Regeneration of Selective Catalyst Reduction Catalysts Deactivated by Pb, As, and Alkali Metals

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ABSTRACT: Owing to increased operating time and Pb, As, and alkali metal poisoning of a catalyst, the activity of the catalyst is lowered. In the present study, we utilized the acetic acid and the traditional sulfuric acid pickling process for regeneration and then performed Brunauer—Emmett—Teller (BET) specific surface area, denitriﬁcation efﬁciency, scanning electron microscopy, and X-ray ﬂuorescence (XRF) analysis of a fresh catalyst, a deactivated catalyst, and a regenerated catalyst for comparison purposes. The experimental results demonstrated that the removal ratios of Pb, As, Na, and K were 99.2, 98.8, 99.9, and 93.9%, respectively. Compared to the traditional sulfuric acid regeneration technology, the acetic acid regeneration technology eliminates the activated liquid immersion step; therefore, the steps are simpler and efﬁcient for the regeneration of selective catalyst reduction catalysts deactivated by Pb, As, and alkali. The current study provides a new method for the regeneration and application of selective catalyst reduction (SCR) catalysts, which is particularly applicable for regenerating a large number of Pb, As, and alkali-metal poisoned catalysts.

1. INTRODUCTION

Coal-fired power plants are the main source of nitrogen oxide emissions. Selective catalytic reduction (SCR) denitriﬁcation technology is the most effective technique to control emissions of nitrogen oxides from coal-fired power plants. The catalyst is the core of SCR denitriﬁcation technology, which often encounters inactivation problems. During the process of operation, high-temperature sintering, micropore clogging, alkali metal poisoning, heavy metals, water, and SO2 poisoning can reduce the catalyst’s activity and shorten the service life. Heavy metals, alkali metals, and their resultant oxide poisoning are the main inﬂuencing factors for catalyst deactivation. The rate of deactivation of waste incineration SCR catalysts is faster than that of coal-fired ﬂue gas. One of the main causes for this observation is that the amounts of heavy metals produced by municipal solid waste (MSW) incineration are higher than those produced by coal combustion, with Pb concentration in the heavy metal emissions reaching as high as 27 mg/g. In China’s coal, the content of alkali metals (K, Na) ranges from 0 to 2.4%. The proportion of alkali metal in coal-fired power plants is very high, and the proportion of alkali coal (alkali metal content greater than 0.3%) accounts for 28.94% of all coal. After burning, K, Na, and other alkali metals are present in flue gas, which can then cause alkali metal poisoning of catalysts.

Lead is a poison that renders SCR catalysts toxic, but research on its effect on SCR catalysts is scarce. Rigby, Kong, Peng, and Senior also studied the mechanism of arsenic poisoning of catalysts. However, studies on the regeneration of arsenic-poisoned catalysts are relatively few. Chen and Lietti studied the mechanism of alkali metal poisoning of vanadium-based SCR catalysts using KNO3 or KCO3 as the precursor of K2O to impregnate the SCR catalysts. Zheng studied the effects of KCl and K2SO4 on commercial vanadium catalysts in the laboratory. Benson studied the mechanism of potassium deactivation of SCR catalysts in boilers burning subbituminous coal and lignite. The results show that the potassium compound reduces the amount of chemically adsorbed NH3 on the catalyst, and the Bronsted acid sites on the catalyst surface are chemically altered.

The cost of the denitriﬁcation catalyst accounts for 50% of the total investment in the denitriﬁcation system. Waste SCR catalyst is classified as hazardous waste and is composed of a variety of heavy metals. If the surplus SCR waste catalyst is not handled correctly, it seriously affects the soil and water environment. So, studying the deactivation mechanism of the denitriﬁcation catalyst and regenerating the waste catalyst are important for prolonging the life of the catalyst and thus reducing the SCR flue gas denitriﬁcation costs and system running costs, as well as alleviating environmental pollution.

The sulfuric acid acidic treatment is a well-established method of regeneration of the deactivation SCR catalyst that involves three steps: washing with water, pickling in sulfuric acid, and activated liquid (VOSO4 and ammonium tungstate).
immersion\textsuperscript{30,31}. This method effectively removes toxic elements such as Pb and alkali metals and increases the number of active sites on the catalyst surface, thereby increasing the activity of the catalyst.\textsuperscript{32–34} The activated liquid immersion step, the main active phase of the deactivated catalyst, is included to replenish the loss of an active component when the alkaline oxide is washed away during the pickling step. Even though this regeneration method has wide applications, it is cumbersome and the cost is high. The objective of the present study is to research the use of organic acids on Pb, As, and alkali metal catalyst poisoning and regeneration, and compare it with the recovery effect of traditional sulfuric acid pickling, in an attempt to discover highly efficient and low-cost SCR denitrification catalyst regeneration technology (Figure 1).

