

Preparation of Mn-Ce/TiO₂ Catalysts and its Selective Catalytic Reduction of NO at Low-temperature

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Abstract. The catalytic performance of NO removal was studied over Mn-Ce/TiO₂ catalysts prepared by rheological phase method under different preparation parameters, such as preparation method, manganese precursor, Mn/(Mn+Ce) molar ratio and calcination conditions. It was found that manganese nitrate and manganese acetate were more conducive to high denitration efficiency than manganese chloride. The highest NO conversion of 92% is achieved at the Ce/(Mn+Ce) molar ratio of 0.15, which is much higher than that of the pure manganese constituent. The increase of calcining temperature favored the crystallization of active components and leads to the decline of catalytic activity.

1. Introduction

Nitrogen oxides (NO_x), which could cause varieties of pollutions to the atmosphere, such as acid rain, photochemical smog and eutrophication of surface water, etc., are among the worst pollutions in the world nowadays. Moreover, they can also be involved in the formation of particulates in air and as a result, have significant adverse effect to ecological environment and human health. Therefore, it is urgent to control the emission of NO_x to avoid further pollution. Selective Catalytic Reduction (SCR), in which reducing agents were used to transform NO_x into N₂ and H₂O with the help of oxygen at the right temperature and the presence of a catalyst, has been proved as an effective technology to reach that goal.

Vanadium-based catalysts doping with WO₃ or MoO₃ are the most prevalent commercial catalysts used in manufacture factories. This kind of catalyst has to be installed upstream the particle matter collector to meet their active temperature of 300~400°C. As a result, the high concentration of dust, fly ash and other harmful impurities in the flue gas would cause such problems as deactivation, blockage or abrasion, leading to the increase of cost. Obviously, low temperature SCR technology can avoid these problems.

According to the literature ^[1-3], transition metal oxides, especially with manganese oxide, have better low-temperature activities than other catalyst. This is mainly due to the advantage of their non-crystal type and valence state exchange of MnO_x over redox reaction. Many studies ^[4-6] found that manganese-cerium oxides had a higher SCR activity than pure manganese oxides. However, most of them were focus on powder catalyst which was difficult to apply in industry.

In this paper, the strip-shaped Mn-Ce/TiO₂ catalysts were prepared by extrusion molding. The effect of preparation parameters, such as preparation method, manganese precursor, Mn/(Mn+Ce) molar ratio, and calcination conditions were investigated. To the best of our knowledge, such research has not been reported before.



2. Experimental

2.1. Catalysts Preparation

The TiO₂ powder was mixed with deionized water and shaped into strips via a mini-extruder, then dried at 60 °C, and finally calcined at 800°C for 6h in a muffle furnace. Ce(NO₃)₃•6H₂O and manganese precursor, including Mn(NO₃)₂•4H₂O (50w%) solution, Mn(CH₃COO)₂•4H₂O and MnCl₂. were dissolved in deionized water. Then the mixed solution was placed on the magnetic stirrer and stirred evenly. The TiO₂ strips were dipped into the beaker containing the mixture. Finally the TiO₂ strips adsorbed completely were dried at 60°C and calcined at 500 °C for 6h in the muffle furnace.

2.2. Catalyst Characterization

Bulk crystalline structures of catalysts were performed on a German D8 advance X-ray diffraction using a Cu K α ($\lambda=0.15406\text{nm}$) X-ray source, within the scan range 10-80°. BET surface area, pore volume, and the pore size distribution were measured by nitrogen adsorption using an Autosorb-iQ physical adsorption system (Quantachrome Instruments, USA).

2.3. Catalyst activity measurement

Standard cylinders to simulate flue gas used in the experiment, the gas composition of NO (600×10^{-6}), NH₃ (600×10^{-6}), O₂ (6%) and N₂ as carrier gas. In all the runs, the total gas flow rate of 833ml/min and GHSV was about 1000 h⁻¹. The loading volume of catalyst sample is 5ml. The SCR activity measurement was carried on in a quartz tube fixed bed reactor which specifications is $\Phi 8 \text{ mm} \times 1000 \text{ mm}$. Using an external electric heating mode, the temperature of fixed bed was controlled by tubular resistance furnace. The NO concentration at the inlet and outlet of the reactor was analyzed by a flue gas analyzer (Testo350, Germany). During the measurements, the NO concentrations at four temperature points, 100°C, 150°C, 200°C and 250°C were measured respectively. And each test temperature point was in stable reaction for at least 10min.

