An Investigation of Selective Catalytic Reduction Catalyst SO₂/SO₃ Conversion in Coal-fired Power Plants

Yang Zhang¹, Zhiqiang Jiang², Zhengang Zhou¹, Yonglong Yang¹, Qianwei Feng¹, Jianping Jiang¹, Zhen Du¹, Dong Guo¹, Xinrong Yan¹∗

¹ Huadian Electric Power Research Institute Co., Ltd., Hangzhou 310030, China
² China Huadian Corporation Ltd., Beijing 100032, China

ABSTRACT

The SO₂/SO₃ conversion in the selective catalytic reduction (SCR) denitrification system of coal-fired power plants plays a significant role in the generation of SO₃. Effectively controlling the conversion rate of SO₂/SO₃ in the denitrification catalyst can substantially mitigate the hazards associated with SO₃. Drawing on 170 SCR catalyst tests, the impact of various factors, including the catalyst’s V₂O₅ content, WO₃/MoO₃ content, inlet SO₂ concentration, inlet flue gas temperature, and area velocity, on the SO₂/SO₃ conversion was systematically investigated. The findings suggest potential optimization opportunities for the SO₂/SO₃ conversion rate in the denitrification catalysts currently used in engineering applications. By understanding the influence patterns of key factors, tailored measures such as selecting appropriate performance indicators, designing catalysts for specific projects, and adjusting key operational parameters in coal-fired power plants can be implemented. These measures are aimed at preventing problems like corrosion and blockage in downstream facilities due to SO₃ and effectively controlling SO₃ emissions.

Keywords: Coal-fired power plant, SCR catalyst, SO₂/SO₃ Conversion, SO₃ emission, Synergistic control

1 INTRODUCTION

Selective Catalytic Reduction (SCR) technology for denitrification has become the main technology for flue gas denitrification in coal-fired power plants due to its high denitrification efficiency, selectivity, and cost-effectiveness (Zhang et al., 2020). The widely used SCR denitrification catalysts are V₂O₅–WO₃/TiO₂ or V₂O₅–MoO₃/TiO₂ (Busca et al., 1998; Liu and Woo, 2006). V₂O₅ is the main active component of the catalyst. However, while catalyzing the reduction of NOₓ, V₂O₅ also significantly catalyzes the oxidation of SO₂ in the flue gas. The higher the V₂O₅ content, the higher the SO₂/SO₃ conversion rate (Topsøe, 1997; Zhang et al., 2019). The oxidation of SO₂ was suppressed in the presence of NH₃ and NO due to their competitive absorption on the V₂O₅ (Liu et al., 2015). The SO₂ produced by SCR denitrification can react with moisture in the flue gas under certain temperature conditions to form H₂SO₄. When the flue gas temperature drops below the acid dew point, H₂SO₄ condenses on the metal walls, causing corrosion to equipment downstream of the denitrification unit, such as air preheaters, electrostatic precipitators, and flues. Ammonia escaping from SCR denitrification reacts with SO₃ to form NH₄HSO₄, which tends to deposit on the surfaces of heat exchange elements in the lower temperature section of air preheaters, leading to equipment blockage and reduced efficiency. The emission of SO₃ into the atmosphere can form sub-micron sulfuric acid mist aerosols, increasing the concentration of primary PM₂.₅ emissions and contributing to the formation of secondary PM₂.₅ in the atmosphere. It also causes acid rain, and soil and vegetation corrosion, and poses significant health risks to humans (Svachula, 1993; Song et al., 2022). Therefore, identifying the key factors and patterns
affecting the SO2/SO3 conversion rate of SCR denitrification catalysts and controlling this conversion rate to reduce SO3 formation is currently a focal research direction in the field of coal-fired power plant SCR denitrification (Zheng et al., 2019a; Zhang et al., 2021a).

