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Study on Evaporation Characteristics of FGD Wastewater in the Spray Drying Tower Using Numerical Simulation and Response Surface Methodology

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ABSTRACT

Nowadays, zero discharge of flue gas desulfurization (FGD) wastewater in coal-fired power plants has attracted great attention from all over the world. In this work, the effects of initial particle size of droplets (*A*), nozzle atomization cone angles (*B*) and initial velocity of droplets (*C*) on the evaporation characteristics of FGD wastewater in the spray drying tower of a 600 MW coal-fired power plant were studied numerically, and the interaction of influencing factors on evaporation characteristics of wastewater was investigated using response surface methodology (RSM). Moreover, the quadratic regression equation of coded factors with the maximum residence time of droplets (*T*) was given and the optimized values of each influencing factor were obtained. The results show that A, B, C, AC, A^2 are significant model terms. The optimal operating parameters are considered to be: $A = 60.109$ µm, $B = 90°$ and $C = 150$ m/s, with the corresponding $T = 0.068$ s. This study is expected to provide some reference for the engineering application of spray drying technology in the zero discharge of FGD wastewater of coal-fired power plants.

Keywords: FGD wastewater, spray drying tower, atomization and evaporation, numerical simulation, response surface methodology

1. INTRODUCTION

The flue gas from coal-fired power plants contains fine particulate matters, SO_x, NO_x and other pollutants, which can cause great pollution to the environment, so it is necessary to remove the pollutants in the flue gas [1]. The limestone-gypsum wet flue gas desulfurization (WFGD) was the most widely used technology in coal-fired power plants to treat SO_2 emissions [2]. However, fine particles, chlorides, arsenic, lead, mercury, and other heavy metals that impact ecosystem and human health in the flue gas are constantly accumulated in the desulfurization slurry [3], which will cause corrosion of the equipment and desulfurization efficiency reduction [4]. Therefore, a certain amount of wastewater should be discharged periodically to ensure the stable operation of the WFGD system [5].

The issue of the treatment of industrial wastewater, especially the FGD wastewater from coal-fired power plants, has drawn the extensive attention of the governments all over the world. Since April 2015, China has promulgated and implemented the “The Action Plan for Prevention and Treatment of Water Pollution” to strengthen the supervision and regulation of wastewater discharge, making zero-emission of power plant wastewater more and more important and urgent [6]. Nevertheless, the wastewater from a WFGD system is difficult to treat because of its high salt content, high suspended matter content, high corrosiveness, and complex composition [7]. At present, the commonly used technologies for the treatment of FGD desulphurization wastewater are chemical precipitation, evaporating crystallization, and flue gas waste heat evaporation. Currently the most widely adopted process in China is chemical precipitation, but the treated wastewater has a high salt content, especially the chloride ions cannot be effectively removed. Evaporating crystallization technology is limited by its drawbacks such as high investment and operating costs, and difficulty in controlling the purity of crystallized salt. Flue gas waste heat evaporation technology includes flue evaporation

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technology and bypass evaporation tower technology. Yet the flue evaporation technology, due to the low flue gas temperature in the flue duct between the air preheater and the electrostatic precipitator (typically only 110-150 °C), has the disadvantage that the evaporation process of the desulfurization wastewater is slow, which may be more prominent especially when the boiler is operating at variable load. In order to make up for the inadequacy of existing technologies, a new flue gas waste heat evaporation technology named bypass evaporation tower technology is put forward [8].

Existing studies have mostly focused on the effects of single factors on evaporation characteristics of FGD wastewater in the spray drying tower. However, studies on the interaction of influencing factors on evaporation characteristics of wastewater are rare. Therefore, taking the spray drying tower in a 600 MW thermal power plant unit as the research object, the evaporation characteristics of FGD wastewater was investigated based on CFD and response surface methodology. The interactive effects of influencing factors on evaporation characteristics of wastewater were further studied, which provides a foundation for the industrial application of the bypass flue spray drying evaporation technology.

2. RESEARCH OBJECT AND NUMERICAL METHODS

2.1 Spray drying tower

A spray drying tower of desulfurization wastewater in a 600 MW coal-fired power plant unit was investigated in this study, as displayed in Fig. 1. The diameter and height of the drying tower are 7.2 m and 17.9 m, respectively. The hot air distributor is a volute type gas distributor with a square inlet section of 1.2 m side length. The hot air distributor is divided into an inner and an outer flow channel, both of which contain several deflectors. The atomizer is a high-speed centrifugal atomizer located 1.575 m below the top of the tower. The model is meshed using ICEM CFD with an unstructured grid and the mesh refinement is performed for the hot air distributor and the vicinity of the atomizer. After the grid independence test, the total number of cells is chosen to be 1853724, which can meet the simulation accuracy and save the computational cost at the same time.

