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Low-temperature SCR of NO with NH_3 over AC/C supported manganese-based monolithic catalysts

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Abstract

Metal oxide/active carbon/ceramic (MO_x/AC/C) monolithic catalysts were prepared by impregnation method for selective catalytic reduction (SCR) of NO_x with NH_3 at low-temperature, and they also had been characterized by elemental analysis, N_2-BET, XRD, SEM and NO-TPD. The adsorption capability of the monolithic catalyst was greatly enhanced due to the attached active carbon. An ultrasonic treatment was used to improve the impregnation process, and which can increase their catalytic activities. More than 90% NO_x conversion could be achieved over the Mn-based monolithic catalysts at low-temperature, and which could be improved further by doping Ce, from 30% to 78% at 100 °C. Mn–Fe–Ce and Mn–V–Ce monolithic catalysts had better tolerance to SO_2 than Mn or Mn–Ce monolithic catalysts.

Keywords: Monolithic catalyst; Active carbon; NO_x; Ammonia; SCR; Low-temperature

1. Introduction

The selective catalytic reduction (SCR) of NO_x by ammonia is the major technology to reduce nitrogen oxide emissions from stationary sources. The common commercialized industrial catalyst for NO_x-SCR are $V_2O_5 + WO_3$ (MoO_3)/TiO_2 catalysts, which are operated under 300–400 °C, and substantial work had been done to improve the performance of vanadium type catalysts [1–5]. However, SO_2 and the high concentrations of ash, e.g. K_2O, CaO and As_2O_3, in the flues reduce their performance and durability. Therefore, the trend is to develop low-temperature catalysts capable of working downstream of the dust removal equipment and desulfuration devices for flue gases without the need for reheating. The present work is focused on the study of several transition metals oxides (Fe, Cr, Ni, Cu and Mn), which are among those known to be active in the low-temperature deNOx SCR reaction (Fe [6–8], Cr [9,10], Ni [11], Cu [6,12–14] and Mn [7,15–23,29–31]).

Carbon had been studied as the catalyst support for the low-temperature NO_x-SCR by many researchers due to its high specific area and its chemical stability. These investigations included many types of carbon materials, granular active carbon (GAC) [7], activated carbon fibers (Nomex-based ACFs) [22,23], A-572 active carbon [24], chars and activated chars [25], carbonized resin [6,17], fluorinated carbon fibers [26] and commercial coal-derived semi-coke [27,28].

In this work, an effective method was developed to prepare active carbon support (AC/C) [29]. Monolithic catalysts were prepared by impregnation of AC/C with certain aqueous solutions of nitrate (Mn, Fe and Cu), and ultrasonic treatment was used to improve this process. Mn-based catalysts showed good activity for NO_x-SCR with NH_3 at low temperature, and they were characterized by elemental analysis, N_2-BET, XRD, SEM and NO-TPD.

2. Experimental

2.1. Catalyst preparation

The ceramic honeycomb support was cut into small column samples, which were 15 mm in length and 12 mm in diameter. After pretreatment with nitric acid solution (40 vol.%) and washing with the de-ionized water, these supports were immersed into the mixed resin solution (PF resins, polyethylene glycol and propanone). Then, the support was flushed with compressed air to remove the excess solution in the channels,

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and cured in air (100 °C, 30 min). The following steps of AC/C support manufacturing process were described in Ref. [17]. In our work, the carbon content of the final AC/C support was 12–14 wt.%. There were four steps in the active components loading procedure: (i) equilibrium adsorption impregnation of metal nitrate solution; (ii) use of ultrasonic to enhance the loading and the dispersion procedure; (iii) washing with the deionized water and drying at 100 °C for 1 h; and (iv) calcining in N_2 at 400 °C for 1 h. The former three steps were adopted in order to maximize the dispersion and loading of metal oxides, and the active sites were formed in the final step.

It is well known that the balance between dispersion and loading of metal oxides is a key factor, which impacts the catalyst activity directly. Increasing the metal oxide loading will result in the aggregation of metal oxides to decrease the dispersion; however, low loading could ensure good dispersion, but the quantity of the active sites over the support will also be too little. Preliminary testing about the loading of metal oxides had been carried out, and the results showed that loading at 8–10 wt.% is best. All of the catalysts in this work were prepared by same methodology; the loading of metal oxides was controlled at 8 wt.%.

2.2. Catalyst characterization

BET-surface areas were measured by N_2 adsorption using a NOVA4000 automated gas sorption system. X-ray diffraction (XRD) measurements were carried out on D8 Advance X-ray diffractometer with Cu Kα radiation. Before the XRD test, the catalyst should be crushed and ground. A scanning electron microscope (HITACHI, S-450) was used to collect the surface information of the monolithic catalyst.