Research and engineering applications both domestically and internationally indicate that the SO2/SO3 conversion rate of denitrification catalysts depends on factors such as catalyst type, formulation, and operational conditions (Svachula, 1993). Regarding the type of catalyst, plate-type catalysts, which use stainless steel mesh as a support, can reduce the use of active components of the catalyst and have certain advantages over honeycomb-type catalysts in controlling the SO2/SO3 conversion rate. Research indicates that the SO2/SO3 conversion rate is linearly related to the catalyst wall thickness, but attention should be paid to the impact on the wear resistance of the catalyst when controlling the catalyst wall thickness (Schwämmle et al., 2013; Zheng et al., 2019b). In terms of catalyst formulation, selecting an appropriate V2O5 content according to different flue gas components and performance requirements can maintain the catalyst’s denitrification activity while minimizing the SO2/SO3 conversion rate (Dunn et al., 1999). Lietti et al. (1996) found that adding WO3 can improve the low-temperature activity of the catalyst, thereby reducing the amount of V2O5 and achieving the effect of controlling SO2/SO3 conversion rate. Additionally, adding additives like Y2O3, GeO2, NiO, and MoO3 to the catalyst can weaken the adsorption capability of SO2 on the catalyst surface and suppress its oxidation activity (Srivastava et al., 2004; Schwämmle et al., 2013; Ji et al., 2015). For example, both Kobayashi and Hagi (2006) and Lu et al. (2019) found that the addition of SiO2 can increase the acid sites on the surface of V2O5–WO3/TiO2 or V2O5–MoO3/TiO2, enhancing the catalyst’s low-temperature activity and reducing the SO2/SO3 conversion rate. However, it’s important to note that additives might adversely affect the catalyst’s performance during actual operations. For instance, a study by Yan et al. (2015) found that a catalyst containing aluminum experienced significant mechanical performance degradation after 8,000 hours of operation due to the reaction of Al2O3 with SO3 in the flue gas, forming Al2(SO4)3. Ji (2016) showed that the addition of MoO3 promotes the formation of NOx, reducing the selectivity of the catalyst. Xiao et al. (2018) found that poisoning catalysts with sodium salts (Na2SO4 and Na2S2O7) can lead to a decrease in de-NOx efficiency, while the SO2/SO3 conversion rate increases significantly. Regarding operational conditions, studies indicate that O2 in coal-fired power plant flue gas has no significant effect on the SO2/SO3 conversion rate. However, the presence of H2O inhibits the oxidation of SO2, and the SO2/SO3 conversion rate of the catalyst increases with rising flue gas temperature (Jiang et al., 2013; Ji et al., 2015). The main pathway of SO2 oxidation is that SO2 is oxidized to form adsorbed SO3 and then reacts with NH3 to generate sulfate or desorbs to generate gaseous SO3 (Li et al., 2020). An increase in temperature will accelerate this reaction process. Wu et al. (2016) observed during field tests on a 600 MW coal-fired unit that when the boiler load increased from 75% to 100% of the rated load, the SO2 produced during the SCR denitrification process decreased from 12.6 mg m⁻³ to 8.4 mg m⁻³. Although the SO2/SO3 conversion rate of the catalyst increased with higher inlet flue temperatures at higher loads, the increased space velocity inside the denitrification reactor and the shorter flue gas residence time hindered the diffusion and adsorption of SO3 in the catalyst’s micropores, reducing the reaction rate. This effect was greater than the temperature’s impact on the conversion rate, ultimately resulting in lower SO3 production at higher loads. Li et al. (2019) found in field experiments on a 340 MW coal-fired unit that when the unit load increased from 50% to 70%, the increased flue temperature raised the catalyst activity and the SO2/SO3 conversion rate, indicating that the temperature’s impact was greater than that of the flue gas residence time. However, when the load increased from 70% to 100%, temperature was no longer a limiting factor. Due to the increased flue gas residence time and ammonia injection, the effects of residence time and competition between NH3 and SO2 for adsorption became dominant, leading to a decrease in the conversion rate. Furthermore, studies have shown that during the use of catalysts, issues such as the loss of active components, reduction in porosity, decrease in surface area, and deposition of elements like K, P, and As in the flue gas can lead to reduced catalyst activity, denitrification efficiency, and SO2/SO3 conversion rate (Yu et al., 2012; Zhang et al., 2021b).

In summary, SCR denitrification technology boasts high efficiency, simplicity in operation and control, and technological maturity. However, the significant issue of SO3 being converted to SO2 in flue gas and the subsequent negative impacts must not be overlooked. Addressing this, the
present study conducts 170 catalyst tests on actual coal-fired units and establishes a comprehensive database for the SO₂/SO₃ conversion of SCR denitrification catalysts. This research systematically examines the influence of catalyst physicochemical properties, process characteristics, and inlet flue gas parameters on the SO₂/SO₃ conversion, offering valuable insights and references for future product development, engineering design, and operational management.

2 METHODS

2.1 Research on the Overview of Units

Denitrification catalysts in 170 SCR units of coal-fired power plants were tested and analyzed. As illustrated in Fig. 1, these units represent the current mainstream in terms of capacity, furnace type, coal type, and catalyst style. The sample primarily includes units with capacities of 300 MW and 600 MW, comprising 74% of the total, while units of 1,000 MW or more account for 7%. Cyclone boilers are the predominant boiler type at 74%, followed by 20% opposed firing boilers and 6% W-flame boilers. In terms of coal type, lignite/bituminous coal and lean coal are the most common, constituting 71% and 24%, respectively, with anthracite at 5%. With regard to coal sulfur content, medium-sulfur coal (1% < S ≤ 2.5%) is the most prevalent, at 52%, followed by low-sulfur coal (S ≤ 1%) and high-sulfur coal (S > 2.5%) at 20% and 28%, respectively. As for the catalyst styles, honeycomb and plate-type catalysts are nearly equally represented, at 52% and 48%, respectively.

