



Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

journal homepage: www.elsevier.com/locate/CJChE

Review

Research progress in the SO₂ resistance of the catalysts for selective catalytic reduction of NO_x☆

Minhua Zhang, Baojuan Huang, Haoxi Jiang, Yifei Chen *

Key Laboratory for Green Chemical Technology of Ministry of Education, R&D Center for Petrochemical Technology, Tianjin University, Tianjin 300072, China
 Collaborative Innovation Center of Chemical Science and Engineering, Tianjin 300072, China



ARTICLE INFO

Article history:

Received 28 October 2016

Received in revised form 1 March 2017

Accepted 12 March 2017

Available online 25 March 2017

Keywords:

Words Selective catalytic reduction (SCR)

SO₂ resistance

catalyst

NO_x

ABSTRACT

The selective catalytic reduction (SCR) of NO_x with NH₃ has been proven to be an efficient technology for NO_x conversion to N₂. However, the catalysts used for SCR usually suffer from the problem of sulfur poisoning which seriously limits their practical application. This review summarized sulfur poisoning mechanisms of various SCR deNO_x catalysts and strategies to reduce deactivation caused by SO₂ such as doping metals, controlling the structures and morphologies of the catalysts, and selecting appropriate supports. The methods and procedures of catalysts preparation and the reaction conditions also have effect on SO₂-resistance of the catalysts. Several novel catalyst systems that exhibited good SO₂ resistance are also introduced. This paper could provide guidance for the development of highly efficient sulfur-tolerant deNO_x catalysts.

© 2017 The Chemical Industry and Engineering Society of China, and Chemical Industry Press. All rights reserved.

1. Introduction

With the growing environmental awareness, the control and prevention of air pollution have attracted extensive attentions in the world. Numerous countries have released stringent regulations to minimize NO_x emissions during the past years. As a major atmospheric pollutant, most NO_x (~95%) derives from transportation (49%) and power plants (46%) [1]. To date, many methods have been used to reduce the emission of NO_x, among which selective catalytic reduction (SCR) of NO_x stands out as one of the most mature and widely applied post-combustion abatement technologies [2]. SCR is a process using the reductant such as ammonia (NH₃) to react with NO_x to produce nitrogen and water in the presence of oxygen [3], and in which technology the suitable catalyst plays an important role. V₂O₅/TiO₂ catalyst with WO₃ or MoO₃ as promoter is a typical and efficient catalyst for SCR process and has already been commercialized [1,2,4]. However, these catalysts possess many disadvantages, one of which is SO₂ oxidation to SO₃. In real operating conditions, SO₂, excess O₂, and vapor are typical impurities present both in the flue gas of power plants and the exhaust gas of vehicles. Among these species, SO₂ usually plays a detrimental role on the performance of deNO_x catalysts and significantly limits their

industrial applications. Accordingly, numerous studies have been conducted in the past few years to develop SO₂-tolerant or resistant catalysts.

This review article highlights the recent progress in SO₂-tolerant or resistant catalysts of SCR. The paper mainly focuses on the sulfur poisoning mechanism and strategies to reduce sulfur poisoning. In addition, some novel catalysts with good SO₂ resistance are also mentioned. This review is hoped to guide the design of proper catalysts for SCR with enhanced SO₂-tolerance.

2. The Sulfur Poisoning Mechanism

2.1. Metal oxide catalysts

In recent years, Mn-based catalysts have been extensively investigated due to their excellent low-temperature activity for the NH₃-SCR reaction. However, Mn-based catalysts are usually prone to deactivation by SO₂ present in flue gas. Fe–Mn based transition metal oxides are highly active for the low-temperature NH₃-SCR reaction [4]. However, the NO conversion on the catalyst decreased significantly to 8%–23% when 1000 ppm SO₂ was added to the feed gas. Mn–Zr mixed oxide catalysts could be poisoned by SO₂ irreversibly [5]. NO conversion over the V₂O₅–WO₃/CeO₂–TiO₂ catalyst also decreased in the presence of 100 ppm SO₂ over the whole temperature window [6].

In general, about 0.05%–0.3% SO₂ that exists in the stack gases could have a serious poisoning effect on SCR catalytic activity [7]. From a practical point of view, it is very important to understand the effect of SO₂ on the activity and structure of SCR catalysts, and finally elucidate the

☆ Supported by the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry, and the National Natural Science Foundation of China (21506150).

* Corresponding author.

E-mail address: yfchen@tju.edu.cn (Y.F. Chen).

deactivation mechanisms for the sake of industrial applications. Many investigations have been carried out to clarify the deactivation mechanisms on different SCR catalysts.

Based on different catalytic systems, various deactivation mechanisms have been reported and few consensus have been reached. Hence, the discussions of the deactivation mechanisms for specific deNO_x catalysts are of great significance. Pan *et al.* [7] studied the effect of SO₂ on the performance of manganese oxides supported on multi-walled carbon nanotubes (MnO_x/MWCNTs) for low-temperature NH₃-SCR, and found that SO₂ led to the irreversible deactivation of the catalyst. Activity test and characterization results indicated that the main cause of catalyst deactivation was the sulfation of the active center atoms. The formation and deposition of ammonium sulfates which clogged the pore channels and the competitive adsorption between NO and SO₂ partially contribute to the deactivation of the catalyst. Yamamoto *et al.* [8] investigated the effect of SO₂ gas on the activity of the photo-assisted selective catalytic reduction of NO with ammonia over a TiO₂ photocatalyst. It revealed that the deactivation of the catalyst was due to the deposition of the ammonium sulfate species which reduced the specific surface area and changed the pore structure. Based on the designed TPDC (temperature programmed decomposition) and TPSR (temperature-programmed surface reaction) experiments, Ma *et al.* [9] proposed a sulfur poisoning mechanism on V-Ti based catalysts which was illustrated in Fig. 1. SO₂ had little influence on the catalytic activities of VTi and VWTi catalysts, which was due to the fact that TiO₂ can act as a sacrificial agent to protect Vⁿ⁺ sites from sulfation and W modification inhibited sulfation of TiO₂. However, compared with TiO₂, CeO₂ was preferential to be sulfated to form sulfates, which could disrupt the redox cycle between Ce³⁺ and Ce⁴⁺ and break the V–O–Ce bridges. Moreover, the generation of SO₃ was greatly promoted on CeO₂-modified catalyst. All of these caused the sulfation of ceria and the deactivation of V1CeWTi. Li *et al.* [10] systematically studied the roles of SO₂ in the NH₃-SCR of NO over different V₂O₅/AC (activated carbon) catalysts and suggested that a tiny amount of VOSO₄ produced from SO₂ and V₂O₅ might result in a sharp decrease of NO conversion. Pore blockage was proved to have little influence on the SCR activity of V₂O₅/AC at temperatures of 200 °C and higher.

As a potential candidate for SCR of NO_x with NH₃ in the medium temperature range, iron titanate catalyst (FeTiO_x) has been studied by many researchers. Liu *et al.* [11] investigated the influence of SO₂ on the activity of the catalyst and found out that NO_x adsorption

capability on FeTiO_x catalyst was strongly inhibited by the sulfation process. The active nitrate species could not continuously form on sulfated catalyst surface. This led to the loss of the activity at low temperatures. Mn substitution could obviously enhance the SCR activity of FeTiO_x catalyst at low temperatures [12]. However, it also resulted in the reduced SO₂-resistant ability. As shown in Fig. 2 (in red), the SCR reaction pathway was cut off because the formation of surface nitrate species was intensely and irreversibly inhibited by the formation of sulfate species [12].

In general, the sulfur poisoning mechanisms could be different for different metal oxide catalytic systems. The main causes are as follows: sulfation of the active center atoms, formation and deposition of ammonium sulfates on the surface of catalysts clogging the pore channels, and the competitive adsorption between SO₂ and NO_x.

2.2. Zeolite-based catalysts

Zeolite-based catalysts emerged as one of the most important SCR catalysts in recent years due to a number of beneficial characteristics such as their unparalleled hydrothermal stability and high adaptability to high space velocity [13–16]. Sulfur tolerance of metal-exchanged zeolite catalysts has also attracted much attention [17,18]. Sulfur poisoning of the Cu-zeolite catalyst can occur via different mechanisms with different forms of feed sulfur and different temperature ranges [19]. As shown in Fig. 3, at lower temperatures, sulfur poisoning was mainly due to the indiscriminate adsorption of SO_x (SO₂ and SO₃) species on Cu sites. At higher temperatures, SO₃ was revealed to have a more significant impact on the activity of the catalyst since the poisoning was irreversible. An investigation into the impact of sulfur oxides on the activity of Cu-SAPO-34 had been conducted by Wijayanti and co-workers [20] to clarify the deactivation mechanism induced by sulfur. The H₂-TPR (temperature-programmed desorption) data (Fig. 4) confirmed that sulfates or other surface SO₂ groups were formed during sulfur treatment and there were less available copper sites that could undergo the redox cycle for the sulfated sample compared to the fresh sample. This indicated that pore blockage could be the main reason for the deactivation. Fe-ZSM-5 was also reported to be sensitive to SO₂ presence [21]. Ma and coworkers proved that the competitive adsorption between SO₂ and NO_x during the SCR reaction led to the decrease NO_x conversion on nanosheet Fe-ZSM-5 catalysts [22].

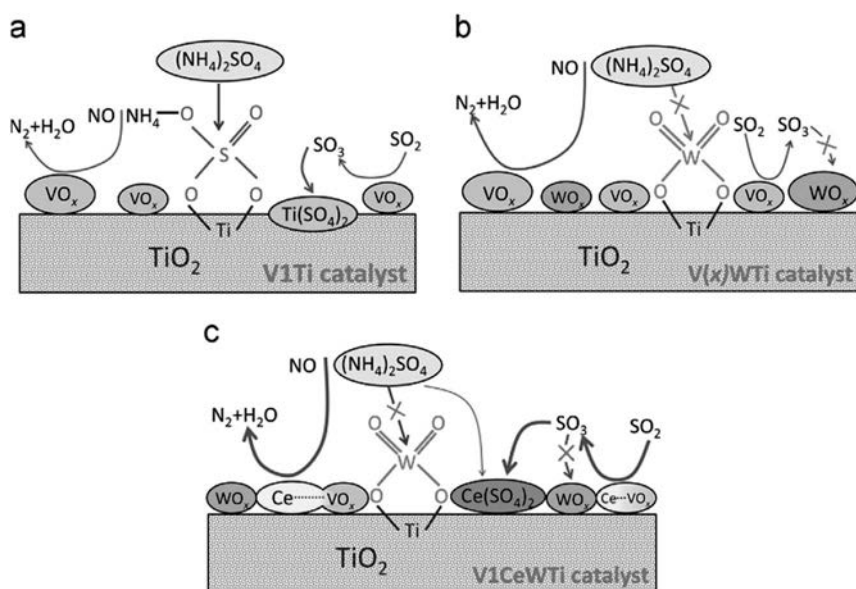


Fig. 1. The SO₂ deactivation mechanism over different catalysts. (a) VTi; (b) V(x)WTi; (c) V1CeWTi [9].

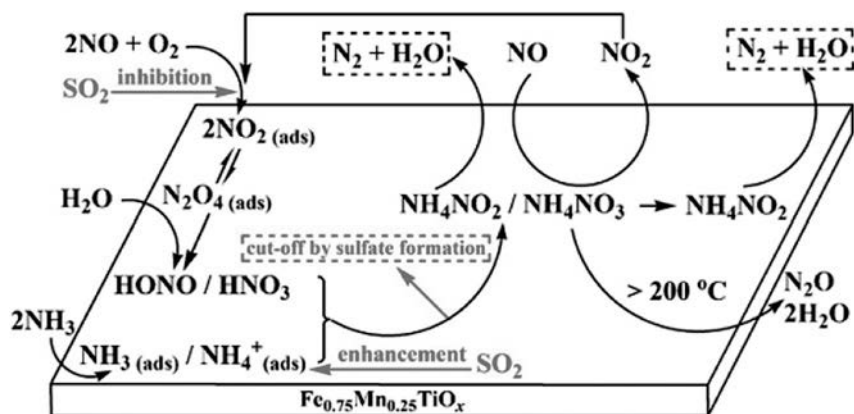


Fig. 2. Proposed mechanism of the NH_3 -SCR reaction over Mn substituted iron titanate catalyst at low temperatures and the influence of SO_2 on the reaction pathway (as shown in red) [12].

