Research on visualization technology for abrasion of flow guide device in denitrification system based on Tabakoff model

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Abstract. In order to obtain the abrasion condition of the internal guide device of denitration system reactor intuitively, based on the particle missing model and takeoff wear model, the gas-solid two-phase flow field in SCR reactor is simulated by ANSYS-CFX calculation software, and the fly ash movement track and wear rate distribution of guide plate are visualized. The simulation results show that through the combination of particle missing model and Tabakoff wear model with CFX software, we can directly see the general wear distribution of the guide device in the flue. The wear rate distribution is mainly affected by the particle size of fly ash, and the wear rate value is mainly affected by the mass concentration. By verifying the field flow field test data and checking the wear and ash accumulation of the guide plate, the technical effectiveness is verified, which provides a technical means for the guide device to prevent wear and blockage.

1. Introduction
Selective catalytic reduction (SCR) denitrification system has the advantages of mature technology, high removal efficiency and good economy, which is widely used in coal-fired power plants [1-3]. The operation effect of SCR denitration system mainly depends on the uniformity of flow field in the system and the operation state of catalyst [4]. However, due to the complex combustion coal quality and variable operation conditions of domestic units, fly ash has increased the wear of flue gas guide plate and catalyst[5], resulting in the deterioration of the uniformity of flue gas flow field, the decrease of catalyst activity, the decrease of SCR denitration efficiency, the increase of ammonia consumption and the increase of ammonia escape rate, which seriously affects the economy of denitration system and the operation reliability of units [6]. Therefore, it is of great significance to study the wear of fly ash on the guide plate and catalyst in the flue of denitration system, in order to reduce the ammonia consumption of the system, prolong the service life of catalyst and improve the operation economy and reliability of the unit.

In recent years, the research on fly ash wear has been carried out by numerical simulation and test. In reference [7], the influence of fly ash concentration and smoke incidence angle on catalyst wear rate was studied by CFD numerical simulation and self-built test bench. In reference [8], based on the operation data of power plant, the cause of catalyst wear on SCR upper layer was analyzed. In reference [9], the position of severe flue wear in actual operation was found by numerical calculation and wear prediction of gas-solid two-phase flow field A 660 MW supercritical coal unit boiler is simulated. In reference [10], a map of a probable decrease in tubes thickness caused by erosion was
made. Using the map it is possible to predict the time between overhauls of different areas in the combustion chamber as well as to identify combustion chamber’s areas.

At present, the research on the wear of denitration system mainly focuses on the independent numerical simulation of single catalyst unit or individual parts of the system, without considering the impact of complex flow field changes in coal-fired power plant on the wear problem, and without systematic research on the fly ash trajectory and wear situation in the reactor. Based on Tabakoff wear model, this paper uses ANSYS CFX to study the wear condition of SCR system guide device, and obtains the wear visualization effect under different particle size and fly ash concentration, which provides a more intuitive visual means for systematic wear control.

2. SCR simulations

2.1. Overview of denitration system

In this paper, the SCR denitration system of a 600MW unit is simulated in 1:1, and the layout mode is "high dust content layout". After the completion of ultra-low emission reconstruction project, three layers of catalyst were installed in SCR, and honeycomb catalyst was used as catalyst.

2.2. Mathematical model and boundary conditions

2.2.1. Simulation approximation hypothesis.

(1) The actual temperature difference between the inlet and outlet of the system is small and the system is adiabatic.

(2) The actual air leakage of the system is small, so it is not considered. Air leakage of the system.

(3) In the flue gas at the upstream of the reactor, no chemical reaction occurs among the components of flue gas.

(4) Flow is steady.

(5) The physical parameters of the fluid are constant.

2.2.2. Governing equation. Flue gas flow process: use ANSYS CFX to solve the three-dimensional steady-state viscous RANS equation to simulate the swirling cooling flow and heat transfer process; turbulent flow: use the standard $k$-$\varepsilon$ two equation turbulence model, use the strengthened wall function method for near wall treatment; use the porous medium model for catalyst area.

a. General control equation

In this paper, the flue gas is chosen as the flow medium and the flow is set as incompressible flow. The general form of the equation is as follows:

$$\frac{\partial (\rho \phi)}{\partial t} + \text{div} (\rho u \phi) = \text{div} (\Gamma \text{grad} \phi) + S$$

b. Turbulence models

The standard $k$-$\varepsilon$ two equation model:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k - \rho \varepsilon - \frac{\partial \left( \rho \varepsilon u_i \right)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + \frac{C_1 \mu k^2 \varepsilon}{k}$$

c. Porous media model

In this paper, the honeycomb shaped catalyst bed will be simulated. If the honeycomb shaped catalyst bed is constructed truthfully in the numerical simulation, the grid will reach tens of millions of grid bodies, which is restricted by the computer conditions. Therefore, the catalyst bed is modeled as a porous media area in the calculation. The rectification grid is also provided with porous media.

