Low-Temperature SCR Catalyst Development

Subjects: Chemistry, Applied

Contributor: Liyun Song, Rui Wu, Wenge Qiu, Hong He

In recent years, low-temperature SCR (Selective Catalytic Reduction) denitrification technology has been popularized in non-power industries and has played an important role in the control of industrial flue gas NOx emissions in China. Currently, the most commonly used catalysts in industry are V2O5-WO3(MoO3)/TiO2, MnO2-based catalysts, CeO2-based catalysts, MnO2-CeO2 catalysts and zeolite SCR catalysts. The flue gas emitted during industrial combustion usually contains SO2, moisture and alkali metals, which can affect the service life of SCR catalysts.

Keywords: selective catalytic reduction ; nitrogen oxides ; low temperature

1. Introduction

Nitrogen oxides (NO_x), including NO and NO_2, are considered as the main air pollutants from industrial and automobile exhausts, which have caused a lot of environmental problems, such as haze issues and ozone depletion. Until now, the selective catalytic reduction of NO_x by ammonia (NH_3-SCR) is accepted to be an effective method to eliminate NO_x pollutants [1].

In SCR denitration technology, the most important thing is the catalyst that should possess the high activity, excellent sulfur oxides and water resistance abilities. The traditional V-based catalysts showed good deNO_x performance at 300–420 °C, which have been well used to abate the flue gas from the power plants. Due to the wide applications of SCR technology, the NO_x emissions from power industry have been well controlled, while NO_x emission control in the non-power industry faces severe challenges due to the low temperature of the flue gas, which is usually below 300 °C. Therefore, it is difficult to use traditional SCR catalysts for the gas pollutant treatment in the non-power industry. In the past ten years, Chinese scholars and industries have made great efforts on denitration in the non-power industry and made remarkable achievements. Wang and Dong et al. [1][2] present the detailed information concerning NH_3-SCR in some non-power industries, showing that the gas condition was more complex and fluctuated than that from the power plant.

2. Low-Temperature SCR Process

Usually, the flue gas temperature of the industrial process, such as in coking and steel sintering processes, is lower than 300 °C and contains many constituents with low concentrations, such as sulfur dioxide and alkali metal salts, and large amounts of water are also present. Thus, the SCR catalyst must be active in the low-temperature range (typically in the range of 160–300 °C) and stable under harsh gas conditions with good sulfur oxides and water resistance performance [3]. In the typical flue gas treatment system of power plants in China, which usually employ high-dust SCR system to control NO_x emissions, the SCR reactor is located upstream of the particulate control devices and flue gas desulfurization (FGD) system. The so-called “medium- and high-temperature SCR” units can be operated in the temperature range of 280–400 °C. For NO_x emission control in the non-power industry, especially in the coking and steel sintering industry, the “low-dust” or “tail-end” configuration of SCR technology should be adopted to decrease the impacts of SO_2 and dust on the SCR catalyst. The low-temperature SCR reactor is located downstream of the particulate control devices and flue gas desulfurization (FGD) system. The SO_2 concentration and dust amount in inlet of the SCR reactor should be lower than 35 and 5 mg/m^3, respectively, to meet the ultra-low emission standards. In the key areas of coal-fired boilers, the value should be lower than 50 and 20 mg/m^3. In this case, the operating temperature of the SCR unit can be decreased to 160 °C. Although SO_2 and dust in the flue gas have very low values, the SCR catalyst needs to operate for three years at a low temperature, posing a severe challenge to SCR catalyst technology.

3. SCR Catalysts

Low-temperature SCR technology is an economic and effective process in abating the NO_x pollutants emitted from the non-power industry. Based on the consensus of the advantages that low-temperature SCR technology possesses, in the last decade, considerable research in China have been devoted to developing catalysts that can work well under low-temperature conditions. The development and research in SCR catalysts have been reviewed and summarized [2][3]. As reported, many kinds of low-temperature SCR catalyst system have been proposed and investigated. The main low-temperature SCR catalyst systems include V_2O_5-WO_3(MoO_3)/TiO_2, Mn complex oxides, CeO_2-based and zeolite catalysts.