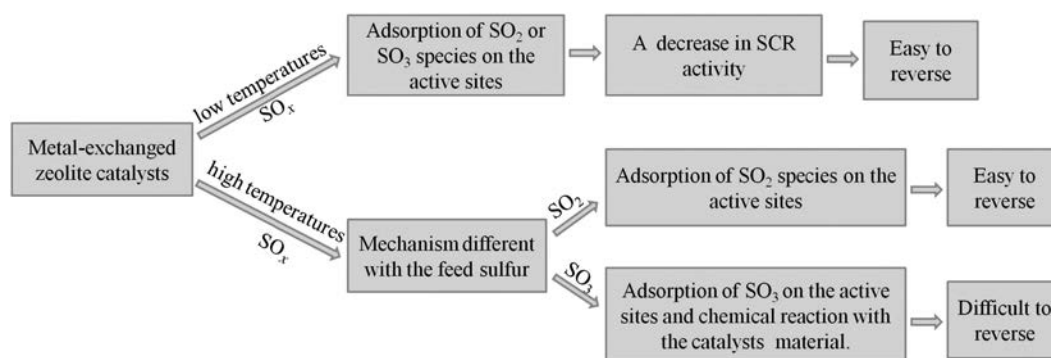


Fig. 3. Sulfur poisoning mechanisms of Cu-zeolite catalysts with different forms of feed sulfur and different temperature ranges.

3. Strategies to Reduce SO_2 Poisoning and the Corresponding Mechanisms

The SO_2 resistance capability of the catalysts in the SCR process is the key factor for its industrialization. Here we summarize several strategies used to reduce the SO_2 poisoning as well as the corresponding mechanisms.

3.1. Metal modification

Modifying catalysts with a tertiary metal is a common method to solve the problem of sulfur poisoning. Transition metals such as Ce,

Sn, Fe, W, Mo, and Co have been used as modifiers with the aim of preparing catalysts with good resistance to SO_2 .

Cerium is a common rare earth metal and has been discussed vastly due to its wide applications in catalysis. As an oxygen reservoir, cerium can store and release oxygen via the redox cycle shifted between Ce^{4+} and Ce^{3+} . CeO_2 showed the excellent SCR activity in the presence of SO_2 at $300\text{--}500^\circ\text{C}$ [23]. It was proposed that sulfation of CeO_2 could promote SCR activity, because the formation of sulfated CeO_2 increased the adsorption of NH_3 and inhibited the catalytic oxidation of NH_3 to NO at the same time [23]. Xiao *et al.* [24] studied the effect of SO_2 on NO reduction over Ce/TiO_2 by steady state kinetic study. Similarly, SO_2 showed a promotion on NO reduction over Ce/TiO_2 at higher temperatures. The mechanism was similar to that mentioned above.

Cerium oxide doping can obviously inhibit the SO_2 -poisoning of the active manganese oxide species, which is widely believed to be one of the major reasons for the deactivation of manganese-based catalysts [25]. In the presence of SO_2 , ammonium salts usually formed and decreased SCR activities through pore blocking. Wang and coworkers [26] used activated carbon honey comb support MnO_x (Mn/ACH) and $\text{CeO}_2\text{--MnO}_x$ (CeMn/ACH) as catalysts for NH_3 -SCR. Compared with Mn/ACH , CeMn/ACH catalyst exhibited better resistance to SO_2 poisoning. The addition of CeO_2 inhibited the formation of ammonium sulfates, thus improving the SO_2 resistance performance. MnO_x supported palygorskite (MnO_x/PG) catalyst doped with CeO_2 was found to improve its SO_2 resistance by enhancing the stability of the active species via the reduction of manganese sulfate [27]. Wang and coworkers [28] also found that the SO_2 resistance could be greatly enhanced for Ce modified MnO_x . The reason was that the formation of $\text{Mn}(\text{SO}_4)_x$ was prevented and the deposition of $(\text{NH}_4)_2\text{SO}_4$ and NH_4HSO_4 was significantly inhibited by the doping of Ce. The mechanism could also apply to Ce modified Mn/TiO_2 catalyst for low-

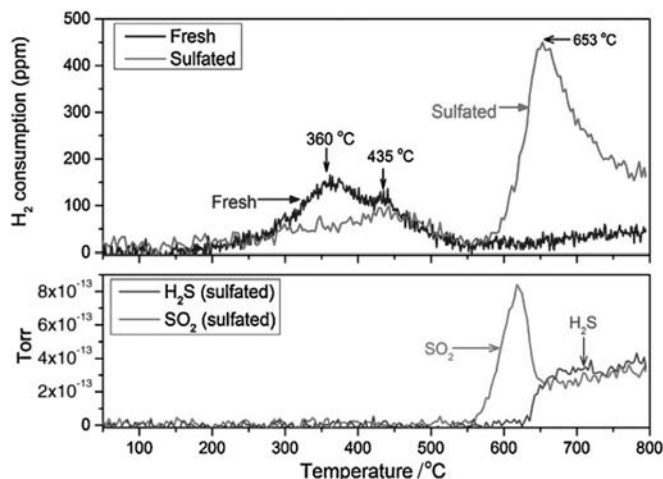


Fig. 4. H_2 -TPR of fresh and sulfated crushed monolith of Cu-SAPO-34 [20].

temperature NH_3 -SCR in the presence of SO_2 [29,30]. The addition of Ce could improve the SO_2 resistance for $\text{Sb-V}_2\text{O}_5/\text{TiO}_2$ catalyst [31,32]. Kwon and coworkers [32] investigated the influence of Ce on the catalytic activity of V/Sb/Ce/Ti in the presence of SO_2 . They proposed that Ce addition to V/Sb/Ti could suppress the formation of NH_4HSO_4 due to the formation of $\text{Ce}_2(\text{SO}_4)_3$, and thus show high resistance to SO_2 . Furthermore, Ce modification could enhance the SO_2 resistance of V-based catalyst [33].

Ce modification was also found to be an effective method to enhance the SO_2 resistance of zeolite-based catalysts. Modifying Cu/ZSM-5 catalyst with Ce greatly improved the SO_2 resistance since it could inhibit the deposition of CuSO_4 [34]. A similar result was also obtained by Lai *et al.* [35]. They revealed that the presence of Ce in the Cu/ZSM-5 catalyst facilitated SO_2 deposition on the Ce site to form a stable Ce sulfate, thus inhibiting the formation of ammonium sulfate and copper sulfate on the surface in the SCR process, and finally improved the sulfur tolerance of the Ce-Cu/ZSM-5 catalyst. Ce doping Fe/β (β is zeolite with $\text{SiO}_2/\text{Al}_2\text{O}_3 = 40$) catalyst was reported to possess outstanding SO_2 anti-poisoning ability, due to that the addition of Ce can reduce the formation of inactive iron sulfate species and then improve SO_2 resistance [36].

Numerous studies have been conducted to investigate Fe-doped catalysts for NH_3 -SCR. According to literatures, Fe doping can significantly enhanced the resistance of SO_2 of the Ce-based [37–39], Mn-based [1,40,41] and Cu-based [42] catalysts. As shown in Fig. 5, SO_2 resistance of Ce/TiO_2 was significantly enhanced by Fe doping [38]. The three dimensional ordered macroporous (3DOM) $\text{Ce}_{0.75}\text{Zr}_{0.2}\text{M}_{0.05}\text{O}_{2-\delta}$ ($M = \text{Fe, Co, Mn, Cu}$) were synthesized as efficient catalysts for SCR of NO_x with NH_3 . The SO_2 tolerance test of the catalysts showed that $\text{Ce}_{0.75}\text{Zr}_{0.2}\text{Fe}_{0.05}\text{O}_2$ exhibited the best sulfur resistance performance [39]. Gao *et al.* [43] prepared a $\text{V}_2\text{O}_5\text{-WO}_3/\text{Fe}_2\text{O}_3/\text{TiO}_2$ catalyst showed better SO_2 -resistant ability compared with $\text{V}_2\text{O}_5\text{-WO}_3/\text{TiO}_2$ and could recovered its activity after cutting off SO_2 . The activity test results indicated that the SO_2 resistance of the catalyst was enhanced by the combination effect of $\text{V}_2\text{O}_5\text{-WO}_3/\text{TiO}_2$ and iron oxide. Teng and coworkers' [44] study demonstrated Fe-doped $\text{Ce-Mn/TiO}_2\text{-ZrO}_2$ significantly decreased the formation rate of sulfates and thus enhanced the SO_2 resistance. Fe-doping also greatly enhanced SO_2 resistance of Mn-Ce/TiO_2 catalyst [45]. Fang *et al.* [42] fabricated a monolith deNO_x catalyst based on 3D hierarchical foam-like $\text{Fe}_2\text{O}_3@\text{CuO}_x$. Their results indicated that the high SO_2 -tolerance was due to the fact that Fe_2O_3 prevented the generation of both ammonium sulfates and copper sulfates.

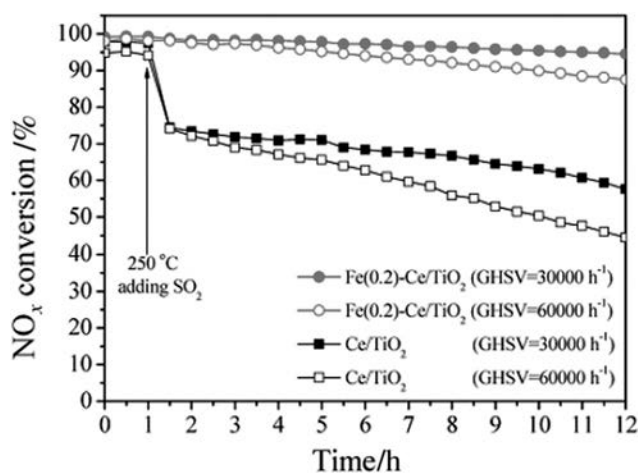


Fig. 5. NO_x conversion of Fe(0.2)-Ce/TiO_2 and Ce/TiO_2 catalysts in the presence of SO_2 at 250°C at two different GHSVs (30000 or 60000 h^{-1}). Reaction conditions: $[\text{NO}] = [\text{NH}_3] = 1000\text{ ppm}$, $[\text{O}_2] = 3\text{ vol\%}$, $[\text{SO}_2] = 500\text{ ppm}$ [38].

Sn also has been used as a modifier to prepare catalysts exhibiting remarkable resistance to SO_2 poisoning [46–52]. Chang *et al.* [47] revealed that Sn-modified $\text{MnO}_x\text{-CeO}_2$ showed remarkably improved SO_2 tolerance. Sn modification could also reduce the irreversible poisoning effect of sulfation on $\text{MnO}_x\text{-CeO}_2$ and Cr-MnO_x catalysts [48,49].

W doping could improve the SO_2 -tolerance capability which was verified by many studies [53–55]. W supported on $\text{Ce}_{0.65}\text{Zr}_{0.35}\text{O}_2$ was reported to act as an efficient catalyst for NH_3 -SCR and showed good SO_2 tolerance capability [56]. A series of $\text{WO}_x\text{-MnO}_x\text{-CeO}_2$ catalysts also exhibited relatively high resistance to SO_2 poisoning [57]. The mechanism of the promoting effect of W addition on the SO_2 -resistance was proposed. After WO_3 doping, the SO_2 oxidation activity of the catalyst was significantly suppressed. The decreased generation of SO_3 inhibited the formation of ammonium and/or metal sulfates on the acidic catalyst surface, which suggested that Ce and/or Mn sites were less affected by SO_2 . Therefore, high SO_2 resistance was achieved on these catalysts.

V modification of SCR catalysts was also investigated [58,59]. Yang [60] developed an Fe/AC (activated carbon) catalyst modified by a small amount of V_2O_5 , which achieved good SO_2 durability at low temperatures. It was found that the vanadium additive promoted the formation of sulfate species, which increased the surface acidity, and hence increased the SO_2 -tolerance.