Figure 1. SCR denitrification catalyst activity evaluation device. (1) Gas cylinders, (2) mass flow meters, (3) buffer tanks, (4) three-way valves, (5) reactors, (6) heating furnaces, (7) catalysts, (8) temperature controllers, (9) cooling tank, (10) flue gas analyzer, (11) phosphoric acid solution.

2. RESULTS AND DISCUSSION

2.1. Catalyst Activity Parameters. In SCR denitrification technology, denitrification efficiency is affected by the catalyst load, temperature, and ammonia–nitrogen ratio, which interfere with catalyst poisoning and regeneration. As shown in Figure 2, the denitrification efficiency of the catalyst in this experiment does not substantially increase after 350 °C. Therefore, to save energy and improve economic efficiency, 350 °C was chosen as the reaction temperature. The catalyst load and ammonia–nitrogen ratio were 100 g and 1:1, respectively (Table 1).

![Figure 2. Effect of different temperatures on denitrification efficiency.](https://dx.doi.org/10.1021/acsomega.0c01283)

Table 1. Reaction Conditions of Catalyst Activity Evaluation

| parameter | unit | value | parameter | unit | value |
|-----------|------|-------|-----------|------|-------|
| NH\textsubscript{3} | ppm | 600 | total flow | mL/min | 900 |
| NO | ppm | 600 | catalyst particle size | mm | 10 |
| O\textsubscript{2} | % | 4 | catalyst loading | g | 100 |
| N\textsubscript{2} | % | 250–420 | measuring point stabilization time | min | 25 |
| H\textsubscript{2}O | % | 16.94 | SO\textsubscript{2} | ppm | 650 |

2.2. Selection of Representative Acids. In this study, several kinds of regeneration liquids listed in Table 2 were selected for the regeneration experiment. Each set of experiments was repeated five times. The average value of the measured outlet NO\textsubscript{x} concentration is shown in Table 2. According to the denitrification efficiency formula 2, the denitrification efficiency was calculated.

For the cause of catalyst deactivation, some may block the pores of the catalyst, resulting in physical deactivation of the catalyst. The other part may react with the V-OH acidic sites of the catalyst to reduce the number of V-OH acidic sites on the catalyst surface, thereby causing chemical poisoning of the catalyst. In the pickling groups consisting of regenerant numbers, no. A2 (acetic acid) (92.12%) showed the highest denitrification efficiency. During cleaning with acetic acid, the acid can react with lead ions attached to the catalyst surface to produce lead acetate. After cleaning with acetic acid, part of lead ion impurities on the catalyst can be removed.

As shown in Figure 2, the denitrification efficiency of the catalyst in this experiment does not substantially increase after 350 °C. Therefore, to save energy and improve economic efficiency, 350 °C was chosen as the reaction temperature. The catalyst load and ammonia–nitrogen ratio were 100 g and 1:1, respectively (Table 1).

Table 2. Average Concentration of Outlet NO\textsubscript{x} of Regenerated Catalysts from Different Regeneration Liquids

| regenerant | export NO\textsubscript{x} average concentration (ppm) | standard deviation (%) |
|------------|---------------------------------------------------|------------------------|
| A0 (fresh catalyst) | 8.48 | 1.08 |
| A1 (deactivated catalyst) | 109.10 | 1.03 |
| A2 (0.5 mol/L acetic acid) | 17.36 | 1.30 |
| A3 (0.5 mol/L citric acid) | 69.76 | 1.10 |
| A4 (0.5 mol/L oxalic acid) | 74.58 | 1.39 |
| A5 (0.5 mol/L sulfuric acid) | 19.09 | 1.28 |
ciency of the catalyst. In the pickling group consisting of regenerant nos. A2–A5, regenerant no. A2 (acetic acid) demonstrated the highest denitriﬁcation efﬁciency. It possesses a certain degree of acidity and thus can increase the acidity of the catalyst. However, its acidity level is weak, and it does little to remove the active ingredients from the catalyst. In contrast, strong acids may wash off the active components of the catalyst and thus reduce the activity of the catalyst.