3.1. V_2O_5-WO_3(MoO_3)/TiO_2

As a typical and efficient catalyst, a V_2O_5-WO_3(MoO_3)/TiO_2 catalyst used in NH_3-SCR technology has been commercialized for several decades. The typical commercial catalyst used in power stations presents low activity at low temperatures (below 300 °C) and cannot meet the need to abate NO_x from non-power industries.

In the past decades, various transition-metal oxides have been researched as catalysts for NH_3-SCR at low temperatures. In order to meet the need of activity, stability, and resistance of SO_2 and H_2O, plenty of methods have been tried to improve SCR performance.

The most direct and convenient method to improve the low temperature activity of V_2O_5-WO_3(MoO_3)/TiO_2 catalyst is to appropriately increase the loading of V_2O_5. However, when V_2O_5 loading increases, the oxidative ability of the catalyst will be increased leading to the enhancement of SO_2 conversion. This is not allowed for the low-temperature SCR technology. Therefore, the catalyst needs to coordinate the redox activity and the surface acid property, reduce the adsorption of SO_2 on the catalyst surface and suppress the oxidation of SO_2. In another way, the NH_3 adsorbed on the Lewis acid sites (V^{5+}-O) on V_2O_5-WO_3(MoO_3)/TiO_2 catalysts can react with NO at low temperatures [4]. By increasing the surface acidity and inhibiting the oxidative ability over the SCR catalysts, the operating temperature window of the V_2O_5-MoO_3/TiO_2 catalyst is expanded to the range of 160–400 °C, which also shows acceptable SO_2 and H_2O resistance at low temperatures [5][6][7]. The V_2O_5-MoO_3/TiO_2 catalysts have been used intensively in denitration reaction projects of coking sintering, refuse incinerators and other non-electric industries in China.

Another way to improve the low-temperature SCR activity of the V_2O_5-WO_3(MoO_3)/TiO_2 catalyst is through modification and doping by introducing other elements into the catalyst system, which is easy to achieve in practice due to the convenience in the preparation. For example, Zhang et al. [8] investigated the effect of Mn, Cu, Sb, and La doping on the SCR performance of the V_2O_5-WO_3(MoO_3)/TiO_2 catalyst. The investigation showed that Mn and Cu could enhance the redox property and weak surface acidity, while Sb and La addition showed promotion in the amount of acid sites. Liang et al. [9] demonstrated that a 3% addition of CeO_2 improved the NH_3 adsorption performance, NO oxidation, and sulfur oxide and the water-resistance of the V_2O_5-WO_3/TiO_2 catalyst.

3.2. MnO_2-Based Catalysts

Manganese-containing catalysts have been paid enough attention due to their variable valence states and excellent redox properties. However, for its poor N_2 selectivity and easy deactivation by SO_2, the catalyst only containing manganese oxide is extremely restricted in the SCR process. Mn-based composite oxides are popular and have proven to be effective catalysts with an enhanced SCR performance [10].

Over MnO_x catalyst, NH_3 species adsorbed on Lewis acid sites (Mn^{3+}) were active at low temperatures. Bidentate nitrates were inactive at low temperatures (below ~225 °C), but active at higher temperatures [11].

Mn-based composite oxides possess excellent redox properties due to their various valence state, which are a benefit to enhance the process of NO oxidation to NO_2. The formation of NO_2 from NO oxidation is considered as a key factor in low-temperature activities because a certain concentration of NO_2 gives an enhancement of the “Fast SCR” reaction at low temperatures. Chen et al. [12] proposed that the redox cycle between $Cr^{5+} + 2Mn^{3+} \leftrightarrow Cr^{3+} + 2Mn^{4+}$ promoted the oxidization of NO to NO_2 at low temperatures. Liu et al. [13] reported that an urchin-like $MnCrO_x$ catalyst possessed good NH_3-SCR activity in the temperature range of 150–350 °C and improved SO_2 resistance.