3. Results and discussion

3.1. Effect of manganese precursor on the catalytic activity

Figure 1 shows the denitration efficiency of the samples, which gradually increased with the temperature. The denitration efficiency curve of Mn-Ce/TiO₂(MN) is similar to Mn-Ce/TiO₂(MA) catalysts, which is significantly higher than Mn-Ce/TiO₂(MC) catalysts in the temperature range of 80~200°C. At 200°C, the denitration efficiency of Mn-Ce/TiO₂(MN) and Mn-Ce/TiO₂(MA) catalysts reaches up to 90% above. By contrast, it is only 70% at 200°C for Mn-Ce/TiO₂(MC) samples. Due to the difference in valence state and structure of MnO_x, the denitration activity for these catalysts is also different. Kapteijn et al.^[1] investigated the activity and selectivity of pure manganese oxides for SCR of NO by ammonia and found that the activity and selectivity for N₂ of the unsupported manganese oxide were determined by the oxidation state and the degree of crystallinity, and that Mn₂O₃ exhibited the highest selectivity for nitrogen while the MnO₂ exhibited the highest activity. The sequence of MnO_x catalytic activity for unit surface area is increased as following: MnO₂ > Mn₅O₈ > Mn₂O₃ > Mn₃O₄.

The XRD patterns of the Mn-Ce/TiO₂ catalysts with different manganese precursors are shown in Figure 2. The XRD patterns for Mn-Ce/TiO₂ (MN) catalysts did not show intense or sharp peaks for manganese oxides or cerium oxides and only anatase phase can be observed. However, for Mn-Ce/TiO₂ (MA) samples, typical diffraction peaks of MnO₂ (JCPDS: 44-0141) were identified. And we can see the diffraction peaks of Mn₈O₁₀C₁₃ (JCPDS: 30-0821). Kang^[7] prepared MnO_x by precipitation and the effects of two factors, temperature in precipitation and calcination temperature, were investigated. The resulting showed that some decomposition and amorphous also help to improve the catalytic activity of catalysts. It is consistent with our study.

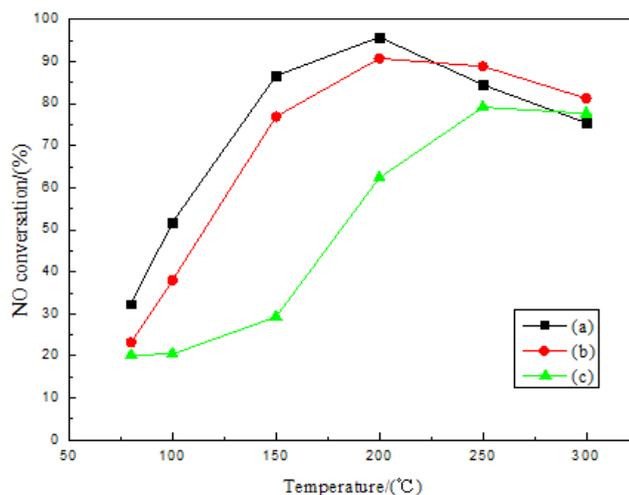


Figure 1 Activity curves of Mn-Ce/TiO₂ catalysts prepared with different manganese precursors
Reaction conditions: NO=600 ppm, NH₃=600 ppm, O₂=6%, GHSV=10000 h⁻¹.
(a) manganese nitrate; (b) manganese acetate; (c) manganese chloride

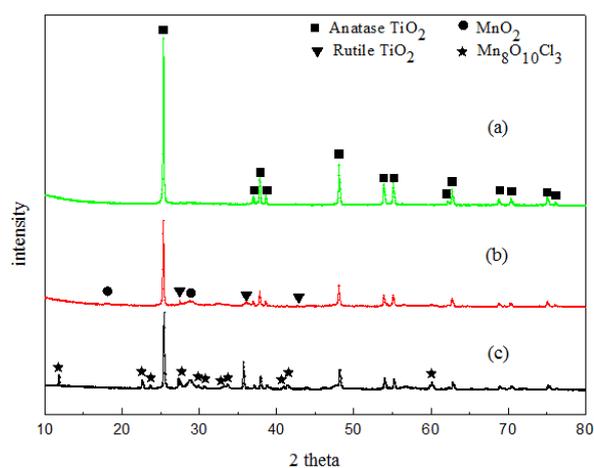


Figure 2 XRD patterns of Mn-Ce/TiO₂ catalysts prepared with different manganese precursors
(a) manganese nitrate; (b) manganese acetate; (c) manganese chloride