X-ray ﬂuorescence (XRF) was applied to detect the ingredient contents of the deactivated catalyst after pickling with different types of acids. The results are shown in Table 3, and it was discovered that the effects of organic acid pickling on the deactivated catalyst were different.

The catalyst samples after pickling regeneration could barely detect the oxide of alkali metal Na (except for A4), and the content of the alkali metal K oxide was also greatly reduced (Table 3). Because there was no accession to activated liquid (VOSO₄ and ammonium tungstate) immersion during the sulfuric acid pickling regeneration process, the vanadium content decreased. The vanadium content decreased from 0.950 to 0.719%. This is consistent with the sulfuric acid regeneration process of alkali metal-poisoned catalyst studied in Sun,38 and the vanadium element was reduced by 22.6%.

Results from A3 and A4 showed that following citric acid and oxalic acid pickling, the vanadium content was signiﬁcantly reduced. The removal of the alkaline oxides from the catalyst simultaneously removed the active substances in the catalyst (V₂O₅), which directly affected the denitriﬁcation efﬁciency after pickling regeneration. The sulfuric acid pickling process did not pass through the third step of activated liquid immersion, and after the acid pickling catalyst, the vanadium content decreased as seen in the A5 data. For acetic acid pickling under the same conditions, acid regeneration of the deactivated catalyst was completed and the active substance V₂O₅ was not removed. The main reason for this is that acetic acid is faintly acidic, reducible, and oxidizable, which can efﬁciently remove the alkaline oxide without affecting the original V₂O₅ catalyst content. Based on the experimental results above, acetic acid was chosen as being a representative of the acidic treatment in the experiment and it was then compared to the traditional sulfuric acid acidic treatment. The experimental results show that the acetic acid regeneration method can remove 100% Na element from alkali, 92.01% from K, and only 1.68% from V₂O₅. The removal rate of basic element Na can only be achieved by sulfuric acid regeneration. It also reached 100%, and the removal rate of K was 91.63%, similar to the acetic acid regeneration method, but V₂O₅ was reduced by 24.32%.

As shown in Table 3, PbO content is higher in a poisoned catalyst than in a fresh catalyst due to the toxic inactivation of the catalyst by lead in the form of PbO. Moreover, XRF analysis results show that most of the PbO is washed away and that the active component of the catalyst is nearly unchanged compared with the deactivation catalyst cleaned with acetic acid. Arsenic in the form of As₂O₃ can cause the toxic inactivation of the catalyst, and the regeneration method of acetic acid washes away most of the As₂O₃ and leaves the active component of the catalyst virtually unchanged. The contents of Na₂O and K₂O in the deactivated catalyst increased by 0.1% compared to those in the fresh catalyst; more basic oxides were loaded on the deactivated catalyst (Na₂O, K₂O, CaO). The V₂O₅ content in the regenerated catalyst was 0.948 and 0.934% after sulfuric acid pickling, activation solution soaking, and acetic acid pickling, respectively. This value is similar to the V₂O₅ content (0.953%) in the fresh catalyst, and both have good regeneration effects. The SO₃ content in the sulfuric acid regeneration catalyst was lower than the fresh catalyst, and the acetic acid regeneration catalyst is lower more. The alkali metals and their oxides were reduced to the initial level and the active ingredient was not affected.

### 2.3. Catalyst Characterization.

The fresh catalyst, deactivated SCR catalysts, and sulfuric acid and acetic acid regenerated SCR catalysts were utilized for performance testing and scanning electron microscopy (SEM) analysis. The XRF performance of the fresh catalyst and sulfuric acid and acetic acid regenerated catalysts was analyzed. Of these, the sulfuric acid-treated deactivated catalyst had to go through the washing—pickling—activated liquid immersion regeneration process, where the first two steps washed away the original active substance V₂O₅ of the catalyst. The washed active substance was replenished by activated liquid immersion during the third step. The acetic acid-treated deactivated catalyst was thoroughly water-washed and acid-washed during the two regeneration steps, and the active material was not supplemented by soaking in the activated liquid.