Catalyst testing was conducted for the denitrification units of the aforementioned 170 units prior to their operation. To ensure comparability of the test results, all tests were carried out at the initial stage of construction of the denitrification units, with catalysts from the same manufacturer and batch. Table 1 lists the range of fluctuations in the main process parameters and physicochemical properties of the catalysts for these units. It is observed that the V₂O₅ content in honeycomb and
Table 1. Fluctuation range of main process parameters and catalyst physicochemical characteristics parameters of the sample unit.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Units</th>
<th>Honeycomb-style</th>
<th>Flat plate style</th>
</tr>
</thead>
<tbody>
<tr>
<td>V₂O₅ content</td>
<td>V₂O₅</td>
<td>%</td>
<td>Minimum value</td>
<td>Maximum value</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.30</td>
<td>2.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.19</td>
<td>4.33</td>
</tr>
<tr>
<td>WO₃ content</td>
<td>WO₃</td>
<td>%</td>
<td>2.36</td>
<td>6.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.01</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02</td>
<td>5.62</td>
</tr>
<tr>
<td>MoO₃ content</td>
<td>MoO₃</td>
<td>%</td>
<td>0.01</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02</td>
<td>5.62</td>
</tr>
<tr>
<td>Inlet flue gas temperature</td>
<td>T</td>
<td>°C</td>
<td>330</td>
<td>425</td>
</tr>
<tr>
<td>Inlet SO₂ concentration</td>
<td>[SO₂]ₜₐₐₐₚ</td>
<td>mg m⁻³</td>
<td>920</td>
<td>12,000</td>
</tr>
<tr>
<td>Area velocity</td>
<td>Aᵥ</td>
<td>m h⁻¹</td>
<td>6.21</td>
<td>20.0</td>
</tr>
<tr>
<td>Space velocity</td>
<td>Sᵥ</td>
<td>h⁻¹</td>
<td>2646</td>
<td>8527</td>
</tr>
</tbody>
</table>

The V₂O₅ content of plate-type catalysts varies within the ranges of 0.30–2.14% and 1.19–4.33%, respectively, with plate-type catalysts generally having a higher V₂O₅ content than honeycomb types. The WO₃ (tungsten trioxide) content in these two types of catalysts ranges from 2.36% to 6.19% and 0.01% to 5.62%, respectively, while the MoO₃ (molybdenum trioxide) content ranges from 0.01% to 2.15% and 0.02% to 6.19%, respectively, with honeycomb catalysts primarily incorporating WO₃ and plate-type catalysts favoring MoO₃. In terms of inlet flue gas temperature, both honeycomb and plate-type catalysts operate within the range of 330–425°C and 327–396°C, respectively, which is within the standard operational temperature range for commercial denitrification catalysts. As for inlet SO₂ concentration, it ranges from 920–12,000 mg m⁻³ for honeycomb catalysts and 878–13,000 mg m⁻³ for plate-type catalysts, indicating a broad spectrum of coal sulfur content in the sampled units, covering the conventional range found in coal varieties used in power generation in China. Regarding area velocity, it varies between 6.21 m h⁻¹ and 20.0 m h⁻¹ for honeycomb catalysts and 7.06 m h⁻¹ and 15.7 m h⁻¹ for plate-type catalysts. Area velocity is the ratio of the flue gas flow rate to the total geometric surface area of the catalyst (the product of catalyst volume and geometric specific surface area), and its calculation formula is as follows:

\[ Aᵥ = \frac{Q}{\sum q_i \times S WINAPI} \]  

where \( Aᵥ \) represents the area velocity, measured in m h⁻¹; \( Q \) is the volume of flue gas, in m³ h⁻¹; \( q_i \) denotes the volume of the \( i \)-th layer of catalyst, in m³; \( S WINAPI \) is the geometric specific surface area of the \( i \)-th layer of catalyst, in m² m⁻³.

The space velocity is the ratio of the flue gas flow rate to the total volume of the catalyst, and its calculation formula is as follows:

\[ Sᵥ = \frac{Q}{\sum q_i} \]  

where \( Sᵥ \) represents the space velocity, in h⁻¹; \( Q \) is the volume of flue gas, in m³ h⁻¹; \( q_i \) denotes the volume of the \( i \)-th layer of catalyst, in m³.

2.2 Experimental Instruments and Methods

2.2.1 Catalyst process characteristics

The testing of the catalyst’s process characteristics was conducted using a custom-made medium-sized testing platform. The rationale for choosing the specific dimensions and arrangements of the catalyst samples within the reactor refers to national and industrial standards of China (GB/T38219-2019; AQSIQ and SAC, 2019; DL/T 1286-2021; NEA, 2021). The main components of this platform include a cylinder group, a gas mixing heater, a simulated reactor, and a flue gas.
Fig. 2. Schematic diagram of catalyst process characteristic testing device.