3.2. Effect of ceria content on the catalytic activity

Results on NO conversion as a function of temperature is given in Figure 3 for Mn-Ce/TiO₂ catalysts with different molar ratios of Mn/(Mn+Ce). As we can see that the NO conversion activity is greatly improved with the increase of Ce loading from 0 to 0.15, but when the Ce/(Mn+Ce) ratio increased from 0.2 to 0.4, it began to decrease. It seems that there is an optimal ceria content beyond which the overloaded Ce would cover the active sites and thus it would be small or even negative to improve the SCR reaction. The highest NO conversion of 92% is achieved at the Ce/(Mn+Ce) molar ratio of 0.15, which is much higher than that of the pure manganese constituent. The catalytic activity for NO conversion decreases in the following order: Mn(85)-Ce(15)/TiO₂ > Mn(90)-Ce(10)/TiO₂ > Mn(80)-Ce(20)/TiO₂ > Mn(60)/Ce(40)-TiO₂ > Mn(100)/TiO₂.

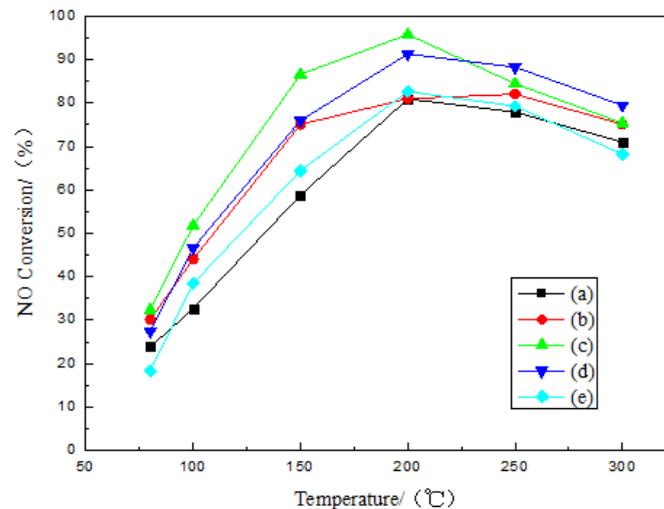


Figure 3 Activity curves of Mn-Ce/TiO₂ catalysts with different molar ratios of Mn/(Mn+Ce)
 Reaction conditions: NO=600 ppm, NH₃=600 ppm, O₂=6%, GHSV=10000 h⁻¹.
 (a) 0%; (b) 10%; (c) 15%; (d) 20%; (e) 40%

Figure 4 shows the powder XRD patterns of the Mn-Ce/TiO₂ samples. According to the main features of the patterns, the samples can be divided into two groups: Mn-pure catalysts (with manganese oxide content of 100%) and Ce-adding catalysts (adding cerium oxide in active component). In all samples, no cerium oxide phases are detected by XRD. For pure manganese oxide sample, i.e. Mn/TiO₂ catalysts, typical diffraction peaks for Mn₂O₃ (JCPDS: 41-1442) are identified besides anatase and little rutile. As a good oxygen reservoir, ceria (CeO₂) has aroused great interest of researchers because of its oxygen storage and reducing properties. After adding Ce, the peaks of Mn oxide are disappeared, due to the synergistic effect of Mn and Ce. As described in previous research^[8], the doped ceria can interact with MnOx and titania species and achieve the enrichment of amorphous manganese oxide active phase, and fortify the available mobile oxygen on the surface of catalyst. These aspects could be attributed to Mn-Ce/TiO₂ samples' high denitration activity.