Gao et al. [14] discovered that $CoMnO_x$ showed high NH_3-SCR activity at low temperatures and delayed the trend of SO_2 poisoning. Zhao et al. [15] found that a lamellar $CoMnO_x$ composite oxide could provide more Lewis acid sites and surface oxygen species than those of $CoMnO_x$ nanoparticles. Wang et al. [16] reported that ballflower-like $CoMnO_x$ catalyst

exhibited good SCR activity and N_2 selectivity in the temperature range of 150–350 °C, showing a certain amount of SO_2 resistance and durability.

The doped component was usually considered to give a promotion of surface lattice oxygen species. Sun et al. [17] investigated the NH_3-SCR activity over the Nb-doped Mn/TiO_2 catalysts with the optimum Nb/Mn molar ratio of 0.12. Rare earth elements were also used in the modifications. Liu et al. [18] and Xu et al. [19] investigated the effect of the introduction of Sm to Mn-TiO_x catalysts. The introduced Sm could improve the dispersion of manganese oxide on the surface of the catalysts, resulting in increases in surface area, the amount of weak Lewis acid sites and surface oxygen.

Among these catalysts, spinel-type materials containing manganese attracted interest in SCR due to their special spatial structures and physical-chemical properties. Gao et al. [20] reported that a Zr^{4+} cation doped $MnCr_2O_4$ spinel, the zirconium incorporated in the crystal of $MnCr_2O_4$ produced higher levels of beneficial Mn^{3+}, Mn^{4+} and Cr^{5+} species, and showed an increase in the acidity and redox ability.

However, these catalysts are very sensitive and exhibit unsatisfactory N_2 selectivity [21]. The stability in the presence of SO_2 and H_2O in the flue gas is still a problem for MnO_2-based catalysts.

3.3. CeO_2-Based Catalysts

He et al. [22][23] reported that the crystal structure, crystallite size and catalytic NH_3-SCR activity over the CeO_2-based catalysts presented a regular change with the increase in CeO_2 concentration. Particularly, the CeO_2-TiO_2 (1:1 in weight) catalyst with an amorphous structure showed a higher BET surface area and a stronger surface acidity than other samples. Meanwhile, favorable Ce^{3+} and the surface-adsorbed oxygen benefited the adsorption of NO_x and NH_3 molecules, which could enhance NH_3-SCR activity.

In the past years, tungsten or molybdenum addition in ceria-based catalysts was paid some attention. Jiang et al. [24] demonstrated that the introduction of WO_3 could improve SCR activity over the $CeWTiO_x$ catalysts due to the enhanced dispersion of Ce species over TiO_2 and the amount of Ce^{3+} and chemisorbed oxygen. Li et al. [25] investigated the adsorption and reactivity of NH_3 and NO over the $CeWTiO_x$ catalyst, showing that over 90% of NO conversion can be obtained in the temperature range of 250–500 °C. Liu et al. [26] reported that the WO_3/TiO_2@CeO_2 core–shell catalyst present a synergistic effect of redox properties and acidity, which is in favor of the excellent NH_3-SCR activity and better SO_2 resistance. Kim et al. [27] found monomeric W in CeO_2/TiO_2 catalyst enhance the SCR reaction activity at low temperatures due to the increased NO adsorption and the formation of unstable NO_x adsorption species. Dong et al. [28] presented that the coverage of MoO_3 weakened the adsorption of nitrate species over the CeO_2-TiO_2 catalyst, giving an increase in the number of Brønsted acid sites. For the CeO_2-based catalyst, cerium sulfate, which is formed in reaction with SO_2 in the flue gas during the SCR process at high temperatures, has attracted wide attention. Fan et al. [29] showed that NH_3-SCR reaction over CeO_2/TiO_2-ZrO_2-SO_4^{2-} mainly followed the L–H mechanism at a low temperature (250 °C) and the E–R mechanism at 350 °C.