Temperature programmed desorption (TPD) experiments of NO were performed by using a monolithic catalyst. The desorbed samples were monitored continuously by a Quintox Flue Gas Analyzer (KM9106, Kane-May). Prior to the TPD-NO experiment, the catalyst sample was pre-treated in a flow of 3% O_2/N_2 at 250 °C for 1 h and then cooled down to room temperature. Chemiadsorption of NO was performed by passing a flow of 500 ppm NO/N_2 through the catalyst at room temperature for 1 h. Afterward, the sample was purged in N_2 until no NO was detected, and the TPD measurements were carried out up to 450 °C with a heating rate of 10 °C min^{-1} in flowing N_2. The gas flow rate was fixed at 300 cm^3 min^{-1}. The amount of NO desorption from catalyst was quantified by calibrating the peak area against that of a standardized NO pulse.

2.3. Catalytic activity measurement

Catalytic activity tests were performed in a quartz tube reactor of 12 mm internal diameter. NO_x, O_2 and SO_2 concentration in the inlet and outlet gases were simultaneously measured by Quintox Flue Gas Analyzer (KM9106, Kane-May). At steady state, a gas N_2 mixture containing 500 ppm NO, 550 ppm NH_3, 3% O_2, 100 ppm SO_2 (when used) was introduced into the reactor. In all tests, the total flow rate was controlled at 300 cm^3 min^{-1}, which corresponded to a gas hourly space velocity (GHSV) of 10,610 h^{-1} (based on the monolith volume). NO_x conversion was obtained by following equation:

$$NO_x \text{ conversion } (\%) = \left[1 - \frac{(NO + NO_2)_{outlet}}{(NO + NO_2)_{inlet}}\right] \times 100$$

2.4. NO oxidation to NO_2

Some previous experiments indicated that the oxidation of NO to NO_2 is important to low-temperature SCR [7,18,20]. Increasing the O_2 content of the airflow could improve NO oxidation, which also could be achieved by doping with another metal element to enhance the oxidizability of catalyst [18]. An oxidation capability investigation for each catalyst would be helpful to further the catalytic mechanism study.

The experiment of NO oxidation to NO_2 was performed in a fix-bed quartz reactor. Samples of each metal oxide (0.2 g) were used and the conversion at each temperature was obtained after 1 h at steady state.

3. Results and discussion

3.1. Characterizations of catalysts

The BET-surface area, pore volume, and pore size of monolithic catalysts were summarized in Table 1. The surface areas were 5.08, 101.3 and 88.71 m^2/g for bared ceramic, AC/C and MnO_x/AC/C. The results showed that the surface area of ceramic support is enhanced greatly by attached AC. Due to calcination, the surface area, pore volume and average pore diameter of all monolithic catalyst samples decreased after the active component loading process.

The adsorption of NO was enhanced greatly because of the attached active carbon, as shown in Fig. 1. The attached AC will increase NH_3 adsorption and activation, and much work had been done to indicate that it is a key step in the low-temperature SCR reaction [30–32]. Due to the limited surface area, the TPD profile of bare ceramic only shows a small peak at 80 °C, and soon disappears. In case of MnO_x/AC/C, one large desorption peak appears at a relative high temperature, 200 °C. The AC/C shows a different TPD profile in which two distinct desorption peaks of NO are observed. The first large peak is centered at about 180 °C and the second one is centered at 400 °C. The amounts of NO desorption calculated based on the results of

Table 1
Characterization of the catalysts

Samples	BET-surface area (m^2/g)	Pore volume (cm^3/g)	Average pore diameter (nm)
Bared ceramic	5.08	0.051	4.01
AC/C	101.3	0.078	3.05
MnO_x/AC/C	88.71	0.057	2.56
MnO_x–CeO_2/AC/C	79.61	0.053	2.55
CuO/AC/C	82.77	0.052	2.56