### Table 2. Adjustable flue gas conditions of test platform.

<table>
<thead>
<tr>
<th>Items</th>
<th>Units</th>
<th>Set value</th>
<th>Allowable Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue Gas Flow Rate (Standard state, wet Basis)</td>
<td>m³ h⁻¹</td>
<td>20–550</td>
<td>±5 (Relative Value)</td>
</tr>
<tr>
<td>Space Velocity (Standard state, wet Basis)</td>
<td>h⁻¹</td>
<td>Design Value</td>
<td>±3 (Relative Value)</td>
</tr>
<tr>
<td>Flue Gas Temperature</td>
<td>°C</td>
<td>Design Value</td>
<td>±3 (Relative Value)</td>
</tr>
<tr>
<td>SO₂ (Standard state, dry basis)</td>
<td>mg m⁻³</td>
<td>Design Value</td>
<td>±1 (Relative Value)</td>
</tr>
<tr>
<td>NO (Standard state, dry basis)</td>
<td>mg m⁻³</td>
<td>Design Value CNO</td>
<td>±1 (Relative Value)</td>
</tr>
<tr>
<td>O₂ (Standard state, dry basis)</td>
<td>%</td>
<td>Design Value</td>
<td>±0.2 (Absolute Value)</td>
</tr>
<tr>
<td>NH₃-N₂O₅ Molar Ratio</td>
<td>——</td>
<td>n/100+2.28/CNO</td>
<td>0/+0.1 (Absolute Value)</td>
</tr>
<tr>
<td>H₂O</td>
<td>%</td>
<td>Design Value</td>
<td>±1 (Relative Value)</td>
</tr>
</tbody>
</table>

Before the tests began, a complete honeycomb catalyst log was cut into samples with a cross-section of 42 × 42 mm², keeping the length consistent with the actual units. Plate-type catalysts were trimmed to create samples with an approximate width of 42 mm placed in a carrier with a 42 × 42 mm² cross-section according to the actual catalyst module pitch, and arranged in the same order as in the denitrification unit, keeping the length consistent with actual plates. These were then arranged in series inside the simulated reactor. The flue gas volume for the test apparatus was determined based on the designed area velocity and space velocity of the denitrification unit, to ensure that the simulated flue gas volume is consistent with the actual engineering. The flow rates of the various gas cylinder groups and the power of the two-stage preheaters were controlled to simulate the actual flue gas composition and temperature parameters based on the catalyst’s design inlet parameters. Concentrations of flue gas components such as SO₃, NO₃, and O₂ before and after the denitrification reaction were monitored online using a flue gas analyzer (Rosemount NGA2000 from Germany). The concentration of SO₃ was measured using a controlled condensation method, with the operating procedure and steps following national and industrial standards of China (GB/T 21508-2008; AQSIQ and SAC, 2008; DL/T 998-2016; NEA, 2016). The SO₃ concentration in flue gas was calculated according to the consumption of standard solutions, and its calculation formula is as follows:

\[
SO₃ = T_{SO₃} \times \frac{V}{V}
\]
where \( \text{SO}_3 \) represents the \( \text{SO}_3 \) concentration of the flue gas, in mg m\(^{-3}\); \( T_{\text{SO}_3} \) represents the titer of \( \text{SO}_3 \) with NaOH standard solution, in mg mL\(^{-1}\); \( \nu \) represents the NaOH standard solution consumption amounts, in mL; and \( V \) represents the volume of dry flue gas sample, in m\(^3\).

Based on the analysis of flue gas components at the inlet and outlet, the denitrification efficiency and \( \text{SO}_2/\text{SO}_3 \) conversion rate were calculated. The formula for calculating denitrification efficiency is as follows:

\[
\eta = \frac{[\text{NO}_x]_{\text{inlet}} - [\text{NO}_x]_{\text{outlet}}}{[\text{NO}_x]_{\text{inlet}}} \times 100 
\]

(4)

where \( \eta \) represents the denitrification efficiency, in \%; \([\text{NO}_x]_{\text{inlet}} \) and \([\text{NO}_x]_{\text{outlet}} \) respectively denote the \( \text{NO}_x \) concentrations (including NO and NO\(_2\)) at the inlet and outlet of the denitrification reactor, in mg m\(^{-3}\).

The formula for calculating the \( \text{SO}_2/\text{SO}_3 \) conversion rate is as follows:

\[
\chi = \frac{M_{\text{SO}_2}}{M_{\text{SO}_3}} \times \frac{[\text{SO}_3]_{\text{inlet}} - [\text{SO}_3]_{\text{outlet}}}{[\text{SO}_2]_{\text{inlet}}} \times 100 
\]

(5)

where \( \chi \) represents the \( \text{SO}_2/\text{SO}_3 \) conversion rate, in \%; \( M_{\text{SO}_2} \) and \( M_{\text{SO}_3} \) are the molar masses of \( \text{SO}_2 \) and \( \text{SO}_3 \), respectively, in g mol\(^{-1}\); \([\text{SO}_3]_{\text{inlet}} \) and \([\text{SO}_3]_{\text{outlet}} \) respectively denote the \( \text{SO}_3 \) concentrations at the inlet and outlet of the denitrification reactor, in mg m\(^{-3}\). \([\text{SO}_2]_{\text{inlet}} \) is the \( \text{SO}_2 \) concentration at the inlet of the denitrification reactor, in mg m\(^{-3}\).