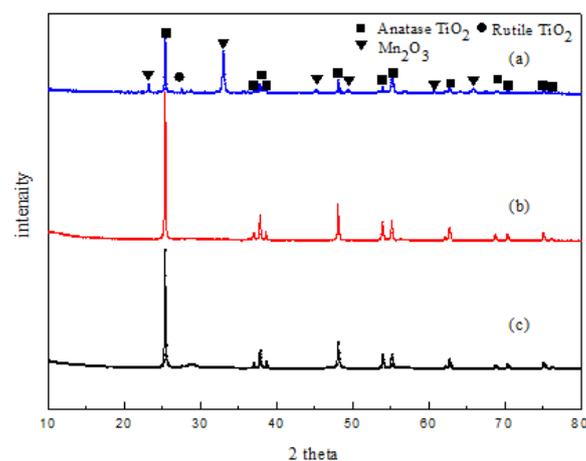


Figure 4 XRD patterns of Mn-Ce/TiO₂ catalysts with different molar ratios of Mn/(Mn+Ce)
 (a) 0%; (b) 15%; (c) 40%

3.3. Effect of calcination temperature on the catalytic activity

The deNO_x performance of the Mn-Ce/TiO₂ catalysts calcined at 500°C, 600°C, 700°C and 800°C for 6h is tested within a reaction temperature range from 100°C to 250°C under a simulate flue gas stream as shown in Figure5. It was observed that, Mn-Ce/TiO₂ catalysts calcined at 500°C and 600°C show superior catalytic activity in the whole temperature range with NO_x conversion above 90% at 150°C, and the NO conversion activity of Mn-Ce/TiO₂-500°C catalysts show some slight decrease at high test temperatures (200~250°C). With the increase of calcination temperature, the activity of catalysts is obviously reduced at low temperature especially below 150°C, indicating the possible severe structural change of Mn-Ce/TiO₂ catalysts after calcination at high temperatures. The denitration rate of Mn-Ce/TiO₂-700°C catalysts drops to 20% at 100°C, while there is almost no active in low temperature of catalysts calcined at 800°C.

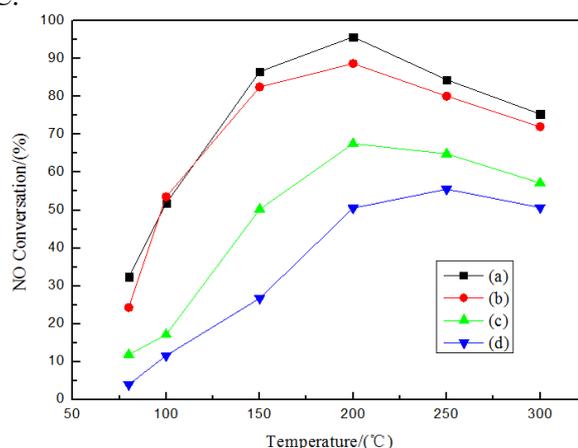


Figure5 Activity curves of Mn-Ce/TiO₂ catalysts calcined at different temperature
Reaction conditions: NO=600 ppm, NH₃=600 ppm, O₂=6%, GHSV=10000 h⁻¹.
(a) 500°C; (b) 600°C; (c) 700°C; (d) 800°C

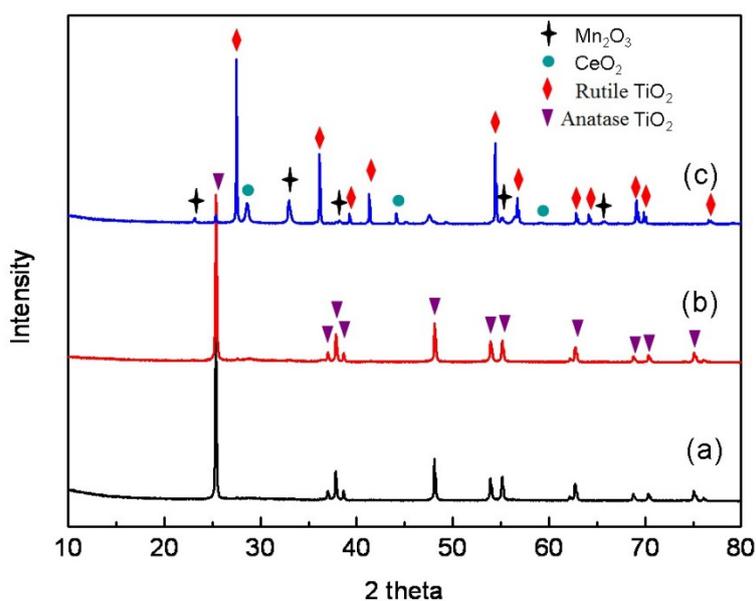


Figure 6 XRD patterns of Mn-Ce/TiO₂ catalysts calcined at different temperature
(a) 500°C, (b) 600°C, (c) 800°C