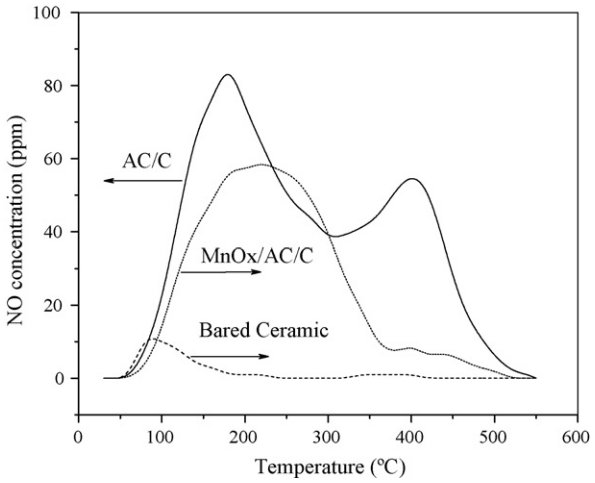

Fig. 1. TPD profiles of NO on bare ceramic (dash line), AC/C (solid line) and MnO_x/AC/C (dot line). Conditions: TPD measurements were carried out up to 550 °C with a heating rate of 10 °C min^{-1} in flowing N_2. The gas flow rate was fixed at 300 cm^3 min^{-1}.

Fig. 1 are 1.23, 16.82 and 27.42 μmol g^{-1} for bare ceramic, MnO_x/AC/C and AC/C. The attached AC over the monolithic catalyst results in an increase in the amount of NO chemiadsorption. This is especially obvious over fresh AC/C supports.

Four samples with different MnO_x loading, 2.5, 5, 8 and 15 wt.%, were analyzed by X-ray diffraction. In Fig. 2, the XRD profiles of the former three samples have no characteristic peaks of manganese oxides. Until the loading increases to 15 wt.%, the manganese oxides could be detected, mainly as Mn_2O_3. Therefore, in this work all monolithic catalysts were prepared at an appropriate metal oxides loading value, 8 wt.%, suggesting that the active sites will be well dispersed on the catalysts.

Further surface information of the catalysts were shown in the followed SEM photos (Fig. 3). The surface of bare ceramic (Fig. 3A) was coarse and there were many macropores on its surface, which would encourage the metal oxides to be dispersed unevenly. The surface of AC/C (Fig. 3B) was improved by the attached AC, which became smoother than it had been, and the rate of mesopores and micropores increased. The partially enlarged photographs of bare ceramic and AC/C (Fig. 3a and b) show more clearly that the amounts of macropores decreased on the surface of AC/C. In another catalyst stability test, we found that the attached AC would be lost by oxidation, at relative high temperature (>250 °C). As Fig. 3C shows, more macropores appeared and some slight AC pieces fell out; each of these phenomena would cause the deactivation of monolithic catalysts. Furthermore, many small particle materials were observed on the monolithic catalyst surface after SO_2 deactivation testing (as Fig. 3c showed), which might be sulfate, i.e. $(NH_4)_2SO_4$. This indicates that one aspect of the SO_2 deactivation of the monolithic catalyst was due to the active sites on the catalyst surface were covered by the sulfate particles, and the SCR reaction could not carried out effectively.

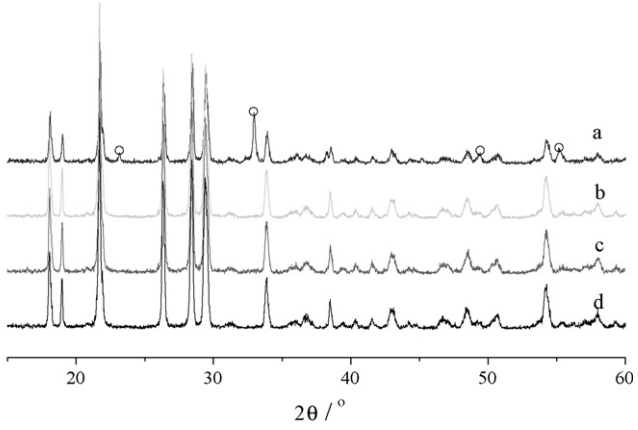

Fig. 2. XRD patterns of MnO_x/AC/C with different manganese oxides loading. The manganese oxides loading of monolithic catalysts are 15%, 8%, 5% and 2.5% (wt.%) to sample a, b, c and d. All samples had been crushed and ground before XRD test.

3.2. Effect of ultrasonic treatment

In the preparation of the catalysts, the ultrasonic treatment was used to improve the impregnation procedure, and which has significant effect on the catalytic activity of monolithic catalyst at low-temperature. In case of MnO_x/AC/C impregnation without ultrasonic treatment, the best loading of manganese oxides is only 2 wt.% (Fig. 4), and after this the activity would decrease as loading increased, especially after 200 °C.

The best loading of manganese oxides was 8 wt.% with aid of ultrasonic treatment for the impregnation. The low-temperature catalytic activity improved greatly; the NO_x conversion increased from 52% to 77% at 150 °C (Fig. 5), but showed almost no variation at high temperature (>200 °C). This is mainly due to the ultrasonic treatment that enhanced the metal component dispersion on the catalyst surface during the impregnation procedure, which results in the increase of active sites on the catalyst surface.