### 2.2.2 Catalyst physical and chemical properties

The methods for testing the physicochemical properties of the catalysts were conducted in accordance with the industrial standard (DL/T 1286-2021; NEA, 2021). The main chemical components of the catalysts were determined using an X-ray fluorescence spectrometer (XRF, Rigaku ZSX Primus IIIX from Japan). Trace elements in the catalysts were measured using an inductively coupled plasma emission spectrometer (ICP, PE Optima 8000 from the United States). The specific surface area of the catalysts was determined using a physical adsorption surface area analyzer (Quanta NOVA 4000e from the United States) based on the multi-point Brunauer–Emmett–Teller (BET) method.

### 3 RESULTS AND DISCUSSION

#### 3.1 Impact of \( \text{V}_2\text{O}_5 \) Content

The analysis of the effect of \( \text{V}_2\text{O}_5 \) content on the \( \text{SO}_2/\text{SO}_3 \) conversion rates for honeycomb and plate-type catalysts, as illustrated in Figs. 3(a) and 3(c), is derived from the test results for each catalyst type. It can be observed that for the honeycomb catalyst, when the \( \text{V}_2\text{O}_5 \) content varies within the range of 0.30–2.14%, the \( \text{SO}_2/\text{SO}_3 \) conversion rate fluctuates between 0.56% and 0.97%. For the plate-type catalyst, as the \( \text{V}_2\text{O}_5 \) content changes within the range of 1.19–4.33%, the \( \text{SO}_2/\text{SO}_3 \) conversion rate varies between 0.55% and 1.12%. However, further fitting results indicate that although the \( \text{SO}_2/\text{SO}_3 \) conversion rate tends to increase with the rising \( \text{V}_2\text{O}_5 \) content, the correlation between the two is relatively weak. This phenomenon might be attributed to the fact that the catalyst tests were conducted under the design conditions of corresponding coal-fired power plant projects. The resulting \( \text{SO}_2/\text{SO}_3 \) conversion rates are influenced by multiple factors, thereby causing interference in the analysis of the impact of a single factor.

To minimize the influence of other parameters, as shown in Figs. 3(b) and 3(d), the effect of the catalyst’s \( \text{V}_2\text{O}_5 \) content on the \( \text{SO}_2/\text{SO}_3 \) conversion rate was analyzed under conditions where other parameters were limited to a less impactful range. It is evident that the \( \text{SO}_2/\text{SO}_3 \) conversion rate of the catalyst significantly increases with the rising \( \text{V}_2\text{O}_5 \) content, and the R-squared values of the fitting trend lines reached 0.6066 and 0.6407, respectively, indicating a noticeably stronger
correlation. Extensive previous research has also shown that V$_2$O$_5$, the main active component in vanadium-titanium catalysts, plays a significant catalytic role in the oxidation of flue gas SO$_2$ with a positive correlation (Pio, 2001; Zhu et al., 2012). At lower V$_2$O$_5$ concentrations, it is distributed in an amorphous state on the catalyst’s surface. However, at higher concentrations, aggregated V species or even crystals may form, significantly enhancing the catalyst’s oxidative performance and leading to a notable increase in the SO$_2$/SO$_3$ conversion rate (Ji et al., 2015). V$_2$O$_5$ is the primary active substance in catalysts used for industrial sulfuric acid production; hence, its concentration should be strictly controlled during catalyst production to prevent the formation of crystals due to high V$_2$O$_5$ concentrations clustering together. Research by Zhao et al. (2016) indicates that with increasing V$_2$O$_5$ content, both the de-NO$_x$ activity and SO$_2$ oxidation activity of the catalyst increase, with the latter rising more rapidly. From this perspective, controlling the V$_2$O$_5$ content is an effective way to reduce the SO$_2$/SO$_3$ conversion rate and is the primary method used by de-NO$_x$ catalyst manufacturers in current engineering projects to adjust the SO$_2$/SO$_3$ conversion rate of their catalyst products.