According to literatures, TiO_2 essentially reacts with neither SO_2 nor SO_3 above 200°C . Therefore, Ti was also used as a modifier for catalysts to improve the sulfur-poisoning resistance [61]. By X-ray photoelectron spectroscopy (XPS) analysis, Xiong *et al.* [62] verified that the loss of surface Mn species on $\text{MnO}_x/\text{CeO}_2$ catalyst was inhibited by doping of Ti, which contributed to improved sulfur durability.

Zhao *et al.* [63] used different transition metals including Cu, Fe, Mn, and Co to modify V_2O_5 -based catalysts supported on TiO_2 . The results showed that the Cu modified catalyst Cu-V/TiO_2 exhibited high activity and N_2 selectivity as well as outstanding $\text{SO}_2/\text{H}_2\text{O}$ durability. Ce-Cu-Ti complex oxide catalyst also demonstrated higher SO_2 -resistant ability than Ce-Ti oxide catalyst [64]. The mechanism of the promoting effect of Cu addition on the SO_2 -resistance of Ce-Ti oxide catalyst was shown in Fig. 6 [65]. The addition of Cu could prevent Ce^{4+} reduction to Ce^{3+} because of the preferable formation of CuSO_4 . In addition, SO_2 adsorption increased the acidity of the catalyst surface. Thus, the preservation of reducibility of Ce^{4+} and the enhanced acidity resulted in the high SO_2 -resistance of Ce-Cu-Ti oxide.

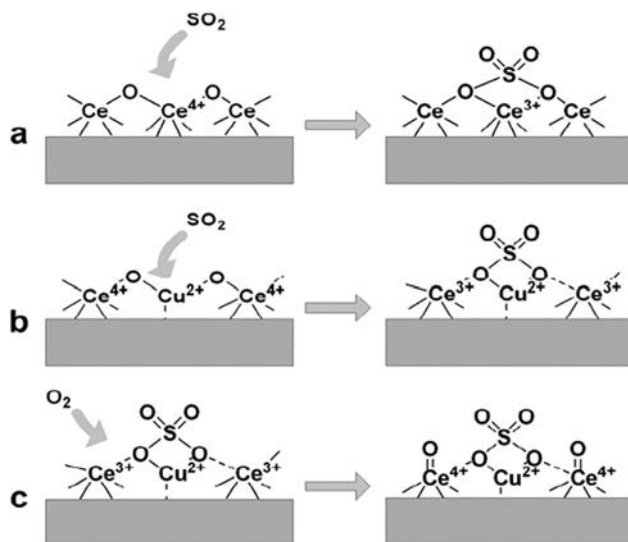


Fig. 6. Graphical description for the effect of Cu addition on the SO_2 -resistance of a Ce-Ti oxide catalyst [65].

Table 1
Metal modification of deNO_x catalysts

Catalysts	Feed composition					GHSV/h ^{−1}	T/°C	X/X ₀ ^①	Ref.
	NO _x /ppm	NH ₃ /ppm	O ₂ /%	SO ₂ /ppm	H ₂ O/%				
<i>Catalysts modified with Ce</i>									
MnCe@CNTs-R	500	500	3	100	–	10000	300	90/97	[25]
CeMn/ACH	500	500	5	300	–	1910	160	44/84	[26]
Mn/ACH								33/63	
Mn ₈ Ce ₅ /PG	600	600	3	400	–	5000	250	99/–	[27]
Mn/PG								60/–	
MnO _x –CeO ₂	600	600	5	500	–	–	160	54/86	[28]
MnO _x								38/80	
Mn–Ce/TiO ₂	1000	1000	3	100	3	–	150	84/100	[29]
Mn/TiO ₂								30/93	
CuCe/ZSM-5	1000	1100	5	15	10	30000	300	80/95	[34]
Cu/ZSM-5								75/95	
Ce ₁ –Cu ₄ /ZSM-5	500	500	5	50	2	55000	200	76/100	[35]
Cu ₄ /ZSM-5								70/100	
2%Ce–2%Fe/β	600	600	5	100	2	48000	280	78/97	[36]
2%Fe/β				100				66/97	
<i>Catalysts modified with Fe</i>									
CeO ₂ –Fe ₃ O ₄ /TiO ₂	500	500	5	200	–	25000	250	98/100	[37]
CeO ₂ /TiO ₂								41/100	
Fe(0.2)–Ce/TiO ₂	1000	1000	3	500	–	30000	250	94/98	[38]
Ce/TiO ₂								55/95	
Ce _{0.75} Zr _{0.2} Fe _{0.05} O ₂	500	500	3	200	–	20000	270	87/95	[39]
Ce _{0.8} Zr _{0.2} O ₂								61/95	
V ₂ O ₅ –WO ₃ /Fe ₂ O ₃ /TiO ₂	550	500	3	100	–	30000	320	75/97	[43]
V ₂ O ₅ –WO ₃ /TiO ₂								61/80	
Fe–Mn/TiO ₂	1000	1000	2.5	100	2.5	15000	150	85/99	[1]
Mn/TiO ₂								48/97	
Fe _{0.04} La _{0.03} Mn _{0.06} /Al ₂ O ₃	1000	1100	5	100	8	15000	260	80/97	[40]
La _{0.03} Mn _{0.06} /Al ₂ O ₃								57/91	
Mn–Fe–Ce	550	550	3	100	–	10600	200	⑤51%	[41]
Mn–Ce								⑤10%	
Fe ₂ O ₃ @CuO _x	500	500	3	250	–	20000	350	90/93	[42]
Fe–Ce–Mn/TiO ₂ –ZrO ₂	3000	3000	7	200	10	67000	140	84/96	[44]
Ce–Mn/TiO ₂ –ZrO ₂								75/93	
Fe(0.15)–Mn–Ce/TiO ₂	600	600	3	100	3	50000	180	84/96	[45]
Mn–Ce/TiO ₂								50/92	
<i>Catalysts modified with Sn</i>									
Ce2Sn1	800	800	5	200	5	50000	360	88/94	[46]
CeTi								70/90	
Sn(0.1)Mn(0.4)CeO _x	1000	1000	2	100	–	35000	250	96/99	[47]
H–Sn/CeO ₂	500	500	3	200	–	45000		78/96	[52]
H–CeO ₂								60/90	
Sn(0.1)–Mn(0.4)–Ce(0.5)–O	1000	1000	2	100	9	35000	220	94/99	[48]
Mn(0.4)–Ce(0.6)–O								56/96	
0.16-Sn/Cr–MnO ₂	500	500	3	200	8	35000	200	87/100	[49]
Cr(0.1)–MnO ₂								72/92	
Ce ₄ SnO _x -400	500	500	5	100	5	20000	300	95/100	[50]
Ce _{0.2} SnTiO _x	1000	1000	5	200	8	30000	300	88/99	[51]
Ce _{0.2} TiO _x								81/98	
<i>Catalysts modified with W</i>									
Mn/Ce/W5/Ti	200	200	8	100	8	30000	180	85/100	[53]
Mn/Ce/Ti								73/100	
10Ce/W/Ti	798	800	3	200	6	120000	270	66/80	[54]
10Ce/Ti								38/72	
CeWAlO _x	1000	1000	5	100	8		300	98/100	[55]
10%WO ₃ /Ce _{0.65} Zr _{0.35} O ₂	1000	1000	5	100	10	30000	300	83/94	[56]
Mn0.4Ce	500	500	2	60	–		150	20/93	[57]
W0.1Mn0.4Ce								60/82	
<i>Catalysts modified with V</i>									
Fe _{0.950} V _{0.050} O _x	500	500	5	100	–		300	95/97	[58]
3% Fe–0.5% V/AC	500	500	5	100	2.5	20000	200	53/99	[60]
3% Fe/AC								50/97	
<i>Catalysts modified with Co</i>									
Mn ₂ Co ₁ O _x	1000	1000	5	100	10	30000	200	92/100	[66]
CoO _x –V ₂ O ₅ –WO ₃	1000	1000	10	100	5	60000	300	88/95	[67]
V ₂ O ₅ –WO ₃								81/93	
Mn/CoCeZrO _x	600	660	6	100	3	45000	180	93/98	[68]
Mn/CeZrO _x								90/97	

(continued on next page)

Table 1 (continued)

Catalysts	Feed composition					GHSV/h ^{−1}	T/°C	X/X ₀ ^①	Ref.
	NO _x /ppm	NH ₃ /ppm	O ₂ /%	SO ₂ /ppm	H ₂ O/%				
<i>Catalysts modified with Zr</i>									
CeNb _{3.0} Zr ₂ O _x	500	500	5	100	5	50000	250	83/100	[71]
CeO ₂ –ZrO ₂ –TiO ₂	1000	1000	3	500	10	50000	350	75/100	[72]
CeO ₂ –ZrO ₂ –TiO ₂								68/100	
MnCeZrO _x	700	700	3	350	10	10000	250	86/95	[73]
MnCeO _x								86/93	
Ce _{0.85} Zr _{0.15} VO ₄	500	500	5	200	8	26000	190	62/95	[74]

^① X: NO_x conversion in the presence of SO₂.

X₀: NO_x conversion without SO₂;

X/X₀ = The ratio of NO_x conversion (X, SO₂ were added) to the initial conversion (X₀, without SO₂);

There are also studies which introduce Co [66–68], Mo [69,70], Nb [71], and Zr [72–74] as modifiers for active component or support to enhance the SO₂ resistance of the NH₃-SCR catalysts. The metal modification of the deNO_x catalysts in recent researches is summarized in Table 1.

3.2. Structure and morphology control

It has been widely accepted that the structure and morphology of the SCR catalysts have a significant influence on the activity as well as the SO₂-resistance of the catalysts [75]. The specific morphology was found to be beneficial for SO₂-resistance. Shi and coworkers [76] synthesized a hierarchically macro-mesoporous Mn/TiO₂ (HM-Mn/TiO₂) catalyst by sol-gel method and used it for NH₃-SCR of NO_x. Compared with Mn/TiO₂, HM-Mn/TiO₂ exhibited higher low-temperature activity and better SO₂-resistance (Fig. 7). The construction of hierarchical transition-metal vanadate nanosheets could also improve the SO₂ resistance [77]. The 3D (three dimensional) flower-like NiMnFe mixed oxides showed great SO₂ resistant ability [78]. The deNO_x catalysts based on hollow porous Mn_xCo_{3-x}O₄ nanocages thermally derived from nanocube-like metal-organic frameworks showed improved SO₂ resistance as compared with the traditional Mn_xCo_{3-x}O₄ nanoparticles [79].

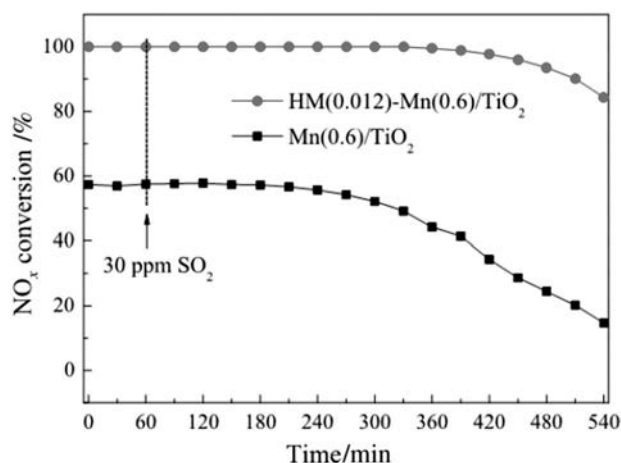


Fig. 7. Influence of SO₂ on NO_x conversion over HM-Mn/TiO₂ and Mn/TiO₂ at 120 °C. Reaction conditions: [NO] = [NH₃] = 1000 ppm, [O₂] = 3 vol%, [SO₂] = 30 ppm, N₂ balance, GHSV = 30000 h⁻¹ [76].