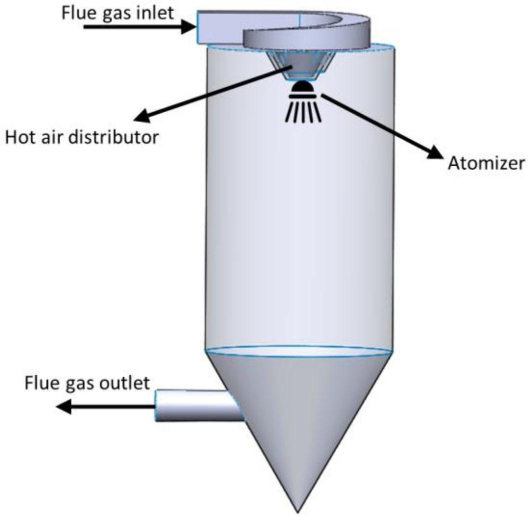

Fig. 1. Schematic diagram of spray drying tower

2.2 CFD methods

The numerical simulation was performed using Fluent 19.0. The Euler–Lagrange method is employed to describe the evaporation characteristics of droplet populations in spray drying process. Since the proportion of water in the FGD wastewater is more than 95%, while the share of particulate matter and salts is less than 5%. Consequently, the evaporation characteristics of FGD wastewater can be replaced by those of pure water.

The flue gas is regarded as the continuous phase modelled by the Eulerian method, and the Realizable *k-ε* model is adopted to simulate the turbulent flow using

Table 1 Initial physical properties of the flue gas

Species mass fraction (%)				Density	Viscosity	Specific heat
N_2	CO_2	O_2	H_2O	($kg\cdot m^{-3}$)	($(kg\cdot(m\cdot s)^{-1})$)	($(J\cdot(kg\cdot k)^{-1})$)
73	13	3	11	1.24	3.22E-05	1159.2

Table 2 Validation of CFD model

Case	Initial particle size of droplets (μm)	Nozzle atomization cone angles (°)	Initial velocity of droplets (m/s)	Simulated outlet temperature(K)	Designed outlet temperature(K)	Relative error(%)
1	75	60	100	410	423	-3.07
2	75	30	150	425	423	0.47
3	120	90	100	442	423	4.49

SIMPLE algorithm [9]. Other than that, the gas phase model uses a species transport model, and the initial physical properties of the flue gas are shown in Table 1.

The dispersed wastewater droplets are treated as the discrete phase described by the Lagrange method, and the discrete random walk model is adopted to track the movement of droplets. The atomization model of liquid droplets uses the solid cone model embedded in the fluent software and the droplet size distribution is uniform. Moreover, droplets are assumed to remain spherical shape during the evaporation.

3. RESULTS AND DISCUSSION

3.1 Validation of CFD results

Fig. 2 shows the streamline of the flue gas for case 1. As can be seen from Fig. 2, the flue gas flowing through the hot air distributor forms a spiral downward flow in the tower, which strengthens the disturbance between the flue gas and liquid droplets, and then enhances the heat and mass transfer between the flue gas and liquid droplets.

The outlet temperature of the spray drying tower obtained from the CFD simulation was compared to the design parameters provided by the manufacturer. The simulated and designed temperatures at the outlet of the tower under different operating conditions and their relative errors are tabulated in Table 2. It is evident from Table 2 that the error between the simulated and designed temperatures is less than 4.5% for each operating condition, indicating that the results of the numerical simulations are in acceptable agreement with the design results to verify the reliability of the CFD model.