In practical engineering applications, when controlling the V$_2$O$_5$ content in catalysts as a single factor, it is generally advisable to reduce the V$_2$O$_5$ content. However, it’s important to note that as the V$_2$O$_5$ content decreases, the de-NO$_x$ performance of the catalyst also diminishes. To meet the required de-NO$_x$ performance, it becomes necessary to increase the volume of the catalyst. This reduction in area velocity can lead to an increase in the SO$_2$/SO$_3$ conversion rate. Therefore, a balance between these two aspects should be carefully considered. Depending on the specific flue gas composition, an appropriate V$_2$O$_5$ content in the catalyst should be selected to maintain its de-NO$_x$ activity while controlling the SO$_2$/SO$_3$ conversion rate as much as possible. Generally, the V$_2$O$_5$ content in honeycomb catalysts should be kept below 1.3%, while for plate-type catalysts, which use a metal mesh as the base material and have thinner walls and less active material, the V$_2$O$_5$ content can be slightly higher but should still be controlled within 3.0%.
3.2 Impact of WO$_3$/MoO$_3$ Content

In current commercial applications, SCR de-NO$_x$ catalysts commonly incorporate WO$_3$ and MoO$_3$ as additives to enhance the catalyst's resistance to SO$_2$, water vapor, and to improve thermal stability. Since honeycomb catalysts are generally produced using an extrusion molding process, adding MoO$_3$ can lead to a decline in their mechanical properties. Therefore, WO$_3$ is predominantly used in these catalysts. In contrast, plate-type catalysts, which use stainless steel mesh as the base material, have superior mechanical properties, allowing for the addition of MoO$_3$, which is more effective in suppressing the SO$_2$/SO$_3$ conversion. As shown in Fig. 4(a), the effect of WO$_3$ on honeycomb catalysts was examined. It was observed that as the WO$_3$ content increases, the SO$_2$/SO$_3$ conversion rate also rises, with the R-squared value of the fitting trend line being 0.4852. Research by Morikawa et al. (1981) studied the impact of various additives on the SO$_2$/SO$_3$ conversion rate of catalysts. Their findings indicate that the addition of WO$_3$ promotes the adsorption of SO$_2$, thereby increasing the SO$_2$/SO$_3$ conversion rate. This is attributed to the formation of W-O-W structures in tungsten oxides, where W=O, similar to V=O, catalyzes the oxidation of SO$_2$.

As illustrated in Fig. 4(b), the impact of MoO$_3$ on plate-type catalysts was investigated. Unlike WO$_3$, it was observed that as the MoO$_3$ content increases, the SO$_2$/SO$_3$ conversion rate decreases, with the R-squared value of the fitting trend line being 0.5084. Research by Kwon et al. (2016) found that the addition of MoO$_3$ significantly inhibits the SO$_2$/SO$_3$ conversion rate of catalysts. This is because MoO$_3$ can weaken the adsorption of SO$_2$ on the catalyst surface and suppress the reaction between SO$_2$ and the V–O bond on the catalyst surface. Furthermore, the higher the Mo$^{6+}$/Mo$^{5+}$ ratio, the better the sulfur resistance. Studies by Zhu et al. (2012) also indicate that MoO$_3$ effectively enhances the low-temperature activity of the catalyst, thereby reducing the
SO₂/SO₃ conversion rate while ensuring de-NOₓ performance. As the loading of MoO₃ increases, the SO₂/SO₃ conversion rate gradually decreases. When the MoO₃ loading mass fraction exceeds 9%, the catalyst maintains high low-temperature catalytic activity while keeping the SO₂/SO₃ conversion rate below 1%. Research by Gao (2013) shows that at flue gas temperatures below 300°C, the inhibitory effect of MoO₃ on the SO₂/SO₃ conversion rate of the catalyst is not significant. However, when the flue gas temperature exceeds 300°C, the SO₂/SO₃ conversion rate significantly decreases as the MoO₃ content in the catalyst increases. Studies by Busca et al. (1998) suggest that adding MoO₃ can inhibit the sulfation of acidic sites on the catalyst surface, thereby reducing the SO₂/SO₃ conversion rate. It also has a mitigating effect on arsenic poisoning of the catalyst.

In practical engineering applications, when controlling the WO₃ and MoO₃ content in catalysts, it's important to consider that adding these additives, such as WO₃ and MoO₃, can enhance the catalyst's resistance to SO₂ and H₂O, improve thermal stability, and increase low-temperature activity (Zhou et al., 2009). However, their impact on the SO₂/SO₃ conversion rate shows different trends. Therefore, for specific engineering conditions, when the inlet flue gas parameters fall within the suitable range for conventional de-NOₓ catalysts, the appropriate amount of these additives should be selected to control the SO₂/SO₃ conversion rate as effectively as possible.

3.3 Impact of Inlet SO₂ Concentration

Fig. 5 shows the impact of inlet SO₂ concentration on the SO₂/SO₃ conversion rate. It is observed that both honeycomb and plate-type catalysts exhibit similar trends: as the inlet SO₂ concentration increases, the SO₂/SO₃ conversion rate decreases, with the fitting trend lines indicating good correlation. Research by Orsenigo et al. (1998) demonstrates that the SO₂/SO₃ conversion rate of catalysts shows a strong dynamic and continuous response to the inlet SO₂ concentration. Zhu et al. (2007) prepared honeycomb-shaped V₂O₅–WO₃/TiO₂ de-NOₓ catalysts in the laboratory, and their findings also indicate that the SO₂/SO₃ conversion rate decreases as the SO₂ concentration increases.