Generally, for the limitation of sulfate formation and low temperature SCR performance, CeO_2-based SCR catalyst does not seem an optimal choice for NO_x elimination under low-temperature conditions at present.

3.4. MnO_2-CeO_2 Catalysts

Rare-earth metal oxides, such as Ce, have been frequently adopted to modify MnO_x as an efficient low-temperature NH_3-SCR catalyst due to their incomplete 4f and empty 5d orbitals [30]. Leng et al. [31] synthesized $MnCeTiO_x$ catalysts and compared the NH_3-SCR activity over the samples with different Mn/Ce mol ratios in the low-temperature range. The results showed that the low-temperature SCR activity over $MnCeTiO_x$ compositions was greatly improved due to the incorporation of Mn, and the best performance (~100% NO conversion and above 90% N_2 yields) across the temperature range of 175–400 °C at GHSV of 80,000 h^{-1}.

In the published lectures, composite transition metal oxides usually showed a higher activity than single oxide materials. Zhang et al. [32] demonstrated the enhanced electron mobility effect that originated from MnO_x and CeO_x, which enhanced low-temperature deNO_x efficiency. Compared to the single composition of CeO_2, MnO_x could increase the pore volume and pore diameter, and enhance the adsorption of NO and NH_3 as well as in the concentrations of Ce^{3+} on the CeO_2-MnO_x catalyst, which is beneficial to increase the redox properties [33].

Yang et al. [34] studied SCR activity over the activated carbon supported Mn-Ce oxide catalysts modified by Fe, on which ca. 90% NO conversion was obtained at 125 °C with GHSV of 12,000 h^{-1}. Zhu et al. [35] synthesized a 3D-structured MnOx-CeO_2/reduced graphene oxide, giving a NO_x conversion of 99% at 220 °C with GHSV of 30,000 h^{-1}.

3.5. Zeolite SCR Catalysts

Ion-exchanged zeolite catalysts with small pores have been accepted as optimum SCR catalysts in NO_x elimination from diesel engine exhaust. Among them, copper or iron exchanged zeolites with a chabazite (CHA) structure, such as Cu/SAPO-34 and Cu/SSZ-13, have received significant attention due to their excellent SCR performance, wide temperature window and thermal stability in harsh conditions [36]. Cu-SSZ-13 exhibits excellent SCR activity (>80% NO conversion) and N_2 selectivity in a wide temperature range of 150−450 °C [37]. Cu/SAPO-34 prepared by a hard-template method using $CaCO_3$ as template present NO_x convention above 90% at 170–480 °C, even introducing 10% H_2O [38]. A heterobimetallic FeCu-SSZ-13 zeolite with high crystallinity was prepared by an economic and sustainable one-pot synthesis strategy, which presents a wide reaction temperature window, excellent hydrothermal stability, high H_2O and SO_2 tolerance, and good gaseous hourly space velocity flexibility [39].

Zeolite catalysts for SCR has been developed rapidly these years, offering a great contribution to abate the NO_x reduction. However, they may be not the optimum choice for NO_x elimination in stationary sources due to the limitations of cost and synthesis strategy.

