resistance of the fly ash decreases, which is beneficial to improve the dust removal efficiency of the electrostatic precipitator. The evaporated wastewater becomes desulphurization supplementary water after cooling in desulphurization absorption tower, which is beneficial to reduce the water consumption of desulphurization system.

**Table 3.** Average water quality of desulphurization wastewater during performance test

| Project | pH (25°C) | TDS (mg/L) | SO\(_4^{2-}\) (mg/L) | Cl\(^-\) (mg/L) | Cond (μs/cm) | SS (mg/L) | COD (mg/L) | Ca\(^{2+}\) (mg/L) | Mg\(^{2+}\) (mg/L) | F\(^-\) (mg/L) | Sulfide (mg/L) | As (μg/L) | Hg (μg/L) | Ni (mg/L) | Cr (mg/L) | Cd (mg/L) | Date |
|---------|-----------|------------|----------------------|----------------|-------------|----------|-----------|----------------|----------------|-------------|----------------|----------|----------|----------|----------|---------|-------|
| Date    | 7.97      | 41400      | 4890                 | 12300          | 49900       | 6780     | 1440      | 1710           | 4600           | 19.3        | 0.03          | 4.0      | 43.9     | 0.26     | 0.19     | 0.07    |

**Table 4.** Performance test results of spray drying device for desulphurization wastewater

| Order number | Project             | Unit     | Design value         | Measured results | Meet the design requirements |
|--------------|---------------------|----------|----------------------|------------------|-----------------------------|
| 1            | Flue gas volume     | m\(^3\)/h| Design / Maximum      | 60340            | /                           |
|              |                     |          | 50000/55000          |                  |                             |
| 2            | Flue-gas temperature | °C      | 355                  | 334              | /                           |
| 3            | Dust concentration  | g/m\(^3\) | -                    | 23.90            | /                           |
| 4            | Flue gas humidity   | %        | -                    | 7.46             | /                           |
| 5            | HCl concentration   | mg/ m\(^3\) | 75                  | 49.79            | /                           |
| 6            | Flue gas oxygen content | %    | -                    | 2.7              | /                           |

**Outlet flue gas**

| Order number | Project             | Unit     | Design value         | Measured results | Meet the design requirements |
|--------------|---------------------|----------|----------------------|------------------|-----------------------------|
| 7            | Flue-gas temperature | °C      | ≥141                 | 180              | achieve                     |
| 8            | Dust concentration  | g/m\(^3\) | -                    | 21.11            | /                           |
| 9            | Flue gas humidity   | %        | -                    | 15.50            | /                           |
| 10           | HCl concentration   | mg/m\(^3\) | -                  | 238.64           | /                           |
| 11           | Flue gas oxygen content | %    | -                    | 3.5              | /                           |

**Other items**
| Order number | Project                          | Unit   | Design value | Measured results | Meet the design requirements |
|--------------|----------------------------------|--------|--------------|------------------|------------------------------|
| 12           | Wastewater treatment capacity    | m³/h   | Design 5.0, Maximum 6.0 | 5.2/6.2          | achieve                      |
| 13           | System power consumption         | kW     | -            | 40.2             | /                             |
| 14           | Systemic resistance              | Pa     | ≤550         | 532              | /                             |
| 15           | Boiler efficiency influence value| %      | 0.5~0.6      | 0.55             | achieve                      |
| 16           | Moisture content of drying products | %     | ≤2           | 0.15             | achieve                      |
| 17           | Chlorine in fly ash              | %      | ≤0.3         | 0.26             | achieve                      |

Note: Flue gas volume is standard, wet base, actual O₂

6. Conclusions and recommendations

The total investment cost of the zero-discharge reconstruction project of desulfurization wastewater is about 20 million, and the investment of water per ton is 2 million. The direct operation cost includes power consumption (about 2.0 ¥/m³) and chemical cost of pH adjustment (about 0.5 ¥/m³), and the coal consumption of the unit will increase slightly (about 1.6~1.8 g/kWh). In general, spray drying process is characterized by simple system, reliable technology, stable operation and convenient operation, which can achieve zero discharge target of desulfurization wastewater of power plant. However, although there are many advantages in the zero-discharge process of desulfurization wastewater, the following aspects are worth further optimized and improvement:

1) The amount of flue gas at the inlet of the spray drying device of desulfurization wastewater is higher than the design value. When the waste water treatment amount is 5.2 m³/h, the outlet flue gas temperature is about 180℃; when the waste water treatment amount is 6.2 m³/h, the outlet flue gas temperature is about 170℃, all of them is higher than the design flue gas temperature of 150℃, which has a certain influence on the boiler efficiency. It is recommended to carry out the optimal adjustment test of flue gas intake. That is, according to the unit load and the quantity of desulphurization wastewater treated, the inlet baffle door is adjusted. On the premise that the waste water is fully evaporated and dried, the flue gas intake of the unit can be reduced as much as possible and the impact on the unit economy can be reduced.

2) The concentration of HCl in the outlet flue gas of desulphurization wastewater spray drying zero discharge device is obviously higher than that in inlet flue gas, which may be related to the volatilization of gaseous chlorine from desulphurization wastewater during evaporation and drying. According to the relevant literature [7-8], water has the tendency of "acidizing" at high temperature. The hydrolyzed H binds to Cl⁻ and spills out in the form of gaseous HCl at high temperature. In addition, salt substances such as NaCl, CaCl₂ and MgCl₂ contained in desulphurization wastewater will be hydrolyzed to form gaseous HCl at high temperature. The increase of HCl content in flue gas will lead to corrosion of metal walls such as flue, baffle and so on. The increase of HCl will also lead to the increase of desulphurization wastewater discharge after entering the wet desulphurization system. But on the one hand, the proportion of HCl volatilized into flue gas is relatively small. On the other hand, the volatile amount of HCl can be effectively reduced by adjusting the pH value of desulphurization wastewater to alkaline. According to the relevant literature [7-8], the pH of desulphurization wastewater can be adjusted to 9~10 by using Ca (OH)₂ solution to inhibit the volatilization of chlorine to the greatest extent, and the solid phase transfer of salt in desulphurization wastewater can be realized. During the performance test, the pH of desulphurization wastewater is between 7.5 and 8.0. It is
suggested that the optimal adjustment test of pH value of desulphurization wastewater should be carried out to reduce the adverse effect of gaseous chlorine volatilization on the subsequent equipment.

3) Under 100% load condition (wastewater treatment capacity 5m^3/h), the chlorine content in fly ash is about 0.26%. Common Portland cement (GB 175-2007) specifies that the mass fraction of fly ash in ordinary Portland cement shall not exceed 20%. When the fly ash is mixed in this maximum proportion, the added value of chlorine content is 0.052%, which meets the requirement of less than 0.06%, so it will not have obvious influence on the comprehensive utilization of fly ash. However, the chlorine content in fly ash is affected by many factors, such as unit load, coal combustion ash, chloride ion concentration in wastewater and wastewater treatment capacity, so it is not easy to control in actual operation, which will limit the proportion of fly ash in cement to a certain extent. A small bypass dust collector can be set up behind the spray drying tower. When the chlorine content in fly ash exceeds the standard, some or all of the drying products can be collected separately, and can be mixed with boiler slag after collection. It is used in some industries such as brick making, which have small restrictions on chlorine content, so as to avoid the influence of desulphurization wastewater drying products on the comprehensive utilization of fly ash.

4) During the performance test, the Cl⁻ of desulphurization wastewater is about 12000mg/L, which is lower than the designed value (20000mg/L). It is suggested that the discharge of desulphurization wastewater should be controlled in 3.0–3.5m^3/h (corresponding to desulphurization wastewater Cl⁻ in 17000–20000mg/L) under full load condition, and the concentration and reduction of desulphurization wastewater before spray drying can also be considered if necessary. It can effectively reduce the amount of flue gas used for wastewater evaporation and reduce the influence on the economy of the unit.

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