![Fig. 5. Effect of inlet SO₂ concentration on SO₂/SO₃ conversion rate](image)

(a) is a honeycomb catalyst, V₂O₅ = 0.5–1.0%, T = 360–380°C, Aᵥ = 9–11 m h⁻¹; (b) is a flat plate catalyst, V₂O₅ = 1.5–2.5%, T = 355–375°C, Aᵥ = 8–10 m h⁻¹).
In practical engineering applications, regarding the control of inlet SO$_2$ concentration, reducing the sulfur content in coal, although it may increase the SO$_2$/SO$_3$ conversion rate in de-NO$_x$ systems, also helps control the production of SO$_3$. This control of production should still be prioritized in real-world applications. Moreover, while the current national standards uniformly require that the SO$_2$/SO$_3$ conversion rate does not exceed 1% (HJ 2053-2018; MEE, 2018), specific engineering projects should still be treated differently. For example, in low-sulfur coal projects, due to the lower inlet SO$_2$ concentration and limited SO$_3$ production, the requirements for the SO$_2$/SO$_3$ conversion rate can be relaxed, both from the perspective of controlling SO$_3$ emissions and preventing blockages in downstream equipment. On the other hand, for high-sulfur coal projects, the high inlet SO$_2$ concentration will inherently reduce the SO$_2$/SO$_3$ conversion rate of the catalyst. Additionally, from the standpoint of controlling SO$_3$ emissions, the conversion rate requirements should be increased. Therefore, the SO$_2$/SO$_3$ conversion rate criteria should be appropriately tightened. Current technical specifications suggest that when the sulfur content in coal is below 2.5%, the SO$_2$/SO$_3$ conversion rate in de-NO$_x$ should be below 1%; when the sulfur content is above 2.5%, the conversion rate should be below 0.75% (HJ 2301-2017; MEE, 2017).

3.4 Impact of Inlet Flue Gas Temperature

Temperature is a critical influencing factor for catalytic reactions. Fig. 6 illustrates the effect of flue gas temperature on the SO$_2$/SO$_3$ conversion rate, showing a significant increase in the conversion rate as the temperature rises. From the figure, it can be seen that with the flue gas temperature rising from 360°C and 350°C to 393°C and 370°C, the SO$_2$/SO$_3$ conversion rates for honeycomb and plate-type catalysts increase from 0.66% and 0.63% to 0.95% and 0.85%, respectively. According to the principles of chemical reaction kinetics, as the temperature increases, the reaction rate of SO$_2$ catalytic oxidation significantly increases, leading to a higher SO$_2$/SO$_3$ conversion rate. Research by Schwaemmle et al. (2012) indicates that within the operational...
temperature range of conventional vanadium-titanium catalysts, there is a significant positive correlation between the SO$_2$/SO$_3$ conversion rate and temperature. Studies by Brinkmann et al. (2001) show that when the flue gas temperature exceeds 420°C, the SO$_2$/SO$_3$ conversion rate of the catalyst dramatically increases. Research by Wang et al. (2013) also demonstrates that the SO$_2$/SO$_3$ conversion rate rapidly increases when the catalyst undergoes high-temperature sintering, which is one of the reasons for setting a maximum continuous operating temperature for current commercial vanadium-titanium catalysts. Currently, in high-temperature flue gas projects, commercial vanadium-titanium catalysts generally control the SO$_2$/SO$_3$ conversion rate by reducing the V$_2$O$_5$ content in the catalyst, but this also results in an increase in catalyst volume (Zhang et al., 2021b).

Regarding the control of inlet flue gas temperature, considering that within the working temperature range of conventional commercial catalysts, the SO$_2$/SO$_3$ conversion rate increases with rising flue gas temperature, it is advisable in engineering applications to control the SO$_2$/SO$_3$ conversion rate of de-NO$_x$ catalysts by managing the combustion conditions of the boiler, especially under high-load conditions, to keep the inlet flue gas temperature of the de-NO$_x$ system as low as possible.

3.5 Impact of Area Velocity

In catalytic reactions, the area velocity and space velocity significantly influence catalytic efficiency. As evident from Formulas (1) and (2), there is a strong correlation between area velocity and space velocity. Therefore, this article focuses only on the impact analysis of area velocity, with results shown in Fig. 7. It can be observed that as the area velocity increases from 7.01 m h$^{-1}$ and 8.71 m h$^{-1}$ to 20.0 m h$^{-1}$ and 14.8 m h$^{-1}$, the SO$_2$/SO$_3$ conversion rates for honeycomb and plate-type catalysts decrease from 0.86% and 1.03% to 0.65% and 0.58%, respectively. This decrease is due to the increased area velocity reducing the residence time of flue gases on the catalyst surface, leading to insufficient reaction time and, consequently, a lower SO$_2$/SO$_3$ conversion.