At low-temperature, the SCR reaction rate is slow, so the increasing of the amount of the active sites over the catalyst surface is very important to improve the catalytic activity; but with the reaction temperature rising, this positive impact will be weaken due to the reaction rate speedup.

3.3. Catalytic activity

Some catalysts supported on active carbon showed good low-temperature activity, e.g. PFCu, PFFe [6], V_2O_5/AC [27] and MnOx/AC/C [29]. Besides, the MnOx–CeO_2 catalyst was reported for its superior catalytic activity at 100–150 °C, and doped Fe or Pr could improve its resistance to SO_2 [18]. So, in this work we prepared series of metal oxide monolithic catalysts, besides above-mentioned metal elements, also investigated noble metal, Pd and Pt. The activity data are summarized in Fig. 6.

As shown in Fig. 6, in single metal oxide catalysts, Mn/AC/C has better low-temperature activity than others (Cu, Fe and V). More than 90% NO_x conversion could be achieved at 180 °C over the Mn/AC/C catalyst, but only 51%, 35% and

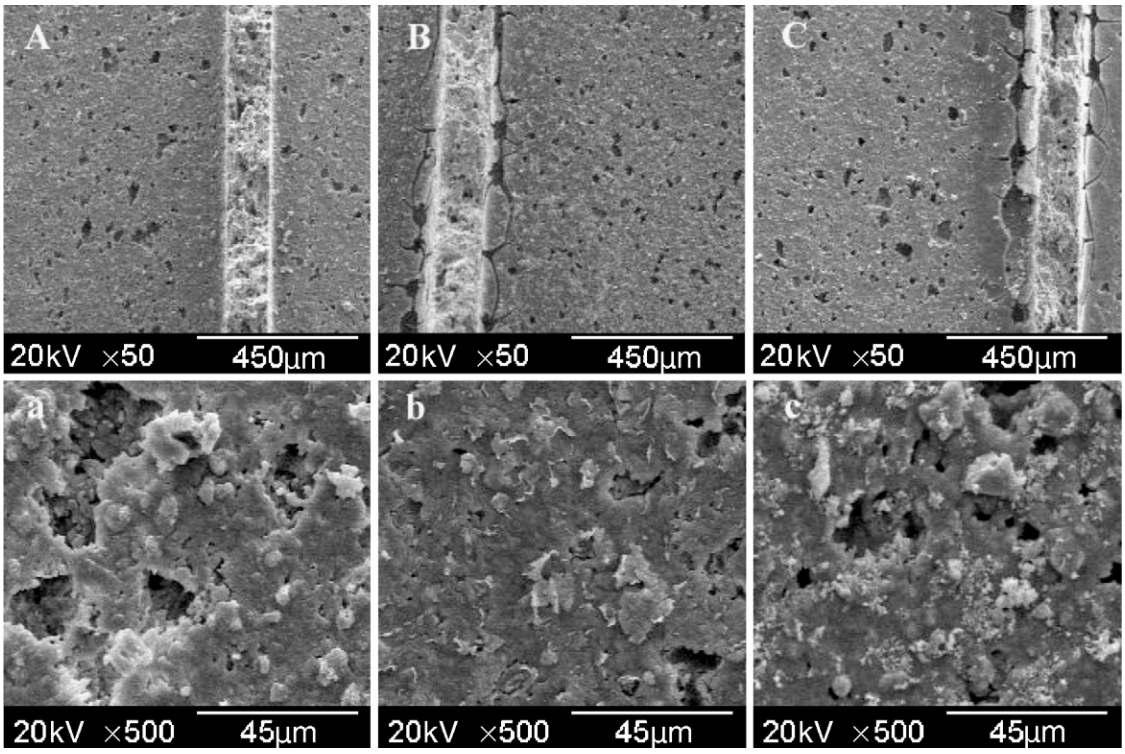

Fig. 3. SEM photos of monolithic catalysts. (A) Bare ceramic support; (B) fresh MnO_x/AC/C catalyst; (C) MnO_x/AC/C after stability activity test; (a) part of A; (b) part of B; (c) MnO_x/AC/C after SO_2 test.

38% over the Cu/AC/C, Fe/AC/C and V/AC/C catalysts, respectively.