The impregnation of the deactivated catalyst after acid washing with sulfuric acid is performed to supplemen the vanadium content lost during the pickling process. In this article, a regeneration liquid consisting of vanadyl sulfate, ammonium paratungstate, and water is disposed. According to the mass fractions of vanadyl sulfate and ammonium paratungstate, 0.5, 1, 1.5, 2, and 2.5% are, respectively,
configured for the activating solution, and the rest for deionized water. The composition of the regeneration liquid is shown in Table 4.

| Ingredient List of Nutrient Solution (%) | activating solution (500 mL) | vanadyl sulfate | ammonium paratungstate | deionized water |
|-----------------------------------------|-----------------------------|-----------------|------------------------|----------------|
| 1                                       | 0.5                         | 0.5             | 99                     |
| 2                                       | 1.0                         | 1.0             | 98                     |
| 3                                       | 1.5                         | 1.5             | 97                     |
| 4                                       | 2.0                         | 2.0             | 96                     |
| 5                                       | 2.5                         | 2.5             | 95                     |

Table 4. Ingredient List of Nutrient Solution %

![Graph](https://example.com/graph)

Figure 3 shows the effect of impregnation with different activating solutions on the denitrification efficiency after sulfuric acid regeneration of the catalyst. It is not difficult to see that the denitrification efficiency of the catalyst impregnated with no. 5 activating solution was 91%, which was 8% higher than the 83% efficiency of the denitrification catalyst after only acid washing with sulfuric acid. It was only 5% lower than the 96% reduction in the denitrification efficiency of fresh catalysts. Therefore, no. 5 activating solution was used to supplement the vanadium content lost during the acid pickling process.

The regeneration criteria were defined as follows: the activity ratio \( K_c \) is higher than 0.9 (\( K_c \) is the activity of the fresh catalyst, and \( K_c \) is the activity of the regenerated catalyst), the \( \text{SO}_2/\text{SO}_3 \) conversion rate is <1, and the specific surface area of the regeneration catalyst is greater than 50 m\(^2\)/g.

The activity \( K_c \) can be obtained according to formula 1.

\[
K_c = 0.5 \times AV \times \ln \frac{MR}{(MR - \eta)(1 - \eta)}
\]  

where \( AV \) is the surface velocity (m/h); \( \eta \) is the denitrification efficiency; and \( MR \) is the molar ratio of ammonia to nitrogen.

Table 5 shows the performance test tables of samples of the fresh catalyst, the deactivated catalyst, the acetic acid pickling regenerated catalyst, and the sulfuric acid pickling regenerated catalyst.

As shown in Table 5, the specific surface area of the deactivated catalyst was 28 m\(^2\)/g, which severely impacts the catalyst performance, while the test data of the sulfuric acid and acetic acid pickling regenerated catalyst performance also agreed with the regeneration criteria. The acetic acid and sulfuric acid regeneration of the catalyst had almost the same efficiencies as denitrification. To the best of Yu’s knowledge, previous approaches all require off-site regeneration, which inevitably contributes to an additional and significant operational cost. Besides, some approaches, such as washing with dilute sulfuric acid, may cause the loss of active components and corrosion of equipment. The sulfuric acid acidic treatment by activated liquid immersion not only supplemented the vanadium substance vanadium but also increased new active sites, inevitably contributing to an additional and significant operational cost.

Table 5. Performance Before and After the Catalyst Sample Regeneration\(^{a,b}\)

| Project | Fresh Catalyst | Deactivation Catalyst | Acetic Acid Pickling Regenerated Catalyst | Sulfuric Acid Pickling Regenerated Catalyst |
|---------|----------------|-----------------------|------------------------------------------|---------------------------------------------|
| Catalyst | Sulfuric Acid | Sulfuric Acid | Sulfuric Acid | Sulfuric Acid |
| Temperature (°C) | 350 | 350 | 350 | 350 |
| Superficial Velocity (Nm/s) | 2.32 | 2.32 | 2.32 | 2.32 |
| Flue gas velocity in the channel (m/s) | 6.52 | 6.61 | 7.23 | 7.23 |
| Ammonia nitrogen ratio | 0.61 | 0.61 | 0.66 | 0.66 |
| Entrance O2 (%) | 4.00 | 4.00 | 4.00 | 4.00 |
| Actual moisture content (%) | 16.94 | 16.94 | 8.00 | 8.00 |
| Entrance NO (µL/L) | 212.90 | 211.50 | 220.30 | 219.70 |
| Export NO (µL/L) | 8.48 | 109.00 | 17.36 | 19.09 |
| Effectiveness (%) | 96.02 | 94.78 | 92.12 | 91.31 |
| Ammonia escape (µL/L) | 1.62 | 27.20 | 1.89 | 1.86 |
| SO2/SO3 (%) | 0.90 | 0.53 | 0.96 | 0.98 |
| Specific surface area (m\(^2\)/g) | 59.00 | 28.00 | 59.02 | 58.45 |
| Pore volume (cm\(^3\)/g) | 0.31 | 0.16 | 0.31 | 0.30 |
| Activity (m/h) | 44.42 | 18.66 | 40.42 | 40.87 |
| Activity ratio (K/K\(_c\)) | 1.00 | 0.42 | 0.91 | 0.92 |