Typically, the calcination temperature mainly affects the oxidized state and crystallinity of MnOx. Figure 6 shows XRD patterns of Mn-Ce/TiO₂ catalysts at different temperatures, all the peaks of Mn-Ce/TiO₂ catalysts calcined at 500°C and 600°C are anatase. It indicated that TiO₂ consists of anatase as the unique phase and MnOx and CeOx were well dispersed over the support calcined at 500°C or 600°C. When the calcination temperature of catalysts were raised to 800°C, the diffraction peaks of Mn₂O₃ (JCPDS:65-7467) and CeO₂ (JCPDS :65-5923) are detected. And there were two crystal forms, anatase and rutile, coexisting in TiO₂, indicating that the crystal form transformation of TiO₂ happened.

Table 1 BET surface area, pore volume and pore diameter measurements of the catalysts calcined at different temperature

Calcination temperature/°C	Surface Area /m ² ·g ⁻¹	Pore Volume /cm ³ ·g ⁻¹	Pore Size /nm
500	10.27	0.06	21.6
600	5.19	0.02	12.1
800	1.13	0.01	25.7

The BET surface areas, pore volumes, and pore sizes of the various catalysts are summarized in Table 2. From Table 2 we can see that the Mn-Ce/TiO₂ (500°C) has the largest surface area (10.27 m²/g) and the surface area of catalysts calcined at 800°C is only 1.13 m²/g. We can see that with the increasing calcination temperature, there is a continuous decrease in the BET surface area and the decrease is larger after calcination at 800°C. It can be due to various factors that the subsequent decline in the surface area upon thermal treatment at higher temperatures, such as growth of crystallite size, formation of various mixed oxide phases, and sintering.

4. Conclusions

In summary, Mn-Ce/TiO₂ catalysts for low-temperature selective catalytic reduction of NO were prepared with rheological phase method under different preparation parameters. Compared with manganese chloride, manganese nitrate and manganese acetate are more suitable as a precursor, leading to the decline of catalytic activity. With the increase of Ce loading from 0 to 0.15, the NO conversion activity is greatly improved, but when the Ce/(Mn+Ce) ratio increased from 0.2 to 0.4, it begins to decrease. With the increase of calcination temperature, the activity of catalysts is obviously reduced at low temperature especially below 150°C.

Acknowledgements

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References

- [1] Kpteljn F, Singoredjo L and Andreini A 1994 Activity and selectivity of pure manganese oxides in the selective catalytic reduction of nitric oxide with ammonia *Appl Catal B* **3** 173
- [2] Thirupathi B and Smirniotis P G 2011 Co-doping a metal (Cr, Fe, Co, Ni, Cu, Zn, Ce, and Zr) on Mn/TiO₂ catalyst and its effect on the selective reduction of NO with NH₃ at low-temperatures *Appl Catal B* **110** 195
- [3] Liu F D, Asakura K, He H, Liu Y C, Shan W P, Shi X Y and Zhang C B 2011 Influence of calcination temperature on iron titanate catalyst for the selective catalytic reduction of NO_x with NH₃ *Catal Today* **164** 520
- [4] Qi G S and Yang RT 2003 Performance and kinetics study for low-temperature SCR of NO with NH₃ over MnOx-CeO₂ catalyst *J Catal* **217** 434
- [5] Machida M, Uto M, Kurogi D and Kijima T 2000 MnO_x-CeO₂ binary oxides for catalytic NO_x sorption at low temperatures: sorptive removal of NO_x *Chem Mater* **12** 31
- [6] Li H, Tang XL, Yi HH and Yu LL 2010 Low-temperature catalytic oxidation of NO over Mn-

- Ce-Ox catalyst *J Rare Earths* **28** 64
- [7] Kang M, Park ED, Kim JM Cu–Mn mixed oxides for low temperature NO reduction with NH₃. *Catal Today*, 2006, 111: 236-241
- [8] Yu D Q, Liu Y and Wu Z B 2010 Low-temperature catalytic oxidation of toluene over mesoporous MnOx–CeO₂/TiO₂ prepared by sol-gel method *Catal Commun* **11** 788