In order to decrease the loss of the active carbon, we tried to improve the low-temperature activity of the catalyst. The low-temperature activity of the Mn-based monolithic catalyst is enhanced by doped cerium, as showed in Fig. 6. Near 80% NO_x conversion could be achieved at 100 °C and more than 90% conversion occurred in a broad temperature range. Besides, noble metal is also considered to improve the SCR catalytic activity of MnO_x–CeO_2/AC/C at even lower temperature. The impact of Pd and Pt are reverse. Pd component doping can improve the low-temperature catalytic activity (100–150 °C), but the promotion is slight. Contrary, when Pt doped, the catalytic activity is abated obviously, which may due to the NH_3 oxidation was promoted extremely by Pt component.

More than 90% NO_x conversion can be achieved over MnO_x-based monolithic catalysts (except Pt–MnO_x–CeO_2/AC/C), and their low-temperature (<200 °C) SCR activity decreased in the following sequence: Pd–MnO_x–CeO_2/AC/C > MnO_x–CeO_2/AC/C > MnO_x/AC/C.

Though high NO_x conversion also could be achieved over CuO and V_2O_5 monolithic catalysts, the operating temperature

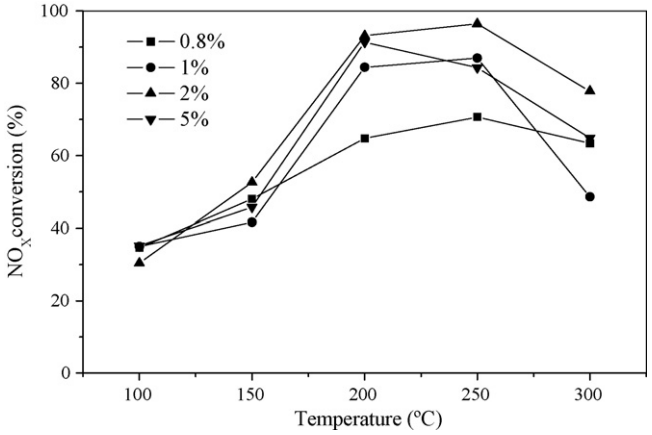

Fig. 4. Activity test of MnO_x/AC/C with different MnO_x loading (without ultrasonic treatment). Conditions: 500 ppm NO, 550 ppm NH_3, 3% O_2, N_2 to balance, GHSV = 10,600 h^{-1}.

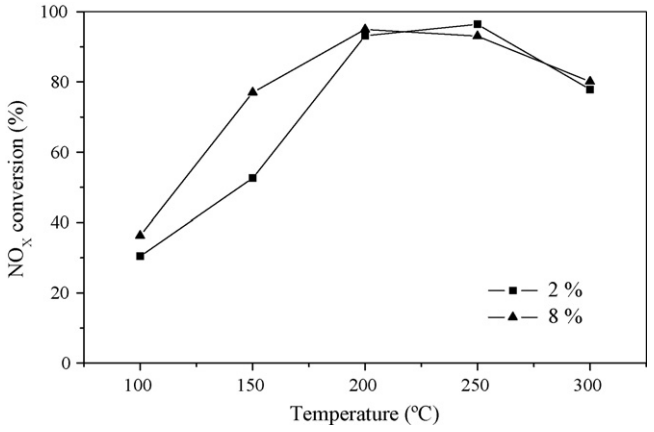

Fig. 5. Catalytic activity comparison of two monolithic catalysts. One was prepared by normal impregnation method, and the best loading of MnO_x is 2 wt.%. Another was prepared by improved impregnation method (with ultrasonic treatment); the best loading of MnO_x is 8 wt.%. Conditions: 500 ppm NO, 550 ppm NH_3, 3% O_2, N_2 to balance, GHSV = 10,600 h^{-1}.

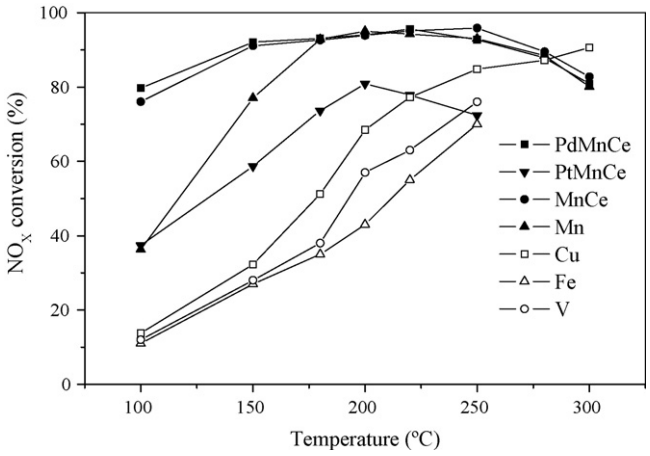

Fig. 6. Catalytic activity comparison of different metal oxides supported on AC/C cellular monolithic catalysts. Conditions: 500 ppm NO, 550 ppm NH_3, 3% O_2, N_2 to balance, GHSV = 10,600 h^{-1}.