\(^{a}K_c\)—Assume the fresh catalyst activity ratio is 1. \(^{b}K\)—Deactivation catalyst/acetic acid pickling regenerated catalyst/sulfuric acid pickling regenerated catalyst activity ratio.
over 90% of the fresh catalyst. The results revealed that the regeneration efficiency was restored to the fresh catalyst level, the denitrification activity was also restored, and the feasibility of acid regeneration was demonstrated.

2.4. SEM Analysis. In this study, the catalyst raw materials, deactivated catalyst, and pickled regenerated catalyst were tested by SEM at different magnifications. The pickling regeneration samples, including sulfuric acid pickling regenerated catalyst and acetic acid pickling regenerated catalyst, were analyzed.

Figure 4a is the fresh SCR catalyst picture at a magnification of $10^5$ times and shows the evenly distributed catalyst surface of the TiO$_2$ particles. The fresh TiO$_2$ particles in the catalyst provide a high degree of dispersion (specific surface area is 59.00 m$^2$/g), and the active substance can be dispersed in the catalyst surface, thereby improving the efficiency of denitrification. Figure 4b shows the deactivation catalyst at $5 \times 10^4$ magnification. The active substances on the surface of the deactivated catalyst were mostly covered and the surface of the catalyst was uneven. This phenomenon is caused by PbO, As$_2$O$_3$, and the oxidation of alkali metals K and Na, which remain on the surface of the deactivated catalyst. These materials covered the surface of the catalyst and occupied its active sites, which seriously affected the denitrification efficiency. This is also the main cause of the SCR catalyst deactivation in power plants.

Figure 5a,b show the characteristics of a deactivated catalyst after using the sulfuric acid ($5 \times 10^4$ magnification) and acetic acid pickling regeneration method ($5 \times 10^4$ magnification), respectively.

Figure 5a,b shows that the catalyst regenerated by sulfuric acid and acetic acid pickling has rougher surface than the surface of the fresh catalyst, as shown in Figure 4a. This is mainly caused by the traces of the poisoned materials remaining on the deactivated catalyst after being washed away with sulfuric acid and acetic acid. Using Figure 4b for comparison, it can be seen that the surface of the regenerated catalyst is not covered by other substances and the TiO$_2$ particles are evenly arranged, with the regeneration effect obvious. Acid treatment may also have a significant influence on surface modification. The results demonstrate that acetic acid and sulfuric acid are effective for regenerating SCR catalysts deactivated by Pb, As, and alkaline poisoning.
3. CONCLUSIONS

For Pb, As, and alkali inactivation of the SCR denitration catalyst, acetic acid and the traditional sulfuric acid pickling processes were utilized for regeneration purposes. In this study, BET, denitration efficiency, SEM, and XRF analysis of the fresh catalyst, the deactivated catalyst, and the regenerated catalyst were investigated. The results demonstrate that acetic acid as a nonreducing organic acid has a similar acid pickling effect to sulfuric acid. Acetic acid possesses a certain degree of acidity and thus can increase the acidity of the catalyst. Sodium carbonate reacts with As$_2$O$_3$ to produce sodium arsenate, which reduces the arsenic toxicity of the catalyst. Changed the microstructure of the catalyst, increasing the specific surface area and pore volume. From the effect of acid-washed deactivated catalyst, the effect of the removal of metal oxides and salts of Na by the acidic treatment was slightly better than that of metal K. After washing away the surface of Na, K metal oxides, and their salts, the surface was uneven. This indicates that alkali metal poisoning not only affects the active site of the catalyst but also affects the specific surface area of the catalyst. When an alkali-deactivated catalyst was regenerates by acetic acid pickling, high efficiency in the removal of alkali metal and its oxide was achieved, and the content of V$_2$O$_5$ in the catalyst was not affected. Therefore, the activated liquid immersion step is not required. Compared to the sulfuric acid acidic treatment, the steps are simplified in the acetic acid method, which not only saves costs but also saves on time and labor. Therefore, acetic acid can be utilized for the regeneration of organic acids into the actual production and application of alkali-deactivated SCR denitration catalysts.