References

1. Wang, X.W.; Li, L.L.; Sun, J.F.; Wan, H.Q.; Tang, C.J.; Gao, F.; Dong, L. Analysis of NOx emission and control in China and research progress in denitration catalysts. Ind. Catal. 2019, 27, 1–23.
2. Guo, K.; Ji, J.W.; Song, W.; Sun, J.F.; Tang, C.J.; Dong, L. Conquering ammonium bisulfate poison over low-temperature NH3-SCR catalysts: A critical review. Appl. Catal. B 2021, 297, 120388.
3. Devaiah, D.; Padmanabha, R.E.; Benjaram, M.R.; Panagiotis, G.S. A Review of Low Temperature NH3-SCR for Removal of NOx. Catalysts 2019, 9, 349.
4. Marberger, A.; Ferri, D.; Elsener, M.; Kröcher, O. The Significance of Lewis Acid Sites for the Selective Catalytic Reduction of Nitric Oxide on Vanadium-Based Catalysts. Angew. Chem. Int. Ed. 2016, 55, 11989–11994.
5. Chao, J.D.; He, H.; Song, L.Y.; Fang, Y.J.; Liang, Q.M.; Zhang, G.Z.; Qiu, W.G.; Zhang, R. Promotional Effect of Pr-Doping on the NH3-SCR Activity over the V2O5-MoO3/TiO2 Catalyst. Chem. J. Chin. Univ. 2015, 36, 523–530.
6. Liang, Q.M.; Li, J.; He, H.; Yue, T.; Tong, L. Effects of SO2 and H2O on low-temperature NO conversion over F-V2O5-WO3/TiO2 catalysts. J. Environ. Sci. 2020, 90, 253–261.
7. Wu, R.; Li, L.C.; Zhang, N.Q.; He, J.D.; Song, L.Y.; Zhang, G.Z.; Zhang, Z.L.; He, H. Enhancement of low-temperature NH3-SCR catalytic activity and H2O & SO2 resistance over commercial V2O5-MoO3/TiO2 catalyst by high shear-induced doping of expanded graphite. Catal. Today 2021, 376, 302–310.
8. Zhang, D.J.; Ma, Z.R.; Wang, B.D.; Sun, Q.; Xu, W.Q.; Zhu, T. Effects of MOx (M=Mn, Cu, Sb, La) on V-Mo-Ce/Ti selective catalytic reduction catalysts. J. Rare. Earths. 2020, 38, 157–166.
9. Liang, Q.M.; Li, J.; Yue, T. Promotional effect of CeO2 on low-temperature selective catalytic reduction of NO by NH3 over V2O5-WO3/TiO2 catalysts. Environ. Technol. Inno. 2021, 21, 101209.
10. Gao, F.Y.; Tang, X.L.; Yi, H.H.; Zhao, S.Z.; Li, C.L.; Li, J.Y.; Shi, Y.R.; Meng, X.M. A Review on selective catalytic reduction of NOx by NH3 over Mn–based catalysts at low temperatures: Catalysts, mechanisms, kinetics and DFT calculations. Catalysts 2017, 7, 199.
11. Kijlstra, W.S.; Brands, D.S.; Smit, H.I.; Poels, E.K.; Bliek, A. Mechanism of the Selective Catalytic Reduction of NO with NH3 over MnOx/Al2O3. J. Catal. 1997, 171, 219–230.
12. Chen, Z.H.; Yang, Q.; Li, H.; Li, X.H.; Wang, L.F.; Chi Tsang, S. Cr-MnOx Mixed-Oxide Catalysts for Selective Catalytic Reduction of NOx with NH3 at Low Temperature. J. Catal. 2010, 276, 56–65.
13. Liu, Y.Z.; Guo, R.T.; Duan, C.P.; Wu, G.L.; Miao, Y.F.; Gu, J.W.; Pan, W.G. A highly effective urchin-like MnCrOx catalyst for the selective catalytic reduction of NOx with NH3. Fuel 2020, 271, 117667.
14. Gao, F.Y.; Tang, X.L.; Yi, H.H.; Zhao, S.Z.; Wang, J.G.; Shi, Y.R.; Meng, X.M. Novel Co-or Ni-Mn binary oxide catalysts with hydroxyl groups for NH3–SCR of NOx at low temperature. Appl. Surf. Sci. 2018, 443, 103–113.
15. Zhao, Q.; Chen, B.B.; Crocker, M.; Shi, C. Insights into the structure-activity relationships of highly efficient CoMn oxides for the low temperature NH3-SCR of NOx. Appl. Catal. B 2020, 277, 119215.
16. Wang, Z.Y.; Guo, R.T.; Shi, X.; Liu, X.Y.; Qin, H.; Liu, Y.Z.; Duan, C.P.; Guo, D.Y.; Pan, W.G. The superior performance of CoMnOx catalyst with ball-flowerlike structure for low-temperature selective catalytic reduction of NOx by NH3. Chem. Eng. J. 2020, 381, 122753.