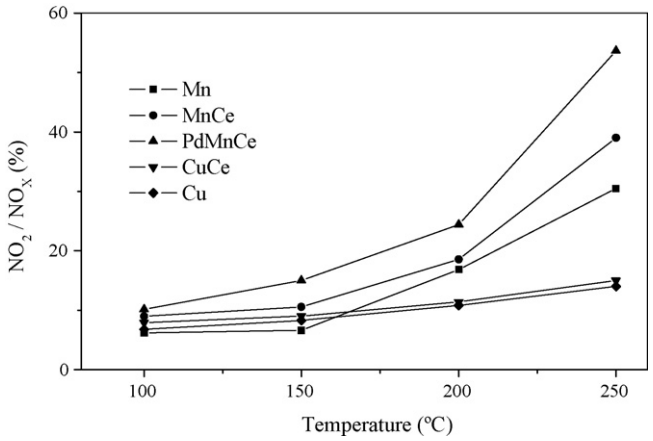

Fig. 8. Oxidation activity of NO to NO_2 by O_2 on different metal oxides catalysts. Conditions: 0.2 g samples, 500 ppm NO, 3% O_2, N_2 to balance, GHSV = 70,700 h^{-1}.

were relative high (>300 °C). High temperature is adverse to the catalyst durability; because the attached AC will be oxidized into CO_2/CO, a reaction accelerated at high temperature.

3.4. Effect of O_2

O_2 is important in the SCR reaction, especially at low-temperature. The prior research about the SCR mechanism over MnO_x–CeO_2 [20] indicates that the NO oxidation to NO_2 and NH_3 activation to NH_2/OH are the key steps in the SCR reaction. Increasing O_2 content or enhancing the oxidizing capability of the catalyst both can improve these two steps. The following experiments were carried out to investigate the effect of O_2 at different temperature over MnO_x/AC/C catalyst.

As Fig. 7 shows, the promoter action of O_2 was obvious at low temperature, 100–150 °C. The NO_x conversion was only 17.1% at 100 °C when the O_2 content was 1%, however, it could achieve 46.3% with 7% O_2. But the improvement of O_2 will be slight as the reaction temperature rises. At 200 °C, the profiles show almost no change with different O_2 content.

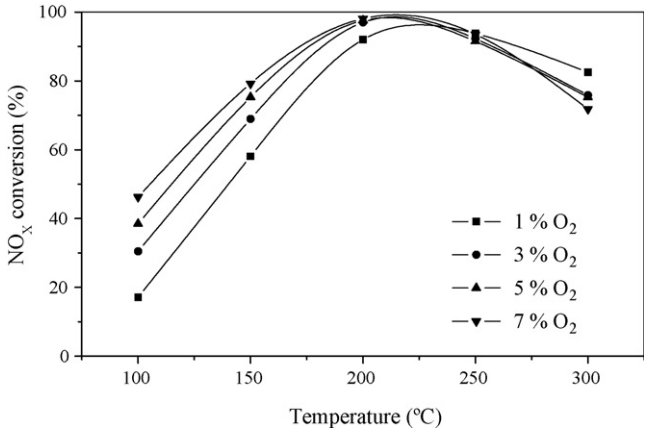

Fig. 7. Effect of O_2 concentration on catalytic performance on MnO_x/AC/C. Conditions: 500 ppm NO, 550 ppm NH_3, 1–7% O_2, N_2 to balance, GHSV = 10,600 h^{-1}.

The importance of O_2 was also verified by a similar work of Qi and Yang [18]. Transient behavior of the catalyst was tested by turning the O_2 off and on in the gas flow. The test showed that the NO conversion declined quickly after O_2 was turned off, but it could be restored by switching the O_2 back on.

3.5. NO oxidation to NO_2

The oxidation activities of NO to NO_2 by O_2 on certain metal oxides (powder) were measured (Fig. 8), and all samples were prepared by the citric acid method [18]. On MnO_x-based catalysts, though, the oxidation activities of NO to NO_2 were limited at low temperature, but quickly increased with rising temperature. As Fig. 8 shows, after Ce and Pd were doped, the oxidization of NO to NO_2 was greater than before. However, the oxidizing capability of CuO and CuO–CeO_2 are very low, and almost no variation occurred with changing the temperature.