Fig. 7. Effect of area velocity on SO$_2$/SO$_3$ conversion rate (a) represents a honeycomb catalyst, V$_2$O$_5$ = 0.5–1.0%, T = 360–370°C, [SO$_2$]$_{\text{inlet}}$ = 2,000–5,000 mg m$^{-3}$; (b) represents a flat plate catalyst. V$_2$O$_5$ = 2.0–3.5%, T = 350–380°C, [SO$_2$]$_{\text{inlet}}$ = 1,000–4,000 mg m$^{-3}$.)
rate. Additionally, the number of pores or the pitch in the catalyst is another important factor affecting area velocity. Taking honeycomb catalysts as an example, a greater number of pores means a larger geometric surface area of the catalyst, higher area velocity, and greater activity per unit volume. However, in practical engineering applications, the choice of pore number or pitch is limited by the concentration of fly ash in the flue gas.

Regarding the control of area velocity, as understood from its definition and calculation formula, during the catalyst product design phase, the area velocity can be increased by maximizing the catalyst's geometric specific surface area, controlling the catalyst wall thickness, and reducing the catalyst volume. This increase in area velocity can, in turn, lower the SO₂/SO₃ conversion rate. However, in the operational phase, when the amount of catalyst is fixed, controlling the area velocity can only be achieved by adjusting the volume of flue gas, which is relatively more challenging.

### 3.6 Comparison of De-NOₓ Efficiency and SO₂/SO₃ Conversion Rate

From the above analysis, it is evident that the impact of various factors on the SO₂/SO₃ conversion rate follows a trend similar to that of de-NOₓ efficiency. For instance, the conversion rate increases with the rise in V₂O₅ content and inlet flue gas temperature and decreases as the area velocity increases. Fig. 8 presents a comparison between de-NOₓ efficiency and the SO₂/SO₃ conversion rate. Although the overall trend indicates that an increase in de-NOₓ efficiency corresponds to an increase in the SO₂/SO₃ conversion rate, the correlation is not particularly strong. This might be because the catalyst tests conducted in this study were based on the conditions set for corresponding engineering projects. Catalyst manufacturers generally tailor their products to the specific conditions of these projects, controlling various parameters comprehensively.

![Fig. 8. Comparison between denitrification efficiency and SO₂/SO₃ conversion rate ((a) represents a honeycomb catalyst, while (b) represents a flat plate catalyst).](image)
This approach aims to achieve the desired de-NOx efficiency while keeping the SO2/SO3 conversion rate within the required standards, thereby minimizing product costs as much as possible.

4 CONCLUSIONS

This article systematically investigates the impact of factors such as V2O5 content, WO3/MoO3 content, inlet SO2 concentration, inlet flue gas temperature, and area velocity on the SO2/SO3 conversion in the SCR de-NOx process of numerous coal-fired power plants, through extensive experimentation on the process characteristics and physicochemical properties of the SCR de-NOx catalysts. The main conclusions are as follows:

1) Currently, the SO2/SO3 conversion rates in different engineering projects fluctuate within the range of 0.55–1.12%, differing by more than double. This indicates, on one hand, that the conversion of SO2 in SCR de-NOx systems significantly contributes to SO3 emission concentrations. On the other hand, it shows that controlling the SO2/SO3 conversion rate of catalysts can effectively reduce the formation of SO3, and there is considerable scope for optimization in specific projects.

2) The SO2/SO3 conversion rate of de-NOx equipment is influenced by multiple factors, including the composition and structure of the catalyst, the operational conditions of the unit, and the catalytic reaction conditions. The SO2/SO3 conversion rate of the catalyst increases with higher V2O5 content, WO3 content, and inlet flue gas temperature, while it decreases with increasing inlet SO2 concentration, MoO3 content in the catalyst, and area velocity.

3) In subsequent catalyst product development, setting technical indicators for engineering projects, catalyst design and selection, and operational processes of the unit, it is essential to determine the most technologically and economically optimal SO2/SO3 conversion rate control measures based on the boundary conditions of different engineering projects. For example, with the goal of controlling the total amount of SO3, the performance requirements for SO2/SO3 conversion rate should depend on different coal sulfur content; the catalyst wall thickness should be controlled while ensuring its anti-wear performance; the combustion of the boiler should be adjusted during operation to minimize the inlet flue gas temperature of the catalyst. Through these measures, efforts are made to avoid corrosion and blockage caused by SO3 in downstream facilities, alleviate the pressure on downstream environmental protection facilities, and create conditions for effective control of SO3 emissions.

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DISCLAIMER

The authors declare no conflicts of interest.

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