Study on Flow Field Optimization for SCR System of Coal-fired Power Plants

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Abstract. Coal-fired power plants are undergoing ultra-low emission retrofits. When the flue structure of the SCR denitrification system of the existing unit is fixed, the internal baffles and static mixers need to be optimized to ensure the flow field uniformity, thus ensuring the denitrification efficiency and controlling the ammonia escape rate. For a 660 MW SCR system, numerical simulation of flue gas flow uniformity and cold state test of physical model were carried out. The results show that the uniformity of the flow field distribution and the mixing effect of ammonia and gas in the SCR denitrification system are effectively improved by adding deflectors and optimizing the static mixers. The research in this paper provides reference for similar engineering design and construction in the future.

1. Introduction
At present, Selective Catalytic Reduction (SCR) flue gas denitrification technology is used for NOx removal technology for coal-fired power units widely. The flue gas enters the flue in front of the SCR reactor from the boiler through the economizer. The ammonia/air mixture is injected into the flue of the SCR denitrification system by the ammonia spray grid, and is fully mixed with the flue gas in the flue. In the SCR reactor, the injected NH3 reacts with the NOx in the flue gas to form H2O and N2 by the catalytic action. After purification, the flue gas is discharged from the outlet flue of the SCR reactor and enters the downstream auxiliary equipment such as the air preheater. The ultra-low emission modification of coal-fired power plants puts forward higher requirements on the flue gas uniformity of the SCR denitrification device. Flow field uniformity is a key factor for the denitrification efficiency and ammonia escape rate.

In this paper, for a 660 MW ultra-supercritical unit, the gas flow field uniformity was effectively provided by optimizing the baffles and the static mixers. Computational Fluid Dynamics (CFD) was used to simulate and optimize the model design. The physical model test verified the calculation results through actual measurements. The experimental results show that the designed baffles and static mixers can significantly enhance the mixing effect of ammonia and gas. The denitrification efficiency is improved and the ammonia escape rate is reduced.

2. Numerical Simulation
The flow field optimization calculation was carried out on the SCR reactor. The turbulent motion of the flue gas in the system was simulated by the standard k-ε turbulence model. The mixture of flue gas and ammonia was simulated by the material transport model. The porous medium model was used to
simulate the catalyst structure of SCR reactor. The formulas used in the simulation calculation process were as follows.

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]  

(1)

\[
\rho \left( u \frac{\partial K}{\partial x} + v \frac{\partial K}{\partial y} + w \frac{\partial K}{\partial z} \right) = \frac{\partial}{\partial x} \left( \Gamma_k \frac{\partial K}{\partial x} \right) + \frac{\partial}{\partial y} \left( \Gamma_k \frac{\partial K}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma_k \frac{\partial K}{\partial z} \right) + G_k - \rho \varepsilon
\]  

(2)

\[
\rho \left( u \frac{\partial e}{\partial x} + v \frac{\partial e}{\partial y} + w \frac{\partial e}{\partial z} \right) = \frac{\partial}{\partial x} \left( \Gamma_k \frac{\partial e}{\partial x} \right) + \frac{\partial}{\partial y} \left( \Gamma_k \frac{\partial e}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma_k \frac{\partial e}{\partial z} \right) + c_i G_k \varepsilon - \rho C_2 \frac{e^2}{k}
\]  

(3)

\[ S_i = \mu \frac{v_i}{\alpha} + C_2 \frac{1}{2} \rho |v_i| v_i \]  

(4)

\[ \bar{J}_i = \text{mass diffusion of substance i}; \quad R_i = \text{net rate of the chemical reaction product}; \quad S_i = \text{additional rate.} \]

The relative standard deviation \( C_v \) is used to characterize the velocity and concentration distribution characteristics of the SCR system:

\[ C_v = \frac{\sigma}{\bar{x}} \times 100\% \]  

(6)

\[ \sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2} \]  

(7)

\[ \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \]  

(8)

Some assumptions and simplifications are made to facilitate the simulation calculation. The flue gas is regarded as an incompressible Newtonian fluid. The flue gas velocity distribution at the economizer inlet is evenly distributed. The CFD model simulates only one side because the two reactors are symmetrically arranged. CFD modeling includes modeling of ammonia injection grids, catalyst layers, static mixers and flue systems. The catalyst lamination is simulated by porous media, and a pressure loss equivalent to the actual operating value is generated for simulation. The influence of internal structures (frames, beams, etc.) that have less influence on the flow field is ignored in the CFD model. The thickness of the baffle is relatively small compared to the flue size, and the thickness is assumed to be zero in the simulation.

Three-dimensional modeling of the SCR system was made, using a tetrahedral and hexahedral mesh to divide the three-dimensional model into regions. The grid of the nozzle exit section flue was encrypted. In order to prevent the nonlinear divergence of the wall surface, the variable relaxation coefficient method with low relaxation iteration was adopted. The standard wall function was adopted for the model wall.

The catalyst section was simulated with porous media. The parameter settings were adjusted to ensure that the simulated resistance was consistent with the actual resistance. The exit boundary conditions were set in areas where there was no backflow.
The physical model test system was made of carbon steel and plexiglass according to the actual unit of 1:15. The ash content in the flue gas was replaced by glass beads of the same particle size. The NH$_3$ was replaced by CO gas.