The resistance formula of porous media model is as follows:

$$\Delta p = \left( \frac{\mu \nu}{\alpha} + \frac{C_1 \rho \nu^2}{2} \right) \Delta m$$
Among them, $\rho = 1.239 \text{kg/m}^3$, $\alpha$ is the permeability of porous media, $\mu$ is the viscosity coefficient, $C_2$ is the pressure jump coefficient, and $\Delta m$ is the thickness of air distribution plate.

d. Transport equation of components

Because SCR system involves the mixing of various gas components, the material transport model is selected for simulation. The conservation equation takes the following general form, where $R_I$ is the net production rate of chemical reaction and $S_i$ is the additional production rate caused by discrete phase.

$$ N_i = \int n \left( \frac{\partial}{\partial t} (\rho Y_i) + \nabla \cdot (\rho \nu Y_i) \right) = -\nabla J_i + R_i + S_i $$

e Tabakoff wear model

Tabakoff wear model is based on the high-speed wear test results of Virginia coal ash impact particles, ANSI304, 410 and aluminum. The model has a high agreement with the experiment in the prediction of boiler wear in coal-fired power plant, and has been widely used and adopted [10].

Tabakoff wear model wear amount $e$ is defined as the erosion amount of unit mass fly ash on metal surface:

$$ E = K_e \left\{ 1 + C_i \left[ K_2 \sin(90/\alpha_0)\alpha_i \right] \right\} u_p^2 \left( \cos \alpha_i \right)^2 \left( 1 - R_t \right) + K_3 \left( u_p \sin \alpha_i \right)^4 $$

Among them, $E$—Surface wear rate, kg/(m$^2$·s);
$\alpha_i$—Relative angle between particle path and target surface;
$u_p$—Particle velocity, m/s
$R_t$—Tangential recovery ratio
$\alpha_0$—Maximum wear angle, degree

When $\alpha_0 < 3\alpha_1$, $C_i=1$ or $C_i=0$, According to the recommended value $\alpha_0 = 25^\circ$, $K_i=1.505101 \times 10^{-6}$, $K_2=0.2960$, $K_3=5.0 \times 10^{-12}$.

For the rebound of colliding particles, the empirical equation established by Tabakoff et al. The expression of normal recovery coefficient :

$$ e_p = \frac{U_{p,n}}{u_{p,n}} = 1.0 - 0.4159 \alpha_i - 0.494 \alpha_i^3 + 0.292 \alpha_i^4 $$

The expression of tangent recovery coefficient :

$$ e_t = \frac{U_{p,t}}{u_{p,t}} = 1.0 - 2.12 \alpha_i + 3.0775 \alpha_i^3 - 1.1 \alpha_i^4 $$

In this paper, Tabakoff wear model is used to quantitatively evaluate the impact of dust particles on the guide plate, rectifier grid, catalyst layer and blade area.

3. Results and analysis

According to Tabakoff’s wear empirical equation and Paper[11], the amount of wear is related to fly ash particle size, particle velocity, cutting angle and flue gas density. The cutting angle is mainly determined by flue gas movement track, and flue gas density is mainly affected by temperature and fly ash particle size. Therefore, this paper mainly studies the visualization technology of movement track and guide plate wear of different dust particle size in SCR reactor under different flue gas velocity.

3.1. Movement track of different dust particle size

Figure 1 shows the particle trajectories of dust particles with the flue gas velocity of 10m/s, mass concentration of 30g/Nm$^3$, particle size of 20μm, 45μm and 80μm in SCR reactor, and the distribution of flue gas streamline is calculated as a reference. It can be seen that the flue gas moves smoothly and well under the guidance of the guide plate and the rectifier grid, while the dust particles have poor follow-up in the flue gas due to the large density and inertia, and some of them are carried by the flue gas and thrown on the inner wall of the reactor, the guide plate and the wall of the rectifier grid. The larger the dust particle size is, the worse the dust particle follow-up performance is. Especially at the
variable cross-section and turning of the flue, the larger the dust distribution deviation in the flue, the faster the abrasion of the guide plate at the corresponding position will be caused.

3.2. Wear analysis
Figure 2 shows the modeling of the main flow guide devices in SCR reactor, including flow guide plate, baffle gate, rectifier gate, etc. Through the CFD calculation of particle missing model and tabakoff wear model, the wear of the above flow guide devices is described and displayed in detail.