According to the sulfur poisoning mechanisms mentioned above, the reaction of SO₂ with metal oxides is a main issue for SO₂-induced deactivation. After that, the thermodynamically stable sulfate phases were formed and deposited on the catalysts surface, leading to the reduction in the number of chemisorption sites for NO_x. From this aspect, weakening the interaction between SO₂ and the active component seems to be an effective way to extend the SO₂ tolerance of the SCR catalysts.

With this in mind, Cai *et al.* [80] synthesized a multi-shell Fe₂O₃@MnO_x@CNTs catalyst to solve the problem that MnO_x can be easily deactivated by SO₂ in the flue gas, which has significantly hindered the application of Mn-based catalysts. The activity test results showed that SO₂ resistance was greatly enhanced due to the additional Fe₂O₃ shell. As shown in Fig. 8, the XRD pattern and TG curves indicated that less sulfate species were formed on the surface of the Fe₂O₃@MnO_x@CNTs catalyst, which provided evidence of the anti-sulfation ability of Fe₂O₃ shell. The results revealed that the over-coated Fe₂O₃ could serve as a protective layer to restrain the formation of manganese sulfate, leading to the desirable SO₂ resistance of the multi-shell catalyst. MoFe/Beta@CeO₂ core-shell catalyst using CeO₂ thin film as the shell could not only suppress the formation of sulfate species and ammonium nitrate but also restrain the generation of iron sulfate, leading to a high SO₂ tolerance [81]. Similarly, a core-shell structured meso-TiO₂@MnO_x/CNTs catalyst with the mesoporous TiO₂ layers coated on carbon nanotubes (CNTs) supported MnO_x and CeO_x nanoparticles also showed excellent SO₂-resistant ability [82]. Ce, W and Ti-containing mixed oxide catalysts were also prepared with a core-shell structure and employed as NH₃-SCR catalysts [83]. Compared with Ce-W, the TiO₂-coated Ce-W@TiO₂ catalyst exhibited increased surface W atomic abundance and superior SO₂ resistance. In contrast, Ce-Ti-W catalyst prepared via a conventional co-precipitation method exhibited inferior SO₂ resistance to Ce-W. To reduce the SO₂ poisoning of Ce-based catalysts, Zhang *et al.* [84] developed a series of inverse TiO₂/CeO₂ catalysts. Compared with the normally discussed CeO₂/TiO₂ catalyst, the inverse TiO₂/CeO₂ catalyst exhibited much better performance in the presence of 200 ppm SO₂. Yang and Chen [85] reported that SO₂ could not access into the body of HPW while NO, NH₃, and O₂ could. Inspired by this, with HPW as the protecting shell, CeO₂@HPW catalyst showed improved SO₂ resistance [86].

3.3. Appropriate support

For industrial applications, supported catalyst is a better candidate compared with the unsupported oxide catalyst, because of its low pressure drop, high thermal and mechanical stability, large surface area, and highly dispersed active sites. The optimization of the interaction between support and active components could probably solve the SO₂ poisoning problem in NH₃-SCR [87]. The utilization of supports that possess high- or super-acidity was found to be an effective solution, because of the prevented SO₂ adsorption [86].

The structure of the support has a great influence on the sulfur tolerance of the deNO_x catalyst. Using three-dimensionally ordered macroporous carbon (3DOMC) as support, a novel MnO_x/3DOMC nano-composite catalyst was fabricated [88]. Compared with the MnO_x/NAC (MnO_x supported on Norit activated carbon) and MnO_x/TiO₂ catalysts, MnO_x/3DOMC catalyst exhibited superior SO₂ resistance. A hexagonal WO₃ (HWO) supported V-based catalyst V₂O₅/HWO showed simultaneous resistance to alkalis and sulfur poisoning [89]. The combined effect of alkali metal and SO₂ on the performance of

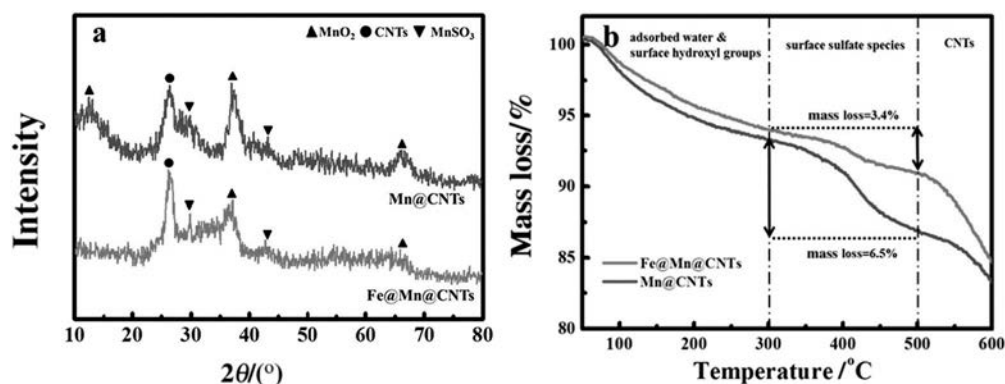


Fig. 8. Figure (a) XRD pattern and (b) TGA curves of the catalysts after the SO₂ tolerance test [80].

deNO_x catalysts has received much attention because SO₂ could increase the deactivation induced by the alkali metal [90]. As illustrated in Fig. 9, the presence of SO₂ almost had no influence on the SCR activity of the V₂O₅/HWO catalyst. The reason was that the spontaneous migration of alkalis into the HWO tunnels generates the exposed catalytic active sites. However, under the same conditions, the conventional V₂O₅/WO₃-TiO₂ catalyst was severely poisoned and completely lost the SCR activity within 4 h. The hexagonal boron nitride as carrier also demonstrated promotional effects on the resistance to SO₂ [91]. Among different supported V-based catalysts (nano-TiO₂, meso-TiO₂, nano-ZrO₂, meso-Al₂O₃ and meso-SiO₂), V₂O₅/meso-TiO₂ showed the best SO₂ poisoning resistance due to the higher pore volume of meso-TiO₂, which enabled a larger tolerance capacity to ammonium sulfate and sulfite [87]. Novel wire-mesh honeycomb-supported Ce-Fe/TiO₂ (Ce-Fe/WMH) and V₂O₅/WO₃/TiO₂/Al₂O₃/wire-mesh honeycomb (WMH) were also developed as NH₃-SCR catalysts. Both of the catalysts showed promising resistance to SO₂ poisoning, which might be attributed to the unique three-dimensional structure [92,93].

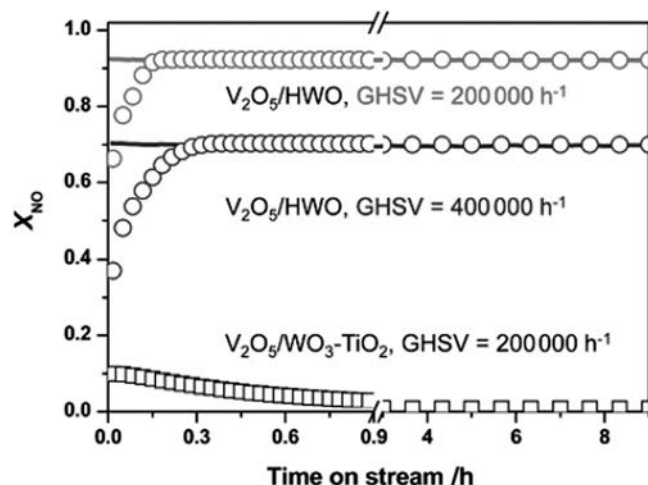


Fig. 9. X_{NO} over the V₂O₅/HWO and the V₂O₅/WO₃-TiO₂ catalysts at the reaction temperature of 350 °C. Reaction conditions: 500 ppm of NO, 500 ppm of NH₃, 3.0 vol% O₂, 1300 mg·m⁻³ SO₂, and balanced N₂, gas flow rate = 1000 ml·min⁻¹ [89].

The modification of supports has become a hot topic in catalysis due to the exposure of more active facets. The facet effects of supports were also employed to improve the resistance to SO₂. Zhao and co-workers [94] used (001) plane-exposed TiO₂ nanosheets (TiO₂-NS) and TiO₂ nanoparticles (TiO₂-NP) which are dominated by (101) facets as supports to develop a novel ZrCeVO₄/TiO₂ catalyst for NH₃-SCR. The activity test results showed that the TiO₂-NS-supported catalyst exhibited much

better SO₂ durability than the catalyst supported by the TiO₂-NP. As illustrated in Fig. 10, the deactivation caused by SO₂ was due to the formation of (NH₄)₂SO₄/NH₄HSO₄ and NH₄NO₃ which covered the active sites on the surface. However, the formation of (NH₄)₂SO₄/NH₄HSO₄ and NH₄NO₃ could be inhibited on the TiO₂-NS support. The micromorphology of Ce in Fe₂O₃/CeO₂ catalyst was also reported to have effect on the SO₂ resistance. The Fe₂O₃/CeO₂ catalyst supported on CeO₂ nano-rods (CeO₂-NR), which mainly exposed (110) and (100) facets, showed excellent catalytic performance and SO₂ tolerance [95].

Researchers have also utilized graphene (GE) or graphene oxide (GO) as support to prepare catalysts for NH₃-SCR. As a result, the SO₂ resistance of the catalysts is significantly improved. The introduction of GO prevented the sulfation of the active component due to its pre-sulfuration effects [96]. Introduction of GE could also result in enhanced H₂O and SO₂ tolerance of the catalysts [97]. Xiao *et al.* [98] had prepared a MnO_x-CeO₂/GE catalyst and using XPS confirmed that the content of Ce increased after the introduction of GE. CeO₂ inhibited the formation of manganese sulfate on the catalyst surface and hence demonstrated good resistance to SO₂.

The type of catalyst carriers plays a key role in the NH₃-SCR and could affect SO₂ resistance of the catalysts. For instance, in comparison with 3Ag/Al₂O₃, 3Ag/bauxite tended to be more resistant to SO₂ poisoning in SCR of NO_x [99]. Synthesized TiO₂ catalyst loaded with Mn showed better resistance to sulfur poisoning than Mn-loaded commercial TiO₂ (P25) in the presence of SO₂. Subsequent analysis verified that the formation of sulfated titanium and manganese sulfate was significantly inhibited, and the deposition concentration of ammonium sulfate on active sites was low enough, making the catalyst resistant to SO₂ poisoning [100]. In some research, CeO₂ was loaded on various supports, including single-component oxides (TiO₂, ZrO₂, Al₂O₃, and SiO₂) and composite oxides (TiO₂-SiO₂, TiO₂-ZrO₂, and TiO₂-Al₂O₃, TiO₂-SiO₂-Al₂O₃ supports). The results showed that Ce/TiO₂-SiO₂ and Ce/TiO₂-SiO₂-Al₂O₃ exhibited strong resistance to SO₂ poisoning [101,102]. In summary, the SO₂ resistance ability can be improved by varying the supports of SCR catalysts.

4. Other Factors Influence SO₂-resistance

4.1. Preparation methods and conditions

It is well known that the preparation process has a great effect on the activity of catalysts. Generally, varied preparation methods could significantly affect the physical/chemical properties (including particle morphologies, surface properties, valence states, *etc.*) of the resulting catalysts. Such varied properties could have a strong influence on the behavior of the catalysts. Thus, the influence of preparation parameters, such as preparation methods and preparation conditions on the catalytic performance and SO₂ resistance of NH₃-SCR catalysts had been investigated systematically.