17. Sun, P.; Huang, S.X.; Guo, R.T.; Li, M.Y.; Liu, S.M.; Pan, W.G.; Fu, Z.G.; Liu, S.W.; Sun, X.; Liu, J. The enhanced SCR performance and SO2 resistance of Mn/TiO2 catalyst by the modification with Nb: A mechanistic study. Appl. Surf. Sci. 2018, 447, 479–488.
18. Liu, L.J.; Xu, K.; Su, S.; He, L.M.; Qing, M.X.; Chi, H.Y.; Liu, T.; Hu, S.; Wang, Y.; Xiang, J. Efficient Sm modified Mn/TiO2 catalysts for selective catalytic reduction of NO with NH3 at low temperature. Appl. Catal. A Gen. 2020, 592, 117413.
19. Xu, Q.; Fang, Z.L.; Chen, Y.Y.; Guo, Y.L.; Guo, Y.; Wang, L.; Wang, Y.S.; Zhang, J.S.; Zhan, W.C. Titania-Samarium-Manganese Composite Oxide for the Low Temperature Selective Catalytic Reduction of NO with NH3. Environ. Sci. Technol. 2020, 54, 2530–2538.
20. Gao, E.H.; Sun, G.J.; Zhang, W.; Bernards, M.T.; He, Y.; Pan, H.; Shi, Y. Surface lattice oxygen activation via Zr4+ Cations substituting on A2+ sites of MnCr2O4 forming ZrxMn1-xCr2O4 catalysts for enhanced NH3-SCR performance. Chem. Eng. J. 2020, 380, 122397.
21. Yu, J.; Guo, F.; Wang, Y.L.; Zhu, J.H.; Liu, Y.Y.; Su, F.B.; Gao, S.Q.; Xu, G.W. Sulfur poisoning resistant mesoporous Mn-base catalyst for low-temperature SCR of NO with NH3. Appl. Catal. B 2010, 95, 160–168.
22. Sun, X.L.; He, H.; Su, Y.C.; Yan, J.F.; Song, L.Y.; Qiu, W.G. CeO2-TiO2 Mixed Oxides Catalysts for Selective Catalytic Reduction of NOx with NH3: Structure-properties Relationships. Chem. J. Chin. Univ. 2017, 38, 814–822.
23. Cheng, J.; Song, L.Y.; Wu, R.; Li, S.N.; Sun, Y.M.; Zhu, H.T.; Qiu, W.G.; He, H. Promoting effect of microwave irradiation on CeO2-TiO2 catalyst for selective catalytic reduction of NO by NH3. J. Rare. Earths. 2020, 38, 59–69.
24. Jiang, Y.; Xing, Z.M.; Wang, X.C.; Huang, S.B.; Wang, X.W.; Liu, Q.Y. Activity and characterization of a Ce–W–Ti oxide catalyst prepared by a single step sol–gel method for selective catalytic reduction of NO with NH3. Fuel 2015, 151, 124–129.
25. Li, X.; Li, J.H.; Peng, Y.; Chang, H.Z.; Zhang, T.; Zhao, S.; Si, W.Z.; Hao, J.M. Mechanism of Arsenic Poisoning on SCR Catalyst of CeW/Ti and its Novel Efficient Regeneration Method with Hydrogen. Appl. Catal. B 2016, 184, 246–257.
26. Liu, S.S.; Wang, H.; Wei, Y.; Zhang, R.D. Core-shell structure effect on CeO2 and TiO2 supported WO3 for the NH3-SCR process. Mol. Catal. 2020, 485, 110822.
27. Kim, G.J.; Lee, S.H.; Nam, K.B.; Hong, S.C. A study on the structure of tungsten by the addition of ceria: Effect of monomeric structure over W/Ce/TiO2 catalyst on the SCR reaction. Appl. Surf. Sci. 2020, 507, 145064.