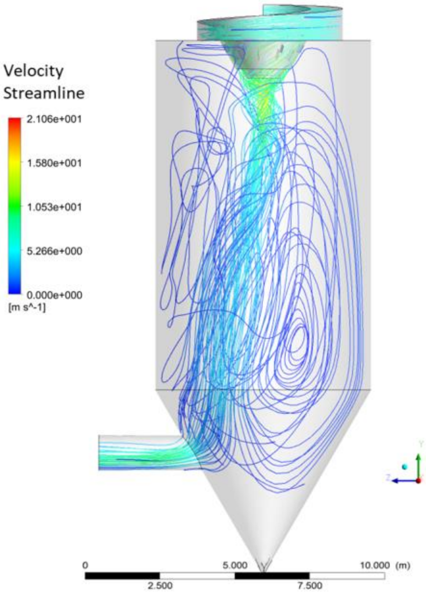

Fig. 2. The streamline of the flue gas

3.2 Response surface design optimization

Three-parameter Box-Behnken Design (BBD) was implemented to optimize the evaporation behavior of FGD wastewater. The maximum droplet residence time (*T*) was chosen as the response variable to measure the speed of droplet evaporation, while the initial particle size of droplets (*A*), nozzle atomization cone angles (*B*) and initial velocity of droplets (*C*) were adopted as the factors. The level range of influencing factors was specified on the basis of published studies. Experimental design and data processing were performed using Design-Expert 13 software. A total of 17 groups of experiments were designed, with three factors and two levels. The experimental data and the corresponding response observations are listed in Table 3.

Table 3 BBD experimental design and results

Case	*A* (μm)	*B* (°)	*C* (m/s)	*T* (s)
1	75	60	100	0.515
2	75	30	150	0.447
3	120	90	100	1.101
4	75	60	100	0.515
5	30	60	150	0.161
6	75	60	100	0.515
7	75	30	50	0.869
8	120	30	100	1.584
9	120	60	150	0.668
10	75	90	50	0.526
11	30	60	50	0.642
12	30	30	100	0.610
13	75	90	150	0.375
14	75	60	100	0.515
15	75	60	100	0.515
16	120	60	50	1.925
17	30	90	100	0.419

In the present study, the quadratic design was employed as response model. The results of the analysis of variance (ANOVA) method suggested that *A*, *B*, *C*, *AC*, A^2 are significant model terms. The model *F*-value of 27.86 implies the model is significant, and the binary regression equation of coded factors with the response *T* was obtained as follows:

$$T = 0.5324 + 0.4308A - 0.1361B - 0.2889C - 0.1940AC + 0.3563A^2$$

As can be seen from the obtained coded regression equation, terms *A* and A^2 have a positive synergistic effect on the maximum droplet residence time, while terms *B*, *C*, and *AC* act in the opposite way to the aforementioned terms. Of all the influencing factors, the initial particle size of droplets, has the greatest positive influence on the maximum droplet residence time, given that it has the largest positive coefficient of 0.4308. In contrast, the initial velocity of droplets has the greatest negative impact on the maximum residence time of droplets.

Based on the constructed quadratic polynomial regression equation model, the effect of the interaction between two factors, *A* and *C*, on *T* is illustrated in a three-dimensional diagram (Fig. 3). As can be seen from Fig. 3, when *A*, *B*, and *C* are set within the original parameters. The objective is to minimize *T*. The final optimization results obtained are *A* = 60.109 μm, *B* = 90°, *C* = 150 m/s, with the corresponding maximum droplet residence time *T* = 0.068 s.

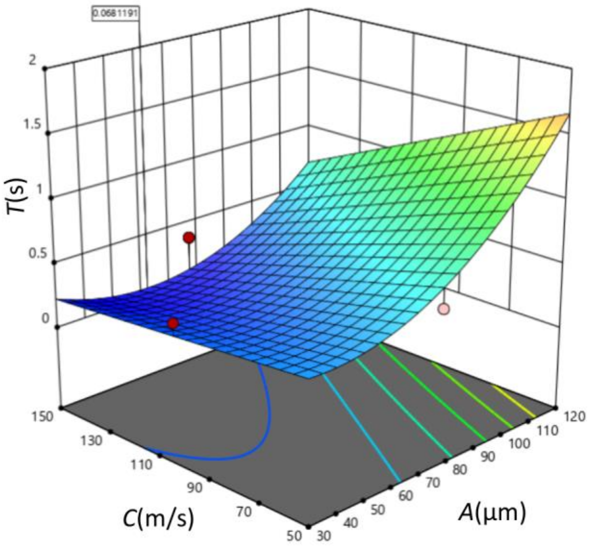

Fig. 3. Effect of significant interaction terms on maximum residence time of droplets

4. CONCLUSION

The results are summarized as follows:

(1) A comparison of the simulated results with the designed values shows that the adopted CFD methods can reasonably predict the evaporation characteristics of FGD wastewater in the spray drying tower.

(2) Among all the influencing factors, the initial particle size of droplets has the greatest positive effect on the maximum droplet residence time, due to its largest positive coefficient of 0.4308. On the contrary, the initial velocity of droplets has the greatest negative influence on the maximum droplet residence time.

(3) The results indicate that the optimum values of initial particle size of droplets, nozzle atomization cone angle and initial velocity of droplets were 60.109 μm, 90°, and 150 m/s, respectively, within the experimental design space boundary.

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