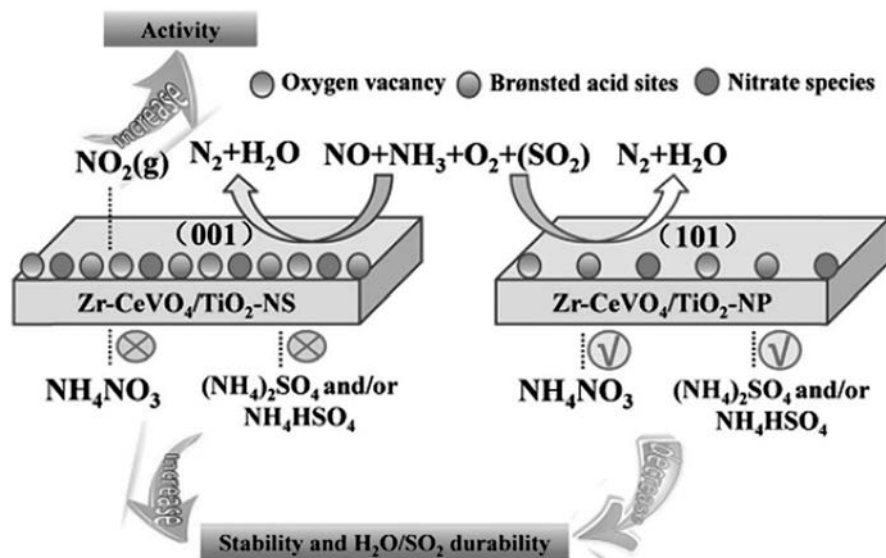


Fig. 10. Promoted SCR performance and the corresponding mechanism of the TiO₂ nanosheet- and nanoparticle-based catalysts [94].

Guo and coworkers [103] prepared CeO₂/Al₂O₃ catalyst samples by the following three methods: single step sol-gel, impregnation and co-precipitation method. The results indicated that catalyst prepared by sol-gel method had the best SO₂-tolerant performance. Larger surface area, higher dispersion of CeO₂ on Al₂O₃, higher NH₃ adsorption capacity and improved redox ability may be accounted for the better SO₂ resistance of the catalyst prepared by single sol-gel method. Investigations on CeO₂-CuO/Al₂O₃ [104], MnO_x/TiO₂ [105], CeO₂/TiO₂ [106] and Ce-O-P [107] catalysts got the same result. The mesopore channels in catalysts prepared by sol-gel method could be able to maintain a dynamic balance between the formation and decomposition of ammonium sulfates in SCR reaction. FTIR analysis indicated that catalyst prepared by sol-gel method was of the weakest sulfation extent among the catalysts prepared with different methods, which agreed well with its good SO₂ resistance [104].

Hydrothermal method is commonly used to prepare catalysts with strong resistance against SO₂. For example, Liu and coworkers [108] prepared Mn-Ce-Ti mixed-oxide catalyst by the hydrothermal method which exhibited excellent SO₂ resistance with a broad operation temperature window. Ce-Ti-W-O_x catalyst prepared by the hydrothermal method also exhibited good resistance to SO₂ and the inhibiting effect of SO₂ was reversible [109]. Moreover, solvothermal methods such as pyridine-thermal route, ethanol-thermal route were also used to prepare catalysts supported on carbon nanotubes [110–112]. Compared with the catalysts prepared by other methods, the highly dispersed metal oxides on carbon nanotubes (CNTs) catalyst prepared by the pyridine-thermal route or ethanol-thermal route presented the best SO₂ resistance.

Recently, some novel catalyst preparation methods were also adopted to prepare deNO_x catalysts with enhanced SO₂ resistance. For example, NiMnFe mixed oxides derived from LDH (layered double hydroxide) [78] and the hollow porous Mn_xCo_{3-x}O₄ nanocages thermally derived from metal-organic frameworks [79] showed good resistance to SO₂.

The preparation parameters during the synthesis process can greatly affect the nano-structures and morphologies, which play a dominant role in the catalytic performance. Wu *et al.* [113] investigated the effect of pH during co-precipitation on the structural and physicochemical properties of a FeVO₄/TiO₂-WO₃-SiO₂ catalyst. Characterization results indicated that the catalyst showed the best catalytic activity with high resistance to SO₂ poisoning when the active component was synthesized at pH = 4.5. The pH values adopted during the synthesis of Sb-V/CeO₂-TiO₂ showed the similar effect on the SO₂ resistance of the catalysts [114].

4.2. Reaction conditions

Reaction conditions such as temperature and composition of the flue gas were also found to be important for the catalytic activity as well as sulfur tolerance of the deNO_x catalysts.

Formation and decomposition of sulfate species on the catalyst surface are directly related to the reaction temperature. Therefore, reaction temperature has a great influence on SO₂ deactivation of the SCR catalysts [10]. For example, the deactivation mechanism for Mn-Ce/TiO₂ catalyst in NH₃-SCR in the presence of SO₂ at different temperatures was different [115]. At 100 °C, the catalyst deactivation was mainly due to the formation and deposition of (NH₄)₂SO₄ and NH₄HSO₄. However, at higher temperature (200 °C), the irreversible deactivation was caused by sulfated metal sites. The effect of SO₂ and H₂O on the activity of Ce-Ti mixed-oxide catalysts was also bound up with the reaction temperature [116]. The Cr_{0.2}-V_{0.8}/TiO₂ catalyst [117] showed similar behavior with the Ce-Ti mixed-oxide. As illustrated in Fig. 11, in a 12 h test with flue gas containing 100 ppm SO₂, the NO_x conversion remained at about 99% at 220 °C and no signs of sulfur poisoning were observed. However, the introduction of SO₂ severely decreased the NO_x conversion at 180 °C.

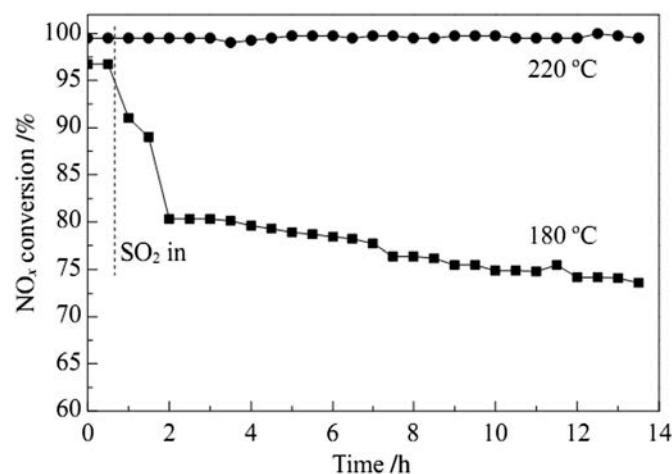


Fig. 11. Resistance to SO₂ of Cr_{0.2}-V_{0.8}/TiO₂ catalyst. Reaction conditions: 220 °C or 180 °C, GHSV = 60000 ml·h⁻¹·g⁻¹, [SO₂] = 100 ppm [117].

Coexisting gases are also essential factors in determining the catalytic performance and sulfur tolerance of the SCR catalysts. The O_2 concentration, for instance, can significantly affect SO_2 deactivation and regeneration behavior over SCR catalyst. Li *et al.* [118] found that the extent of SO_2 deactivation was O_2 concentration dependent over $CuO-CeO_2$ catalyst. The deactivated catalyst could be reactivated under 5.0 vol% O_2 , which could be attributed to the involvement of NO_2 into the reactions. They revealed that NO_2 could react with NH_3/NH_4^{+} and promoted the decomposition of sulfate deposited on the catalyst surface. The NO_2/NO_x ratio also reported to had influences on the SO_2 resistance performance of a vanadium-based catalyst [119]. Therefore, by controlling the reaction parameters of the SCR process, we can suppress the SO_2 induced catalyst deactivation, which is important for the industrial application of SCR catalysts.

4.3. S, P-containing/-treatment

Some S-containing catalysts exhibited good SO_2 resistance capability. For example, Yu *et al.* [120] prepared a series of $CuSO_4/TiO_2$ catalysts and found that SO_2 had little effect on the activity. Supported Fe and Cu sulfates on Ce– TiO_x also proved to exhibited an enhanced resistance to SO_2 [121]. Marcin *et al.* proposed that the controlled sulfation of the commercial catalyst prior to the SCR process may improve its SO_2 resistance [122]. Ke *et al.* [123] found that the Co_3O_4 catalyst was very effective in NH_3 -SCR after being sulfated by SO_2 which may be due to the formation of bulk cobalt sulfate. In addition, it exhibited good resistance to SO_2 under a long term operation condition. Moreover, the S-treated W–CeZr, CeZr oxides [124], Ni–Ce–La composite oxides [125] and sulfated Mn–Co–Ce/ TiO_2/SiO_2 [126] were also found to have an enhanced NO_x conversion and SO_2 resistance performance. Phosphates, the solid acid materials, exhibited promising properties for catalysis application. The phosphates Ce–O–P were employed in the SCR process as a novel catalyst and showed a good SO_2 resistance ability [107].

5. Conclusions and Perspectives

To date, extensive studies have been conducted on the development of $deNO_x$ catalysts and an increasing attention has been paid to the deactivation of the SCR catalysts. Sulfur poisoning, which contributes to the deactivation of the $deNO_x$ catalysts, is usually irreversible. Extensively investigations have been carried out to elucidate the sulfur deactivation mechanisms on different catalysts in order to improve the SO_2 -tolerant ability of the SCR catalysts. The sulfur poisoning mechanisms may vary on different catalysts. However, there exist several underlying causes: sulfation of the active center atoms, formation and deposition of ammonium sulfates on the catalyst surface clogging the pore channels, and the competitive adsorption between SO_2 and NO_x . To reduce SO_2 poisoning, there are several strategies including modifying the catalysts with the transition metals, preparing catalysts with specific structure and morphology, and selecting appropriate supports. Moreover, methods used to prepare the catalysts and the reaction conditions could have a great influence on the SO_2 -resistance of the catalysts.

Although considerable progress has been achieved, the activity test time in the presence of SO_2 is relatively short. Therefore, it is still a challenge to develop catalysts with good SO_2 resistance for industrial applications. The rapid development of theoretical calculations can assist the investigation of SO_2 resistance. Theoretical calculations can help to illustrate the reaction mechanisms that are difficult to access merely by experimental study. It may become a main research area in the field of SCR catalysts in the future. Moreover, it may provide guidance for future research on the development of high SO_2 resistance catalysts.

Recently, metal–organic frameworks, which are known to be porous crystalline materials with a large surface area were used as SCR catalysts and exhibited good SO_2 resistance [127–129]. Besides, more novel SCR catalysts should be developed to attain good sulfur tolerance.