28. Li, L.L.; Li, P.X.; Tan, W.; Ma, K.L.; Zou, W.X.; Tang, C.J.; Dong, L. Enhanced low-temperature NH3-SCR performance of CeTiOx catalyst via surface Mo modification. Chin. J. Catal. 2020, 41, 364–373.
29. Fan, J.; Ning, P.; Song, Z.X.; Liu, X.; Wang, L.Y.; Wang, J.; Wang, H.M.; Long, K.X.; Zhang, Q.L. Mechanistic Aspects of NH3-SCR Reaction over CeO2/TiO2-ZrO2-SO42− Catalyst: In Situ DRIFTS Investigation. Chem. Eng. J. 2018, 334, 855–863.
30. Kwon, D.W.; Nam, K.B.; Hong, S.C. The role of ceria on the activity and SO2 resistance of catalysts for the selective catalytic reduction of NOx by NH3. Appl. Catal. B 2015, 166–167, 37–44.
31. Leng, X.S.; Zhang, Z.P.; Li, Y.S.; Zhang, T.R.; Ma, S.B.; Yuan, F.L.; Niu, X.N.; Zhu, Y.J. Excellent low temperature NH3-SCR activity over MnaCe0.3TiOx (a = 0.1–0.3) oxides: Influence of Mn addition. Fuel Process. Technol. 2018, 181, 33–43.
32. Zhang, X.L.; Zhang, X.C.; Yang, X.J.; Chen, Y.Z.; Hu, X.R.; Wu, X.P. CeMn/TiO2 catalysts prepared by different methods for enhanced low-temperature NH3-SCR catalytic performance. Chem. Eng. Sci. 2021, 238, 116588.
33. Yang, C.; Yang, J.; Jiao, Q.R.; Zhao, D.; Zhang, Y.X.; Liu, L.; Hu, G.; Li, J.L. Promotion effect and mechanism of MnOx doped CeO2 nano-catalyst for NH3-SCR. Ceram. Int. 2020, 46, 4394–4401.
34. Yang, J.; Ren, S.; Zhang, T.S.; Su, Z.H.; Long, H.M.; Kong, M.; Yao, L. Iron doped effects on active sites formation over activated carbon supported Mn-Ce oxide catalysts for low-temperature SCR of NO. Chem. Eng. J. 2020, 379, 122398.
35. Zhu, K.M.; Yan, W.Q.; Liu, S.J.; Wu, X.D.; Cui, S.; Shen, X.D. One-step hydrothermal synthesis of MnOx-CeO2/reduced graphene oxide composite aerogels for low temperature selective catalytic reduction of NOx. Appl. Surf. Sci. 2020, 508, 145024.
36. Zhang, R.D.; Liu, N.; Lei, Z.G.; Chen, B.H. Selective Transformation of Various Nitrogen-Containing Exhaust Gases toward N2 over Zeolite Catalysts. Chem. Rev. 2016, 116, 3658–3721.
37. Cui, Y.R.; Wang, Y.L.; Walter, E.D.; Szanyi, J.; Wang, Y.; Gao, F. Influences of Na+ co-cation on the structure and performance of Cu/SSZ-13 selective catalytic reduction catalysts. Catal. Today 2020, 339, 233–240.
38. Li, R.; Wang, P.Q.; Ma, S.B.; Yuan, F.L.; Li, Z.B.; Zhu, Y.J. Excellent selective catalytic reduction of NOx by NH3 over Cu/SAPO-34 with hierarchical pore structure. Chem. Eng. J. 2020, 379, 122376.

39. Yue, Y.Y.; Liu, B.; Qin, P.; Lv, N.G.; Wang, T.H.; Bi, X.T.; Zhu, H.B.; Yuan, P.; Bai, Z.S.; Cui, Q.Y.; et al. One-pot synthesis of FeCu-SSZ-13 zeolite with superior performance in selective catalytic reduction of NO by NH3 from natural aluminosilicates. Chem. Eng. J. 2020, 398, 125515.