4. EXPERIMENTAL SECTION

4.1. Experimental Raw Materials and Equipment. All of the catalyst raw materials utilized in the experiment were sampled from Jiangsu Wande. The fresh honeycomb catalyst ($V_2$O$_5$-WO$_3$/TiO$_2$-SiO$_2$) was used as the experimental material. The percentage of V$_2$O$_5$, TiO$_2$, WO$_3$, and SiO$_2$ was 0.953%, 88.566%, 4.618%, and 2.634%, respectively. The component of catalysts was measured by X-ray fluorescence (XRF). Nitrogen adsorption surface area measurements were performed at 77 K after drying the sample (200 °C for 1 h) using an SA 3100 analyzer (Coulter). The apparent nitrogen surface area was calculated by the Brunauer—Emmett—Teller (BET) equation. The surface morphology of catalysts was studied by a scanning electron microscope (SEM). The SO$_2$ concentration was measured by the Ecom-J2KN flue gas analyzer (Germany RBR).

4.2. Preparation and Regeneration of the Catalysts. The samples for Pb-poisoned, As-poisoned, and alkali metal-poisoned catalysts were prepared through wet impregnation. For sample preparation, fresh catalyst samples cut into pieces with 25 channels were impregnated with a 500 mL aqueous mixed solution containing Pb(NO$_3$)$_2$ (3 wt %), arsenic standard liquid (Certified Reference Material, CRM, 0.1 μg/mL), K$_2$SO$_4$ (2 wt %), and Na$_2$SO$_4$ (2 wt %) soaked for 2 h, and then calcined in a muffle furnace at 350 °C for 5 h to obtain catalyst samples deactivated by lead, arsenic, and alkali. Then, a variety of organic acids (acetic acid, citric acid, and oxalic acid) and the traditional inorganic acid (sulfuric acid) were used on the deactivation catalyst for the pickling regeneration and compared to acid pickling regeneration effect of each acid, after which the acid with the best effect was chosen for further exploration. The deactivated samples were first impregnated with 1 L of acid solutions for 5 min under ultrasound and then washed (continuous air stirring, 100 mL/min, 0.05 MPa) at 25 °C for a certain time. Afterward, the samples were dried at 120 °C for 2 h. The removal rate of Pb, As, and alkali metal and the denitration efficiency of the regenerated catalyst were used as the expected parameters for selecting acid.

4.3. Catalyst Activity Evaluation System. The activity of the denitration catalyst was evaluated in a laboratory-made quartz tubular reactor. The entire system consisted of three parts designed for gas distribution, catalytic reaction, and analytical test. The schematic of the experimental system is shown in Figure 1.

The gas distribution system included the numbers (1) to (3), and the ratio of ammonia to nitrogen was in the range of 0.9−1.2. Since NO accounted for 95% of NO$_x$ and the rest was NO$_2$, the gas distribution system was dominated by NO. Numbers (5) to (8) were catalytic reaction systems, and the reaction temperature was controlled between 200 and 500 °C. Numbers (9) to (11) were exhaust gas detection and analysis systems. Typical reaction conditions for catalyst activity evaluation are shown in Table 1. The denitration efficiency was evaluated according to formula 2.

$$\text{NO}_x\% = \frac{(\text{NO}_{\text{in}} + \text{NO}_{2\text{in}}) - (\text{NO}_{\text{out}} + \text{NO}_{2\text{out}})}{\text{NO}_\text{in} + \text{NO}_2\text{in}}$$

4.4. Catalyst Characterization. The catalysts before and after poisoning were characterized and analyzed. The elemental components of the catalyst samples were analyzed using XRF to determine the effect of the content of each component on denitrification efficiency. The microstructure of the catalyst surface and blockage clearance were analyzed through SEM, and the efficiency of the regeneration process was investigated. The specific surface area, porosity, and pore size of the catalyst were analyzed using a Beckman coulter SA 3100 specific surface area analyzer to compare the effect of the internal structure of the catalyst on its activity before and after regeneration.

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Notes
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