References

- [1] G. Qi, R.T. Yang, Low-temperature selective catalytic reduction of NO with NH_3 over iron and manganese oxides supported on titania, *Appl. Catal. B* 44 (2003) 217–225.
- [2] L. Yan, Y. Liu, H. Hu, H. Li, L. Shi, D. Zhang, Investigations on the antimony promotional effect on CeO_2-WO_3/TiO_2 for selective catalytic reduction of NO_x with NH_3 , *ChemCatChem* 8 (2016) 2267–2278.
- [3] K.Q. Tran, P. Kilpinen, N. Kumar, In-situ catalytic abatement of NO_x during fluidized bed combustion—a literature study, *Appl. Catal. B* 78 (2008) 129–138.
- [4] R.Q. Long, R.T. Yang, R. Chang, Low temperature selective catalytic reduction (SCR) of NO with NH_3 over Fe–Mn based catalysts, *Chem. Commun.* (2002) 452–453.
- [5] J. Zuo, Z. Chen, F. Wang, Y. Yu, L. Wang, X. Li, Low-temperature selective catalytic reduction of NO_x with NH_3 over novel Mn–Zr mixed oxide catalysts, *Ind. Eng. Chem. Res.* 53 (2014) 2647–2655.
- [6] K. Cheng, J. Liu, T. Zhang, J. Li, Z. Zhao, Y. Wei, G. Jiang, A. Duan, Effect of Ce doping of TiO_2 support on NH_3 -SCR activity over $V_2O_5-WO_3/CeO_2-TiO_2$ catalyst, *J. Environ. Sci. (China)* 26 (2014) 2106–2113.
- [7] S. Pan, H. Luo, L. Li, Z. Wei, B. Huang, H_2O and SO_2 deactivation mechanism of $MnO_x/MWCNTs$ for low-temperature SCR of NO_x with NH_3 , *J. Mol. Catal. A Chem.* 377 (2013) 154–161.
- [8] A. Yamamoto, K. Teramura, S. Hosokawa, T. Tanaka, Effects of SO_2 on selective catalytic reduction of NO with NH_3 over a TiO_2 photocatalyst, *Sci. Technol. Adv. Mater.* 16 (2015) 024901.
- [9] Z. Ma, X. Wu, Y. Feng, Z. Si, D. Weng, L. Shi, Low-temperature SCR activity and SO_2 deactivation mechanism of Ce-modified $V_2O_5-WO_3/TiO_2$ catalyst, *Prog. Nat. Sci. Mater. Int.* 25 (2015) 342–352.
- [10] P. Li, Z. Liu, Q. Li, W. Wu, Q. Liu, Multiple roles of SO_2 in selective catalytic reduction of NO by NH_3 over V_2O_5/AC catalyst, *Ind. Eng. Chem. Res.* 53 (2014) 7910–7916.
- [11] F. Liu, K. Asakura, H. He, W. Shan, X. Shi, C. Zhang, Influence of sulfation on iron titanate catalyst for the selective catalytic reduction of NO_x with NH_3 , *Appl. Catal. B* 103 (2011) 369–377.
- [12] F. Liu, H. He, Selective catalytic reduction of NO with NH_3 over manganese substituted iron titanate catalyst: Reaction mechanism and H_2O/SO_2 inhibition mechanism study, *Catal. Today* 153 (2010) 70–76.
- [13] A. Kumar, M.A. Smith, K. Kamasamudram, N.W. Currier, A. Yezerets, Chemical $deSO_x$: an effective way to recover Cu-zeolite SCR catalysts from sulfur poisoning, *Catal. Today* 267 (2016) 10–16.
- [14] W. Shan, H. Song, Catalysts for the selective catalytic reduction of NO_x with NH_3 at low temperature, *Catal. Sci. Technol.* 5 (2015) 4280–4288.
- [15] D.W. Brookshear, J.g. Nam, K. Nguyen, T.J. Toops, A. Binder, Impact of sulfation and desulfation on NO_x reduction using Cu-chabazite SCR catalysts, *Catal. Today* 258 (2015) 359–366.
- [16] Y.J. Kim, H.J. Kwon, I. Heo, I.S. Nam, B.K. Cho, J.W. Choung, G.K.Y. Moon-Soon Cha, Mn–Fe/ZSM-5 as a low-temperature SCR catalyst to remove NO_x from diesel engine exhaust, *Appl. Catal. B* 126 (2012) 9–12.
- [17] K. Wijayanti, K. Leistner, S. Chand, A. Kumar, K. Kamasamudram, N.W. Currier, A. Yezerets, L. Olsson, Deactivation of Cu-SSZ-13 by SO_2 exposure under SCR conditions, *Catal. Sci. Technol.* 6 (2016) 2565–2579.
- [18] Y. Jangjou, M. Ali, Q. Chang, D. Wang, J. Li, A. Kumar, W.S. Epling, Effect of SO_2 on NH_3 oxidation over a Cu- $SAPO-34$ SCR catalyst, *Catal. Sci. Technol.* 6 (2016) 2679–2685.
- [19] A. Kumar, M.A. Smith, K. Kamasamudram, N.W. Currier, H. An, A. Yezerets, Impact of different forms of feed sulfur on small-pore Cu-zeolite SCR catalyst, *Catal. Today* 231 (2014) 75–82.
- [20] K. Wijayanti, S. Andonova, A. Kumar, J. Li, K. Kamasamudram, N.W. Currier, A. Yezerets, L. Olsson, Impact of sulfur oxide on NH_3 -SCR over Cu- $SAPO-34$, *Appl. Catal. B* 166–167 (2015) 568–579.
- [21] M.L.M. de Oliveira, C.M. Silva, R. Moreno-Tost, T.L. Farias, A. Jiménez-López, E. Rodríguez-Castellón, Simulation of SCR equipped vehicles using iron-zeolite catalysts, *Appl. Catal. A* 366 (2009) 13–21.
- [22] L. Ma, H. Qu, J. Zhang, Q. Tang, S. Zhang, Q. Zhong, Preparation of nanosheet Fe–ZSM-5 catalysts, and effect of Fe content on acidity, water, and sulfur resistance in the selective catalytic reduction of NO_x by ammonia, *Res. Chem. Intermed.* 39 (2013) 4109–4120.
- [23] S. Yang, Y. Guo, H. Chang, L. Ma, Y. Peng, Z. Qu, N. Yan, C. Wang, J. Li, Novel effect of SO_2 on the SCR reaction over CeO_2 : Mechanism and significance, *Appl. Catal. B* 136–137 (2013) 19–28.
- [24] X. Xiao, S. Xiong, Y. Shi, W. Shan, S. Yang, Effect of H_2O and SO_2 on the selective catalytic reduction of NO with NH_3 over Ce/ TiO_2 catalyst: Mechanism and kinetic study, *J. Phys. Chem. C* 120 (2016) 1066–1076.
- [25] D. Zhang, L. Zhang, L. Shi, C. Fang, H. Li, R. Gao, L. Huang, J. Zhang, In situ supported MnO_x-CeO_x on carbon nanotubes for the low-temperature selective catalytic reduction of NO with NH_3 , *Nanoscale* 5 (2013) 1127–1136.
- [26] Y. Wang, X. Li, L. Zhan, C. Li, W. Qiao, L. Ling, Effect of SO_2 on activated carbon honeycomb supported CeO_2-MnO_x catalyst for NO removal at low temperature, *Ind. Eng. Chem. Res.* 54 (2015) 2274–2278.
- [27] L. Zhang, X. Zhang, S. Lv, X. Wu, P. Wang, Promoted performance of a MnO_x/PG catalyst for low-temperature SCR against SO_2 poisoning by addition of cerium oxide, *RSC Adv.* 5 (2015) 82952–82959.
- [28] Y. Wang, L. Yang, W.P. Liao, F. Wang, Research of SO_2 resistance of MnO_x catalyst modified by Ce for low temperature SCR with NH_3 , *Adv. Mater. Res.* 356–360 (2011) 529–532.
- [29] Z. Wu, R. Jin, H. Wang, Y. Liu, Effect of ceria doping on SO_2 resistance of Mn/ TiO_2 for selective catalytic reduction of NO with NH_3 at low temperature, *Catal. Commun.* 10 (2009) 935–939.