3.6. SO_2 deactivation

In order to evaluate the effect of SO_2 on catalytic activity, catalytic tests in which SO_2 100 ppm was added to the feed gas were performed at 200 °C.

The results of experiments are plotted in Fig. 9, in which the bars indicate the ratio of NO_x conversions (X, SO_2 were added) to the initial conversion (X_0, without SO_2). In our tests, the catalytic activity of all monolithic catalysts was decreased, and only V_2O_5/AC/C performed better. Though MnO_x/AC/C and MnO_x–CeO_2/AC/C had good low-temperature activity, both were easily deactivated by SO_2. Doping the MnO_x-based monolithic catalysts with Fe or V improved the resistance to SO_2, but the value of X/X_0 was still not ideal, only 51% when doped with Fe and 56% when doped using V. Furthermore, their activity could not be restored when SO_2 was turned off.

When these observations were combined with the SEM photo, Fig. 3c, the SO_2 deactivation of catalysts might have two causes. On one hand, the metal oxides on the supports, acting as

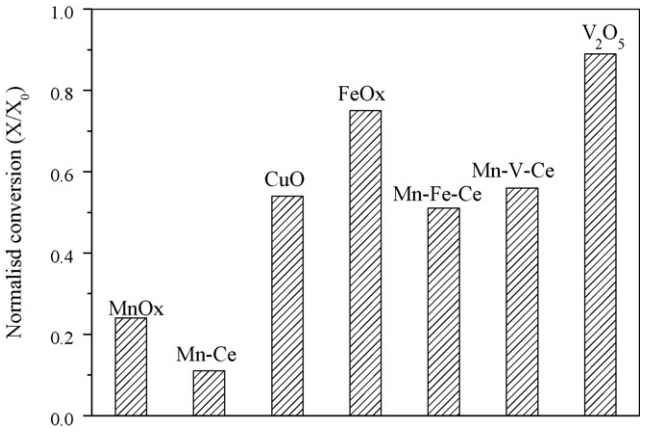

Fig. 9. Effect of SO_2 on activities on different monolithic catalysts. Conditions: 500 ppm NO, 550 ppm NH_3, 100 ppm SO_2, 3% O_2, N_2 to balance, 200 °C, GHSV = 10,600 h^{-1}.

active sites of the monolithic catalyst, were sulfated by SO_2 and lost activity. Alternatively, the reductant (NH_3) reacted with SO_2 and produced $(NH_4)_2SO_4$. Along with the reaction, more and more $(NH_4)_2SO_4$ particles formed and deposited on the catalyst's surface, covering many active sites, which resulted in a blocking of the SCR reaction. The first effect of SO_2 was irreversible, but subsequent impacts could be eliminated by washing to remove the deposited $(NH_4)_2SO_4$ or heating at relative high temperature to decompose it.

In other investigations [16,17,33,34], the results indicated that the deactivation of SO_2 will be weak with increasing temperature, and interestingly, adding SO_2 could improve the SCR reaction after 300 °C, but not at low temperature (<200 °C).

4. Conclusion

The present work has shown that the MnO_x-based monolithic catalysts are more active than other metal oxide catalysts for low-temperature SCR reactions of NO with NH_3 in the presence of excess oxygen. More than 90% NO_x conversion was obtained over the range of 150–250 °C under the condition of GHSV = 10,600 h^{-1}. During the catalyst preparation, ultrasonic treatment can promote the dispersion of metal oxides on the surface of the AC, and improve the low-temperature catalytic activity, especially at 150 °C (Fig. 5). The investigation of O_2 effect and the oxidation of NO to NO_2 on monolithic catalysts both indicate that NO oxidation is one of the essential factors of low-temperature SCR reaction. Doping with Ce and Pd can improve the MnO_x-based monolithic catalysts, and result in the SCR reaction being performed more effectively. The tolerance to SO_2 of MnO_x-based catalysts could be enhanced by doping with Fe and V, and more than 50% of the catalytic activity could remain under conditions of 100 ppm SO_2 in the flue gas. The deactivation of SO_2 might be caused by two reasons, metal oxides sulfuration which is irreversible or $(NH_4)_2SO_4$ deposition.