At the beginning of the experiment, the centrifugal induced draft fan was started first. The SCR cold physical model was connected by the cyclone separator. The glass beads were supplied by the screw feeder controlled by the frequency converter. Compressed air entered the buffer tank by the air compression mechanism to control the flow rate through the rotameter. The diluted CO entered the SCR reactor through an ammonia spray grid and a static mixer.

3. Analysis and discussion

Mathematical modeling is carried out according to the actual size of the unit. The simulation calculations are carried out for the BMCR working conditions. Firstly, the SCR reaction system in the original scheme of the unit is analyzed. The inlet flue of the system is gradually expanded from 10200 mm to 15500 mm in the straight distance of 2560 mm. The number of baffles installed in the diverging section is too small, so that the uniformity of the flue gas velocity distribution in the vertical ascending section of the inlet flue is affected. In the optimization scheme, the number of deflectors in the diverging section of the flue gas inlet is increased, baffles are added at the outlet of the diverging section of the vertical ascending flue. The tubular static mixer downstream of the ammonia spray grid was changed to a circular plate static mixer. The ammonia blending effect is effectively improved.

According to the simulation results of the original SCR reactor, the flow velocity of the flue gas is too large near the center line of the boiler and the outside of the vertical ascending flue. At the far end of the diverging section, the flue gas velocity is low due to the influence of eddy currents. In this scheme, the span and the diverging rate of the diverging section of the flue are too large, and the number of baffles installed in the diverging section is small. It is difficult for the flue gas to be diverted into the diverging inclined section. These factors affect the uniformity of flow field distribution upstream of the ammonia spray grid.

The new design scheme is modeled and analyzed. The velocity distribution of the flue gas in the diverging section of the ascending flue tends to be uniform. The velocity profile of the vertical rise flue center section is shown in Figure 1.

![Figure 1](image)

In the new design, the flue gas velocity distribution is significantly improved in the flue section of the diverging section and after the AIG. On the upstream section of AIG, the gas velocity $C_v$ decreased from 52.85% to 29.11%. On the downstream section of the static mixer, the $C_v$ value of flue gas velocity decreased from 39.28% to 17.22%. The two speed distributions are shown in Figure 2 and Figure 3, respectively.
After optimization of the design, the velocity distribution uniformity of flue gas is significantly improved on the vertical rising section and the inlet section of the first layer of catalyst. Taking the numerical simulation results under BMCR conditions as an example, in the original scheme, the velocity distribution deviation is 18.07% on the inlet section of the first layer. After optimization, the velocity distribution deviation decreased to 13.97% on this section. Streamline diagram of NH$_3$ concentration distribution in SCR reactor is shown in Figure 4.
In the optimization scheme, the ammonia concentration molar ratio distribution on the inlet section of the first catalyst was calculated. By matching the appropriate ammonia spray valve adjustment, the final ammonia-nitrogen molar ratio distribution is less than 5%. The new design meets the requirements for retrofitting technical indicators.

The ammonia-nitrogen molar ratio characteristics of the SCR system after ammonia injection were analyzed. Under the BMCR condition, in the original scheme, the standard deviation of the ammonia molar ratio of is 9.05% on the upstream section of the first layer of catalyst. The simulation result shows that the standard deviation of the ammonia molar ratio distribution decreases to 3.63 % in the optimization scheme.

In the optimization scheme, a wide range of eddy current regions at the inner and outer sides of the bend are avoided by installing a suitable baffle at a place where the flow area or the direction of fluid movement changes drastically. This design reduces the generation and extent of secondary flow. It is worth noting that the placement of the baffles and static mixers adds some system resistance. Therefore, it is necessary to comprehensively balance the improvement performance of the speed and concentration distribution deviation and overall pressure loss characteristics of the SCR system.

The temperature field analysis results show that the temperature distribution is relatively uniform in the original SCR reactor. Under the operating conditions of the BMCR, the gas average temperature is 644.6K on the first catalyst inlet section. The temperature variation range is within ±3.1℃. In the optimization scheme, the temperature range of the flue gas is further reduced, within ±2.7℃.

The main equipment’s used in the physical model system include the SMART-AR866 hot wire anemometer and the ecom-J2KN portable multi-function flue gas analyzer. The parameters of the AIG upstream section velocity distribution, the flow characteristics and CO concentration distribution on the first layer catalyst inlet were tested.

The results show that the average gas velocity is 12.99 m/s on the upstream section of the ammonia spray grid under the BMCR condition. On this section, the standard deviation of the velocity distribution is 27.36%. The average gas velocity was 3.80 m/s and the velocity distribution deviation were 14.56% on the inlet section of the first catalyst. On this section, the deviation of the ammonia concentration distribution was 4.16%. Therefore, this optimization scheme guarantees the performance indexes of the first layer catalyst inlet section. The inlet flue gas conditions that meet the requirements ensure the efficiency of the catalytic reaction in the SCR reactor.

4. Conclusion
In the ultra-low emission modification process of coal-fired power plants, the mixing effect of flue gas and ammonia is not ideal. The denitrification catalyst cannot fully exert its catalytic effect. In the case of a certain flue structure, the uniformity of the flue gas and the mixing uniformity of gas and ammonia can be improved by optimizing the inner baffles and the static mixers. The combination of numerical simulation and physical model cold test can be used to guide the optimal design of SCR reactor and provide theoretical analysis basis for ultra-low emission reform of coal-fired power plants.

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