- [30] L. Wei, S. Cui, H. Guo, X. Ma, L. Zhang, DRIFT and DFT study of cerium addition on SO_2 of Manganese-based Catalysts for low temperature SCR, *J. Mol. Catal. A Chem.* 421 (2016) 102–108.
- [31] K.J. Lee, P.A. Kumar, M.S. Maqbool, K.N. Rao, K.H. Song, H.P. Ha, Ce added Sb- $\text{V}_2\text{O}_5/\text{TiO}_2$ catalysts for low temperature NH_3 SCR: physico-chemical properties and catalytic activity, *Appl. Catal. B* 142–143 (2013) 705–717.
- [32] D.W. Kwon, K.B. Nam, S.C. Hong, The role of ceria on the activity and SO_2 resistance of catalysts for the selective catalytic reduction of NO_x by NH_3 , *Appl. Catal. B* 166–167 (2015) 37–44.
- [33] W. Cha, S.H. Ehrman, J. Jurng, CeO_2 added $\text{V}_2\text{O}_5/\text{TiO}_2$ catalyst prepared by chemical vapor condensation (CVC) and impregnation method for enhanced NH_3 -SCR of NO_x at low temperature, *J. Environ. Chem. Eng.* 4 (2016) 556–563.
- [34] L. Pang, C. Fan, L. Shao, K. Song, J. Yi, X. Cai, J. Wang, M. Kang, T. Li, The Ce doping Cu/ZSM-5 as a new superior catalyst to remove NO from diesel engine exhaust, *Chem. Eng. J.* 253 (2014) 394–401.
- [35] S. Lai, D. Meng, W. Zhan, Y. Guo, Y. Guo, Z. Zhang, G. Lu, The promotional role of Ce in Cu/ZSM-5 and in situ surface reaction for selective catalytic reduction of NO_x with NH_3 , *RSC Adv.* 5 (2015) 90235–90244.
- [36] S.Y. Jiang, R.X. Zhou, Ce doping effect on performance of the Fe/ β catalyst for NO_x reduction by NH_3 , *Fuel Process. Technol.* 133 (2015) 220–226.
- [37] W.L. Zhen, R.T. Guo, W.G. Pan, Low temperature selective catalytic reduction of NO on CeO_2 - $\text{Fe}_2\text{O}_3/\text{TiO}_2$, $\text{CeO}_2/\text{TiO}_2$ catalysts prepared by coprecipitation method, *Adv. Mater. Res.* 960–961 (2014) 234–239.
- [38] Y. Shu, H. Sun, X. Quan, S. Chen, Enhancement of catalytic activity over the iron-modified Ce/ TiO_2 catalyst for selective catalytic reduction of NO_x with ammonia, *J. Phys. Chem. C* 116 (2012) 25319–25327.
- [39] S. Cai, D. Zhang, L. Zhang, L. Huang, H. Li, R. Gao, L. Shi, J. Zhang, Comparative study of 3D ordered macroporous $\text{Ce}_{0.75}\text{Zr}_{0.25}\text{O}_{2-x}$ ($M = \text{Fe}, \text{Cu}, \text{Mn}, \text{Co}$) for selective catalytic reduction of NO with NH_3 , *Catal. Sci. Technol.* 4 (2014) 93–101.
- [40] W. Zhao, C. Li, P. Lu, Q. Wen, Y. Zhao, X. Zhang, C. Fan, S. Tao, Iron, lanthanum and manganese oxides loaded on $\gamma\text{-Al}_2\text{O}_3$ for selective catalytic reduction of NO with NH_3 at low temperature, *Environ. Technol.* 34 (2013) 81–90.
- [41] X. Tang, J. Hao, H. Yi, J. Li, Low-temperature SCR of NO with NH_3 over AC/C supported manganese-based monolithic catalysts, *Catal. Today* 126 (2007) 406–411.
- [42] C. Fang, L. Shi, H. Hu, J. Zhang, D. Zhang, Rational design of 3D hierarchical foam-like $\text{Fe}_2\text{O}_3/\text{CuO}_x$ monolith catalysts for selective catalytic reduction of NO with NH_3 , *RSC Adv.* 5 (2015) 11013–11022.
- [43] R. Gao, D. Zhang, X. Liu, L. Shi, P. Maitarad, H. Li, J. Zhang, W. Cao, Enhanced catalytic performance of $\text{V}_2\text{O}_5\text{-WO}_3/\text{Fe}_2\text{O}_3/\text{TiO}_2$ microspheres for selective catalytic reduction of NO by NH_3 , *Catal. Sci. Technol.* 3 (2013) 191–199.
- [44] Y.X. Teng, C.Y. Song, X.N. Lu, Z.S. Tong, Y.S. Qin, Influence of Fe doping on Ce-Mn/ TiO_2 - ZrO_2 catalysts for low-temperature selective catalytic reduction of NO, *Adv. Mater. Res.* 898 (2014) 447–451.
- [45] B. Shen, T. Liu, N. Zhao, X. Yang, L. Deng, Iron-doped Mn-Ce/ TiO_2 catalyst for low temperature selective catalytic reduction of NO with NH_3 , *J. Environ. Sci.* 22 (2010) 1447–1454.
- [46] M.E. Yu, C. Li, G. Zeng, Y. Zhou, X. Zhang, Y.E. Xie, The selective catalytic reduction of NO with NH_3 over a novel Ce-Sn-Ti mixed oxides catalyst: promotional effect of SnO_2 , *Appl. Surf. Sci.* 342 (2015) 174–182.
- [47] H. Chang, J. Li, X. Chen, L. Ma, S. Yang, J.W. Schwank, J. Hao, Effect of Sn on $\text{MnO}_x\text{-CeO}_2$ catalyst for SCR of NO_x by ammonia: Enhancement of activity and remarkable resistance to SO_2 , *Catal. Commun.* 27 (2012) 54–57.
- [48] H. Chang, X. Chen, J. Li, L. Ma, C. Wang, C. Liu, J.W. Schwank, J. Hao, Improvement of activity and SO_2 tolerance of Sn-modified $\text{MnO}_x\text{-CeO}_2$ catalysts for NH_3 -SCR at low temperatures, *Environ. Sci. Technol.* 47 (2013) 5294–5301.
- [49] M. Qiu, S. Zhan, D. Zhu, H. Yu, Q. Shi, NH_3 -SCR performance improvement of mesoporous Sn modified Cr-Mn O_x catalysts at low temperatures, *Catal. Today* 258 (2015) 103–111.
- [50] X. Li, Y. Li, S. Deng, T.A. Rong, A Ce-Sn- O_x catalyst for the selective catalytic reduction of NO_x with NH_3 , *Catal. Commun.* 40 (2013) 47–50.
- [51] P. Zhang, Q. Hou, SnO_2 modified Ce-Ti- O_x catalyst for the selective catalytic reduction of NO_x with NH_3 , *React. Kinet. Mech. Catal.* 117 (2016) 119–128.
- [52] C. Fang, L. Shi, H. Li, L. Huang, J. Zhang, D. Zhang, Creating hierarchically macro-/mesoporous Sn/ CeO_2 for the selective catalytic reduction of NO with NH_3 , *RSC Adv.* 6 (2016) 78727–78736.
- [53] D.W. Kwon, K.B. Nam, S.C. Hong, Influence of tungsten on the activity of a Mn/Ce/W/Ti catalyst for the selective catalytic reduction of NO with NH_3 at low temperatures, *Appl. Catal. A* 497 (2015) 160–166.
- [54] D.W. Kwon, S.C. Hong, Promotional effect of tungsten-doped $\text{CeO}_2/\text{TiO}_2$ for selective catalytic reduction of NO_x with ammonia, *Appl. Surf. Sci.* 356 (2015) 181–190.
- [55] P. Zhang, K. Li, Q. Lei, Enhanced activity of tungsten doped CeAlO_3 catalysts for the selective catalytic reduction of NO_x with NH_3 , *React. Kinet. Mech. Catal.* 116 (2015) 523–533.
- [56] Z. Fang, B. Yuan, T. Lin, H. Xu, Y. Cao, Z. Shi, M. Gong, Y. Chen, Monolith $\text{Ce}_{0.65}\text{Zr}_{0.35}\text{O}_2$ -based catalysts for selective catalytic reduction of NO_x with NH_3 , *Chem. Eng. Res. Des.* 94 (2015) 648–659.
- [57] Z. Ma, X. Wu, Y. Feng, Z. Si, D. Weng, Effects of WO_3 doping on stability and N_2O escape of $\text{MnO}_x\text{-CeO}_2$ mixed oxides as a low-temperature SCR catalyst, *Catal. Commun.* 69 (2015) 188–192.
- [58] P. Zhang, D. Li, Selective catalytic reduction of NO with NH_3 over iron-vanadium mixed oxide catalyst, *Catal. Lett.* 144 (2014) 959–963.
- [59] B. Wu, Effect on additives adding of Mn-Ce/ TiO_2 selective catalytic reduction NO by NH_3 at low-temperature, *Adv. Mater. Res.* 955–959 (2014) 25–29.
- [60] W. Yang, F. Liu, L. Xie, Z. Lian, H. He, Effect of V_2O_5 additive on the SO_2 resistance of a $\text{Fe}_2\text{O}_3/\text{AC}$ catalyst for NH_3 -SCR of NO_x at low temperatures, *Ind. Eng. Chem. Res.* 55 (2016) 2677–2685.
- [61] Z. Lian, F. Liu, H. He, Enhanced activity of Ti-modified $\text{V}_2\text{O}_5\text{-CeO}_2$ catalyst for the selective catalytic reduction of NO_x with NH_3 , *Ind. Eng. Chem. Res.* 53 (2014) 19506–19511.
- [62] Y. Xiong, C. Tang, X. Yao, L. Zhang, L. Li, X. Wang, Y. Deng, F. Gao, L. Dong, Effect of metal ions doping ($M = \text{Ti}^{4+}, \text{Sn}^{4+}$) on the catalytic performance of $\text{MnO}_x/\text{CeO}_2$ catalyst for low temperature selective catalytic reduction of NO with NH_3 , *Appl. Catal. A* 495 (2015) 206–216.
- [63] X. Zhao, L. Huang, H. Li, H. Hu, J. Han, L. Shi, D. Zhang, Highly dispersed $\text{V}_2\text{O}_5/\text{TiO}_2$ modified with transition metals (Cu, Fe, Mn, Co) as efficient catalysts for the selective reduction of NO with NH_3 , *Chin. J. Catal.* 36 (2015) 1886–1899.
- [64] X. Gao, X.S. Du, L.W. Cui, Y.C. Fu, Z.Y. Luo, K.F. Cen, A Ce-Cu-Ti oxide catalyst for the selective catalytic reduction of NO with NH_3 , *Catal. Commun.* 12 (2010) 255–258.
- [65] X.S. Du, X. Gao, L.W. Cui, Y.C. Fu, Z.Y. Luo, K.F. Cen, Investigation of the effect of Cu addition on the SO_2 -resistance of a Ce-Ti oxide catalyst for selective catalytic reduction of NO with NH_3 , *Fuel* 92 (2012) 49–55.
- [66] J. Qiao, N. Wang, Z. Wang, W. Sun, K. Sun, Porous bimetallic $\text{Mn}_2\text{Co}_3\text{O}_x$ catalysts prepared by a one-step combustion method for the low temperature selective catalytic reduction of NO_x with NH_3 , *Catal. Commun.* 72 (2015) 111–115.
- [67] Q.M. Zhang, C.L. Song, G. Lv, F. Bin, H.T. Pang, J.O. Song, Effect of metal oxide partial substitution of V_2O_5 in $\text{V}_2\text{O}_5\text{-WO}_3/\text{TiO}_2$ on selective catalytic reduction of NO with NH_3 , *J. Ind. Eng. Chem.* 24 (2015) 79–86.
- [68] X. Zhang, B. Shen, K. Wang, J. Chen, A contrastive study of the introduction of cobalt as a modifier for active components and supports of catalysts for NH_3 -SCR, *J. Ind. Eng. Chem.* 19 (2013) 1272–1279.
- [69] X. Li, Y. Li, Molybdenum modified CeAlO_3 catalyst for the selective catalytic reduction of NO with NH_3 , *J. Mol. Catal. A Chem.* 386 (2014) 69–77.
- [70] D.W. Kwon, K.H. Park, S.C. Hong, Enhancement of SCR activity and SO_2 resistance on VO_x/TiO_2 catalyst by addition of molybdenum, *Chem. Eng. J.* 284 (2016) 315–324.
- [71] S. Ding, F. Liu, X. Shi, H. He, Promotional effect of Nb additive on the activity and hydrothermal stability for the selective catalytic reduction of NO_x with NH_3 over CeZrO_x catalyst, *Appl. Catal. B* 180 (2016) 766–774.
- [72] Y. Jiang, Y. Yan, S.B. Huang, X.X. Zhang, X.W. Wang, W.X. Song, Selective catalytic reduction of NO with NH_3 over a Ce-Zr-Ti oxide catalyst, *Adv. Mater. Res.* 864–867 (2014) 353–356.
- [73] F. Cao, J. Xiang, S. Su, P. Wang, L. Sun, S. Hu, S. Lei, The activity and characterization of $\text{MnO}_x\text{-CeO}_2\text{-ZrO}_2/\gamma\text{-Al}_2\text{O}_3$ catalysts for low temperature selective catalytic reduction of NO with NH_3 , *Chem. Eng. J.* 243 (2014) 347–354.
- [74] X. Zhao, L. Huang, H. Li, H. Hu, X. Hu, L. Shi, D. Zhang, Promotional effects of zirconium doped CeVO_4 for the low-temperature selective catalytic reduction of NO_x with NH_3 , *Appl. Catal. B* 183 (2016) 269–281.
- [75] M. Aguilar-Romero, R. Camposco, S. Castillo, J. Marín, V. Rodríguez-González, L.A. García-Serrano, I. Mejía-Centeno, Acidity, surface species, and catalytic activity study on $\text{V}_2\text{O}_5\text{-WO}_3/\text{TiO}_2$ nanotube catalysts for selective NO reduction by NH_3 , *Fuel* 198 (2017) 123–133.
- [76] Y. Shi, S. Chen, H. Sun, Y. Shu, X. Quan, Low-temperature selective catalytic reduction of NO_x with NH_3 over hierarchically macro-mesoporous Mn/ TiO_2 , *Catal. Commun.* 42 (2013) 10–13.
- [77] L. Huang, X. Zhao, L. Zhang, L. Shi, J. Zhang, D. Zhang, Large-scale growth of hierarchical transition-metal vanadate nanosheets on metal meshes as monolith catalysts for De- NO_x reaction, *Nanoscale* 7 (2015) 2743–2749.
- [78] H. Li, D. Zhang, P. Maitarad, L. Shi, R. Gao, J. Zhang, W. Cao, In situ synthesis of 3D flower-like NiMnFe mixed oxides as monolith catalysts for selective catalytic reduction of NO with NH_3 , *Chem. Commun.* 48 (2012) 10645–10647.
- [79] L. Zhang, L. Shi, L. Huang, J. Zhang, R. Gao, D. Zhang, Rational design of high-performance DeNO_x catalysts based on $\text{Mn}_x\text{Co}_{3-x}\text{O}_4$ nanocages derived from metal-organic frameworks, *ACS Catal.* 4 (2014) 1753–1763.
- [80] S. Cai, H. Hu, H. Li, L. Shi, D. Zhang, Design of multi-shell $\text{Fe}_2\text{O}_3/\text{MnO}_x/\text{CNTs}$ for the selective catalytic reduction of NO with NH_3 : Improvement of catalytic activity and SO_2 tolerance, *Nanoscale* 8 (2016) 3588–3598.
- [81] J. Liu, Y. Du, J. Liua, Z. Zhao, K. Cheng, Y. Chen, Y. Wei, W. Song, X. Zhang, Design of MoFe/Beta/ CeO_2 catalysts with a core-shell structure and their catalytic performances for the selective catalytic reduction of NO with NH_3 , *Appl. Catal. B* 203 (2017) 704–714.
- [82] L. Zhang, D. Zhang, J. Zhang, S. Cai, C. Fang, L. Huang, H. Li, R. Gao, L. Shi, Design of *meso*- $\text{TiO}_2/\text{MnO}_x\text{-CeO}_x/\text{CNTs}$ with a core-shell structure as DeNO_x catalysts: promotion of activity, stability and SO_2 -tolerance, *Nanoscale* 5 (2013) 9821–9829.
- [83] X. Liu, P. Ning, H. Li, Z.X. Song, Y.C. Wang, J.H. Zhang, X.S. Tang, M.Z. Wang, Q.L. Zhang, Probing NH_3 -SCR catalytic activity and SO_2 resistance over aqueous-phase synthesized Ce-W/ TiO_2 catalyst, *J. Fuel Chem. Technol.* 44 (2016) 225–231.
- [84] L. Zhang, L. Li, Y. Cao, X. Yao, C. Ge, F. Gao, Y. Deng, C. Tang, L. Dong, Getting insight into the influence of SO_2 on $\text{TiO}_2/\text{CeO}_2$ for the selective catalytic reduction of NO by NH_3 , *Appl. Catal. B* 165 (2015) 589–598.
- [85] R.T. Yang, N. Chen, A new approach to decomposition of nitric oxide using sorbent/catalyst without reducing gas: Use of heteropoly compounds, *Ind. Eng. Chem. Res.* 33 (1994) 825–831.
- [86] X. Weng, X. Dai, Q. Zeng, Y. Liu, Z. Wu, DRIFT studies on promotion mechanism of $\text{H}_3\text{PW}_{12}\text{O}_{40}$ in selective catalytic reduction of NO with NH_3 , *J. Colloid Interface Sci.* 461 (2016) 9–14.
- [87] F. Guo, J. Yu, M. Chu, G. Xu, Interaction between support and V_2O_5 in the selective catalytic reduction of NO by NH_3 , *Catal. Sci. Technol.* 4 (2014) 2147–2155.
- [88] X. Gao, L. Li, L. Song, T. Lu, J. Zhao, Z. Liu, Highly dispersed MnO_x nanoparticles supported on three-dimensionally ordered macroporous carbon: A novel nanocomposite for catalytic reduction of NO_x with NH_3 at low temperature, *RSC Adv.* 5 (2015) 29577–29588.