Acknowledgements

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References

[1] B. Stefan, H. Thomas, Appl. Catal. B 28 (2000) 101–111.
[2] S. Djerad, L. Tifouti, M. Crocoll, W. Weisweiler, J. Mol. Catal. A: Chem. 208 (2004) 257–265.
[3] S.T. Choo, S.D. Yim, I.S. Nam, S.W. Ham, J.B. Lee, Appl. Catal. B 44 (2003) 237–252.
[4] V.I. Pârvulescu, S. Boghosian, V. Pârvulescu, S.M. Jung, P. Grange, J. Catal. 217 (2003) 172–185.
[5] N. Macleod, R.M. Lambert, Catal. Lett. 90 (2003) 111–115.
[6] H. Teng, L.Y. HSU, Y.C. Lai, Environ. Sci. Technol. 35 (2001) 2369–2374.
[7] M. Yosikawa, A. Yastutake, I. Mochida, Appl. Catal. A 173 (1998) 239–245.
[8] G. Ramis, M.A. Larrubia, J. Mol. Catal. A: Chem. 215 (2004) 161–167.
[9] M.J. Illan-Gomez, A. Linares-Solano, C. Salinas-Martinez de Lecea, Energy Fuel 9 (1995) 976–983.
[10] B.L. Duffy, H.E. Curry-Hyde, N.W. Cant, P.F. Nelson, Appl. Catal. B 5 (1994) 133–147.
[11] J. Blanco, P. Ávila, S. Suárea, J.A. Martín, C. Knapp, Appl. Catal. B 28 (2000) 235–244.
[12] J. Blanco, P. Avila, S. Suárez, M. Yates, J.A. Martin, L. Marzo, C. Knapp, Chem. Eng. J. 97 (2004) 1–9.
[13] G. Centi, S. Perathoner, D. Biglino, E. Giamell, J. Catal. 152 (1995) 75–92.
[14] G. Ramis, L. Yi, G. Busca, M. Turco, E. Kotur, R.J. Willey, J. Catal. 157 (1995) 523–535.
[15] K. Krishna, G.B.F. Seijger, C.M. van den Bleek, H.P.A. Calis, Chem. Commun. 18 (2002) 2030–2031.
[16] T.S. Park, S.K. Jeong, S.H. Hong, S.C. Hong, Ind. Eng. Chem. Res. 40 (2001) 4491–4495.
[17] T. Valdés-Sol'ıs, G. Marbán, A.B. Fuertes, Appl. Catal. B 46 (2003) 261–271.
[18] G. Qi, R.T. Yang, J. Catal. 217 (2003) 434–441.
[19] W.S. Kijlstra, J.C.M.L. Daamen, J.M. van de Graaf, B. Van de Linden, E.K. Poels, A. Bliek, Appl. Catal. B 7 (1996) 337–357.
[20] G. Qi, R.T. Yang, R. Chang, Appl. Catal. B 51 (2004) 93–106.
[21] M. Kantcheva, J. Catal. 204 (2001) 479–494.
[22] G. Marbán, A.B. Fuertes, Appl. Catal. B 34 (2001) 43–53.
[23] G. Marbán, A.B. Fuertes, Appl. Catal. B 34 (2001) 55–71.
[24] K. Jurczyk, R.S. Drago, Appl. Catal. A 173 (1998) 145–151.
[25] M.J. Lázaro, M.E. Gálvez, I. Suelves, R. Moliner, S.V. Vassilev, C. Braekman-Danheux, Fuel 83 (2004) 875–884.
[26] W. An, Q.L. Zhang, K.T. Chuang, A.R. Sanger, Ind. Eng. Chem. Res. 41 (2002) 27–31.
[27] Z.G. Huang, Z.P. Zhu, Z.Y. Liu, Appl. Catal. B 39 (2002) 361–368.
[28] Z.P. Zhu, Z.Y. Liu, S.J. Liu, H.X. Niu, Appl. Catal. B 23 (1999) L229–L233.
[29] T. Valdés-Sol'ýs, G. Marbán, A.B. Fuertes, Catal. Today 69 (2001) 259–264.
[30] M. Richter, A. Trunschke, U. Bentrup, K.W. Brzezinka, E. Schreier, M. Schneider, M.M. Pohl, R. Fricke, J. Catal. 206 (2002) 98–113.
[31] W.S. Kijlstra, D.S. Brands, H.I. Smit, E.K. Poels, A. Bliek, J. Catal. 171 (1997) 219–230.
[32] G. Delahay, S. Kieger, N. Tanchoux, P. Trens, B. Coq, Appl. Catal. B 52 (2004) 251–257.
[33] S. Okazaki, M. Kumasaka, J. Yoshida, K. Kosaka, Ind. Eng. Chem. Prod. Res. Dev. 20 (1981) 301–305.
[34] W.B. Li, R.T. Yang, K. Krist, J.R. Regalbuto, Energy Fuel 11 (1997) 428–432.