Calculate the wear condition of the guide plate perpendicular to the flue gas arrangement according to the position ① in Figure 2, and explain the relationship between the wear rate distribution and the fly ash particle size. Figure 3 shows the visual effect diagram of wear under the dust particles of 20μm, 45μm, 80μm at the flue gas speed of 10m/s and the mass concentration of 30g/Nm³, respectively. In Figure 3, it can be seen that under the particle size of 20μm, the wear area is mainly concentrated in the 3/4 area from the bottom to the top, with the maximum wear rate of $8.79 \times 10^{-6}$ kg/(m²·s); under the particle size of 45μm, the wear area is mainly concentrated in the 1/2 area from the bottom to the top, with the maximum wear rate of $9.45 \times 10^{-6}$ kg/(m²·s); under the particle size of 80μm, the wear area is mainly concentrated in the 1/3 area from the bottom to the top, with the maximum wear rate of $8.23 \times 10^{-6}$ kg/(m²·s). This is because the centrifugal force of fly ash is large in the process of large angle change due to its own inertia, and the trend of large particle dust tends to the outside of the wear guide plate when the smoke changes direction, and the larger the dust particles, the more obvious the trend, indicating that the size of fly ash affects the wear area distribution.

![Figure 1](image-url). Movement track of smoke and dust particles.
Figure 2. modeling of deflector.

Figure 3. Visual effect of wear under different particle sizes. (a) 20μm particles
(b) 45μm particles
(c) 80μm particles

Figure 4 shows the change trend of wear rate at the selected point 0.5m away from the bottom of the guide plate in the leftmost guide plate of position ① under the three particle sizes of 20μm, 45μm, 80μm. It can be seen from Figure 4 that the maximum wear position gradually moves down with the increase of particle size, and the top wear rate decreases rapidly, and the visual effect of this characteristic wear cloud chart is consistent.

The wear condition of the guide plate horizontally arranged in the flue gas is calculated with the guide plate at position ② in Figure 2, and the relationship between the wear rate and the fly ash mass concentration is explained. Figure 5 shows the visual effect diagram of guide plate wear under the flue gas speed of 10m/s, particle size of 45μm, mass concentration of 10g/Nm³, 30g/Nm³ and 45g/Nm³ respectively. It can be seen in Figure 5 that after the mass concentration is increased, the red area in the cloud image gradually expands, and the corresponding maximum wear rate is 2.75×10⁻⁶ kg/(m²·s), 4.33×10⁻⁶ kg/(m²·s), 6.21×10⁻⁶ kg/(m²·s), which implies the wear rate increases with the increase of mass concentration.

Figure 6 shows the change trend of wear rate of the selected point at every 1m wear position between the bottom guide plate of position ② and the left end face.

It can be seen from Figure 6 that under the same dust particle size and flue gas velocity, the wear rate increases with the increase of mass concentration, but it is not strictly linear. Because the wear rate is not only related to the concentration of fly ash, particle size and flue gas velocity, but also
related to the flue structure In this paper, the flue structure is taken into account by the complete modeling of SCR reactor, and the wear condition is closer to the actual operation effect.

Figure 4. Changing trend of wear rate under different particle sizes.

Figure 5. Visual effect of wear under different mass concentration. (a) Mass concentration 15g/Nm³

(b) Mass concentration 30g/Nm³

(c) Mass concentration 45g/Nm³

Figure 6. Changing trend of wear rate under different mass concentration.

Figure 7. Comparison of test data with simulation results.

3.3. Model accuracy verification
In order to verify the effectiveness of the numerical simulation results, the actual measurement speed of the test hole at the reactor inlet center is selected to compare with the simulation results, as shown in Figure 7. It can be seen from the comparison results that the simulation results are in good agreement with the measured data. The maximum deviation and average deviation from the test data are 5.76% and 2.95% respectively.
In the field test, the average concentration of smoke and dust of the unit is around 35g/Nm$^3$, and the flue gas flow rate under full load condition is basically 12m/s. In the field inspection, the wear area is mainly concentrated in the area below 2/3 of the guide plate, and the wear visualization effect trend is basically the same, as shown in Figure 8. According to the visualization technology, the local parts of the guide plate were treated with anti abrasion and ash removal.

![Figure 8. Wear and ash accumulation of guide plate on site.](image)

4. Conclusions

(1) Based on the particle missing model and Tabakoff wear model, the paper calculates the wear of SCR reactor in coal-fired power plant by CFD, obtains the movement track of gas-solid two-phase in the reactor, and realizes the visualization of the internal wear of flue.

(2) The visual effect of guide plate wear in flue is related to flue gas velocity, mass concentration, fly ash particle size and flue structure. The distribution of wear rate is mainly affected by the particle size of fly ash, and the value of wear rate is mainly related to the mass concentration of fly ash.

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