- [89] Z. Huang, H. Li, J. Gao, X. Gu, L. Zheng, P. Hu, Y. Xin, J. Chen, Y. Chen, Z. Zhang, J. Chen, X. Tang, Alkali- and sulfur-resistant tungsten-based catalysts for NO_x emissions control, *Environ. Sci. Technol.* 49 (2015) 14460–14465.
- [90] Q. Li, S. Chen, Z. Liu, Q. Liu, Combined effect of KCl and SO₂ on the selective catalytic reduction of NO by NH₃ over V₂O₅/TiO₂ catalyst, *Appl. Catal. B* 164 (2015) 475–482.
- [91] D. Zhou, Z. Ren, B. Li, Z. Ma, X. Zhang, H. Yang, Influence of hexagonal boron nitride on the selective catalytic reduction of NO with NH₃ over CuO_x/TiO₂, *RSC Adv.* 5 (2015) 31708–31715.
- [92] Y. Shu, T. Aikebaier, X. Quan, S. Chen, H. Yu, Selective catalytic reaction of NO_x with NH₃ over Ce–Fe/TiO₂-loaded wire-mesh honeycomb: Resistance to SO₂ poisoning, *Appl. Catal. B* 150–151 (2014) 630–635.
- [93] Y. Shu, H. Sun, X. Quan, S. Chen, Improvement of water-, sulfur dioxide-, and dust-resistance in selective catalytic reduction of NO_x with NH₃ using a wire-mesh honeycomb catalyst, *Ind. Eng. Chem. Res.* 51 (2012) 7867–7873.
- [94] X. Zhao, L. Huang, S. Namuangruk, H. Hu, X. Hu, L. Shi, D. Zhang, Morphology-dependent performance of Zr–CeVO₄/TiO₂ for selective catalytic reduction of NO with NH₃, *Catal. Sci. Technol.* 6 (2016) 5543–5553.
- [95] J. Han, J. Meeprasert, P. Maitarad, S. Nammuangruk, L. Shi, D. Zhang, Investigation of the facet-dependent catalytic performance of Fe₂O₃/CeO₂ for the selective catalytic reduction of NO with NH₃, *J. Phys. Chem. C* 120 (2016) 1523–1533.
- [96] W. Su, X. Lu, S. Jia, J. Wang, H. Ma, Y. Xing, Catalytic reduction of NO_x over TiO₂–graphene oxide supported with MnO_x at low temperature, *Catal. Lett.* 145 (2015) 1446–1456.
- [97] X. Lu, C. Song, S. Jia, Z. Tong, X. Tang, Y. Teng, Low-temperature selective catalytic reduction of NO_x with NH₃ over cerium and manganese oxides supported on TiO₂–graphene, *Chem. Eng. J.* 260 (2015) 776–784.
- [98] X. Xiao, Z. Sheng, L. Yang, F. Dong, Low-temperature selective catalytic reduction of NO_x with NH₃ over a manganese and cerium oxide/graphene composite prepared by a hydrothermal method, *Catal. Sci. Technol.* 6 (2016) 1507–1514.
- [99] X. Wang, L. Jiang, J. Wang, R. Wang, Ag/bauxite catalysts: Improved low-temperature activity and SO₂ tolerance for H₂-promoted NH₃-SCR of NO_x, *Appl. Catal. B* 165 (2015) 700–705.
- [100] E. Park, M. Kim, H. Jung, S. Chin, J. Jurng, Effect of sulfur on Mn/Ti catalysts prepared using chemical vapor condensation (CVC) for low-temperature NO reduction, *ACS Catal.* 3 (2013) 1518–1525.
- [101] C. Liu, L. Chen, J. Li, L. Ma, H. Arandiyani, Y. Du, J. Xu, J. Hao, Enhancement of activity and sulfur resistance of CeO₂ supported on TiO₂–SiO₂ for the selective catalytic reduction of NO by NH₃, *Environ. Sci. Technol.* 46 (2012) 6182–6189.
- [102] W. Zhao, Y. Tang, Y. Wan, L. Li, S. Yao, X. Li, J. Gu, Y. Li, J. Shi, Promotion effects of SiO₂ or/and Al₂O₃ doped CeO₂/TiO₂ catalysts for selective catalytic reduction of NO by NH₃, *J. Hazard. Mater.* 278 (2014) 350–359.
- [103] R.T. Guo, Y. Zhou, W.G. Pan, J.N. Hong, W.L. Zhen, Q. Jin, C.G. Ding, S.Y. Guo, Effect of preparation methods on the performance of CeO₂/Al₂O₃ catalysts for selective catalytic reduction of NO with NH₃, *J. Ind. Eng. Chem.* 19 (2013) 2022–2025.
- [104] R.T. Guo, W.L. Zhen, W.G. Pan, J.N. Hong, Q. Jin, C.G. Ding, S.Y. Guo, Low-temperature selective catalytic reduction of NO on CeO₂–CuO/Al₂O₃ catalysts prepared by different methods, *Environ. Technol.* 35 (2014) 1766–1772.
- [105] B. Jiang, Y. Liu, Z. Wu, Low-temperature selective catalytic reduction of NO on MnO_x/TiO₂ prepared by different methods, *J. Hazard. Mater.* 162 (2009) 1249–1254.
- [106] X. Gao, Y. Jiang, Y. Fu, Y. Zhong, Z. Luo, K. Cen, Preparation and characterization of CeO₂/TiO₂ catalysts for selective catalytic reduction of NO with NH₃, *Catal. Commun.* 11 (2010) 465–469.
- [107] W. Yao, Y. Liu, X. Wang, X. Weng, H. Wang, Z. Wu, The superior performance of sol–gel made Ce–O–P catalyst for selective catalytic reduction of NO with NH₃, *J. Phys. Chem. C* 120 (2016) 221–229.
- [108] Z. Liu, J. Zhu, J. Li, L. Ma, S.I. Woo, Novel Mn–Ce–Ti mixed-oxide catalyst for the selective catalytic reduction of NO_x with NH₃, *ACS Appl. Mater. Interfaces* 6 (2014) 14500–14508.
- [109] H. Li, G.F. Qu, Y.K. Duan, P. Ning, Q.L. Zhang, X. Liu, Z.X. Song, Performance and characterisation of CeO₂–TiO₂–WO₃ catalysts for selective catalytic reduction of NO with NH₃, *Chem. Pap.* 69 (2015) 817–826.
- [110] C. Fang, D. Zhang, L. Shi, R. Gao, H. Li, L. Ye, J. Zhang, Highly dispersed CeO₂ on carbon nanotubes for selective catalytic reduction of NO with NH₃, *Catal. Sci. Technol.* 3 (2013) 803–811.
- [111] J. Han, D. Zhang, P. Maitarad, L. Shi, S. Cai, H. Li, L. Huang, J. Zhang, Fe₂O₃ nanoparticles anchored in situ on carbon nanotubes via an ethanol-thermal strategy for the selective catalytic reduction of NO with NH₃, *Catal. Sci. Technol.* 5 (2015) 438–446.
- [112] D. Zhang, L. Zhang, C. Fang, R. Gao, Y. Qian, L. Shi, J. Zhang, MnO_x–CeO_x/CNTs pyridine-thermally prepared via a novel in situ deposition strategy for selective catalytic reduction of NO with NH₃, *RSC Adv.* 3 (2013) 8811–8819.
- [113] G. Wu, J. Li, Z. Fang, L. Lan, R. Wang, T. Lin, M. Gong, Y. Chen, Effectively enhance catalytic performance by adjusting pH during the synthesis of active components over FeVO₄/TiO₂–WO₃–SiO₂ monolith catalysts, *Chem. Eng. J.* 271 (2015) 1–13.
- [114] H.T. Danh, Y.E. Jeong, P.A. Kumar, H.P. Ha, Enhanced NH₃-SCR activity of Sb–V/CeO₂–TiO₂ catalyst at low temperatures by synthesis modification, *Res. Chem. Intermed.* 42 (2016) 155–169.
- [115] R. Jin, Y. Liu, Z. Wu, H. Wang, T. Gu, Relationship between SO₂ poisoning effects and reaction temperature for selective catalytic reduction of NO over Mn–Ce/TiO₂ catalyst, *Catal. Today* 153 (2010) 84–89.
- [116] X. Gao, Y. Jiang, Y. Zhong, Z. Luo, K. Cen, The activity and characterization of CeO₂–TiO₂ catalysts prepared by the sol–gel method for selective catalytic reduction of NO with NH₃, *J. Hazard. Mater.* 174 (2010) 734–739.
- [117] R. Yang, H. Huang, Y. Chen, X. Zhang, H. Lu, Performance of Cr-doped vanadia/titania catalysts for low-temperature selective catalytic reduction of NO_x with NH₃, *Chin. J. Catal.* 36 (2015) 1256–1262.
- [118] B. Li, Z. Ren, Z. Ma, X. Huang, F. Liu, X. Zhang, H. Yang, Selective catalytic reduction of NO by NH₃ over CuO–CeO₂ in the presence of SO₂, *Catal. Sci. Technol.* 6 (2016) 1719–1725.
- [119] M. Magnusson, E. Fridell, H. Harellind, Improved low-temperature activity for marine selective catalytic reduction systems, *Proc. IMechE Part M J. Eng. Marit. Environ.* 230 (2016) 126–135.
- [120] Y. Yu, J. Chen, J. Wang, Y. Chen, Performances of CuSO₄/TiO₂ catalysts in selective catalytic reduction of NO_x by NH₃, *Chin. J. Catal.* 37 (2016) 281–287.
- [121] X. Du, X. Wang, Y. Chen, X. Gao, L. Zhang, Supported metal sulfates on Ce–TiO_x as catalysts for NH₃-SCR of NO: high resistances to SO₂ and potassium, *J. Ind. Eng. Chem.* 36 (2016) 271–278.
- [122] M. Kiełtyka, A.P.S. Dias, H. Kubiczek, B. Sarapata, T. Grzybek, The influence of poisoning on the deactivation of DeNO_x catalysts, *C.R. Chim.* 18 (2015) 1036–1048.
- [123] R. Ke, J. Li, X. Liang, J. Hao, Novel promoting effect of SO₂ on the selective catalytic reduction of NO_x by ammonia over Co₃O₄ catalyst, *Catal. Commun.* 8 (2007) 2096–2099.
- [124] A. Väliheikki, T. Kolli, M. Huuhtanen, T. Maunula, R.L. Keiski, Activity enhancement of W–CeZr oxide catalysts by SO₂ treatment in NH₃-SCR, *Top. Catal.* 58 (2015) 1002–1011.
- [125] L. Zhang, H. Qu, T. Du, W. Ma, Q. Zhong, H₂O and SO₂ tolerance, activity and reaction mechanism of sulfated Ni–Ce–La composite oxide nanocrystals in NH₃-SCR, *Chem. Eng. J.* 296 (2016) 122–131.
- [126] L. Qiu, Y. Wang, D. Pang, F. Ouyang, C. Zhang, SO₄^{2–}–Mn–Co–Ce supported on TiO₂/SiO₂ with high sulfur durability for low-temperature SCR of NO with NH₃, *Catal. Commun.* 78 (2016) 22–25.
- [127] P. Wang, H. Zhao, H. Sun, H. Yu, S. Chen, X. Quan, Porous metal–organic framework MIL-100(Fe) as an efficient catalyst for the selective catalytic reduction of NO_x with NH₃, *RSC Adv.* 4 (2014) 48912–48919.
- [128] H. Jiang, Q. Wang, H. Wang, Y. Chen, M. Zhang, MOF-74 as an efficient catalyst for the low-temperature selective catalytic reduction of NO_x with NH₃, *ACS Appl. Mater. Interfaces* 8 (2016) 26817–26826.
- [129] P. Wang, H. Sun, X. Quan, S. Chen, Enhanced catalytic activity over MIL-100(Fe) loaded ceria catalysts for the selective catalytic reduction of NO_x with NH₃ at low temperature, *J. Hazard. Mater.* 301 (2016) 512–521.