Novel CeO$_2$@TiO$_2$ core–shell nanostructure catalyst for selective catalytic reduction of NO$_x$ with NH$_3$

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ARTICLE INFO

Article history:
Received 12 March 2016
Revised 20 May 2016
Accepted 26 May 2016
Available online 17 August 2016

Keywords:
SCR
Core-shell
SO$_2$ resistance
CeO$_2$
TiO$_2$

ABSTRACT

The CeO$_2$@TiO$_2$ core–shell nanostructure catalyst prepared by a two-step hydrothermal method was used for selective catalytic reduction (SCR) of NO$_x$ with NH$_3$ in this study. The catalyst presented the obvious core–shell structure, and the shell was amorphous TiO$_2$ which could protect the active center from the SO$_2$ erosion. The catalyst showed high activity and stability, excellent N$_2$ selectivity and superior SO$_2$ resistance and H$_2$O tolerance. Characterizations such as TEM, HR-TEM, XRD, BET, XPS, NH$_3$-TPD, and H$_2$-TPR were carried out. The results indicated that the catalyst had large surface area and the active sites were well dispersed on the surface. The NH$_3$-TPD, H$_2$-TPR and XPS results implied that its increased SCR activity might be due to the enhancement of NH$_3$ chemisorption and the increase of active oxygen species, both of which were conductive to NH$_3$ activation. The excellent catalytic performance suggests that it is a promising candidate for SCR catalyst.

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INTRODUCTION

Selective catalytic reduction (SCR) of NO$_x$ with NH$_3$ is currently the most favored technologies to reduce NO$_x$ from stationary sources (Busca et al., 1998; Huang et al., 2003; Sheng et al., 2012a). Although V$_2$O$_5$-WO$_3$/TiO$_2$-based catalysts have been widely used for the removal of NO$_x$ from stationary sources (Liu et al., 2014), there are still some problems, such as the toxicity of vanadium species, high starting temperature, narrow active temperature window and falling N$_2$ selectivity at high temperature (Cheng et al., 2014). In order to avoid the deactivation by SO$_2$ and dust, low-temperature SCR with NH$_3$ is thought to be a promising method to remove NO$_x$ in flue gas, for that the unit was located downstream of the particulate control device and desulfurization system (Jin et al., 2010; Qi and Yang, 2003; Roy et al., 2008; Sheng et al., 2012b; Wu et al., 2007; Zhuang et al., 2011). Unfortunately, there is still certain amount of SO$_2$ in this region, which could have a serious toxic effect on SCR catalyst in this low temperature range (Sheng et al., 2012a; Wu et al., 2009; Xu et al., 2009). It is generally accepted that there were two main poisoning mechanism aspects caused by SO$_2$ in the SCR reaction, ammonium sulfate salt deposition and active center damage (Jiang et al., 2010). The former can be regenerated by water washing, thermal regeneration or reductive regeneration (Sheng et al., 2012a). But the latter could lead to more serious deactivation of catalysts and the result is usually irreversible. Therefore, it is extremely desirable to develop high active SCR catalysts in a wide temperature range, with good SO$_2$-tolerance (D.S. Zhang et al. 2013; L. Zhang et al. 2013).

Core–shell nanostructures have been widely researched for their high chemical/thermal stability and recyclability (Li et al., 2016).
In this case, an active center is isolated inside the core–shell nanostructure, which effectively inhibits the migration and sintering of the active components (Ma and Dai, 2011). So far, very few literatures have reported the metal oxide @ TiO2 core–shell nanostructures for the SCR reaction, and most of them presented titanium tubes or CNTs as shell (Chen et al., 2006, 2007; Sun and Bao, 2008). Chen et al. (2011) designed a novel titanate nanotube (TNT) confined CeO2 catalyst and found that it not only has a greater activity and selectivity, but also a remarkable resistance to alkali metal poisoning in denitration application. D.S. Zheng et al. (2013) have reported that mesoporous TiO2@MNOx-CeOx/CNTs with a core–shell structure as SCR catalysts exhibit a high activity, stability and SO2-tolerance.

In recent years, ceria (CeO2) has received tremendous attention for SCR of NOx due to its oxygen storage and redox properties. Xu et al. (2008) have reported that the Ce/TiO2 catalyst had a high activity in the temperature range 275–400°C for the SCR reaction and showed high tolerance to SO2. Moreover, Gu et al. (2010) found that the sulfated CeO2 had observably higher NO conversion than the fresh one, suggesting that ceria could improve the SCR activity after the sulfation.

In this study, a novel CeO2@TiO2 core–shell nanostructure catalyst was prepared through a two-step hydrothermal method. The influences of SO2 in the flue gas on the SCR activity of the catalysts were determined. It is expected that the work conducted herein could give a new insight to solve the catalyst poisoning problem.

1. Material and methods

1.1. Catalysts preparation

The CeO2@TiO2 core–shell nanostructure catalysts were prepared by a two-step hydrothermal method (Fang and Liang, 2012). 21.7 g Ce(NO3)3·6H2O was dissolved in 50 mL deionized water at room temperature, and then 300 mL glycol was added to the above solution under magnetic stirring. The mixture was further stirred ceaselessly until it became homogeneous and then sealed in a Teflon-lined stainless steel autoclave. The autoclave was maintained at 180°C for 8 hr and then cooled to 100°C. The catalyst was denoted as CeO2@TiO2.

The counterpart CeO2/TiO2 nanoparticle catalysts were also prepared in a similar one-step hydrothermal method. 21.7 g Ce(NO3)3·6H2O and 17.6 mL tetrabutyl titanate and appropriate amounts of deionized water and glycol were mixed together. The mixture was sealed in a Teflon-lined stainless steel autoclave at 180°C for 8 hr after a further magnetic stirring. Then the sediment was centrifuged, washed with deionized water and ethanol and dried at 100°C for 12 hr. Finally, the settling was calcined in air at 500°C for 4 hr. The catalyst was denoted as CeO2/TiO2. The CeO2 and TiO2 nanoparticles were prepared using the first hydrothermal step of CeO2@TiO2 catalysts.

1.2. Catalyst characterization

The morphology of the catalysts was characterized by transmission electron microscopy (TEM), high-resolution TEM (HR-TEM) and element mapping using a FEI TECNAI G2 F20 instrument operated at 200 kV. The crystalline structures of the samples were examined by X-ray diffraction patterns (XRD) obtained on a Bruker D8 Advance diffract meter. Then the surface area and pore distribution of the catalysts were calculated by Brunauer-Emmett-Teller (BET) equation using a Micromeritics ASAP 2020 equipment at 77 K by N2 physisorption. The surface atomic states of the catalysts were analyzed by X-ray photoelectron spectroscopy (XPS) with Thermo Escalab 250XI. H2 temperature-programmed reduction (H2-TPR) was performed on a Tianjin XQ TF5080 autosorption apparatus. Prior to H2-TPR experiment, 50 mg catalysts were pretreated with N2 with a total flow rate of 30 mL/min at 300°C for 0.5 hr, then cooled down to room temperature in the N2 atmosphere. Finally, the temperature was raised to 600°C at a constant heating rate of 10°C/min in a flow of H2 (5 vol.%)/N2 (30 mL/min). The H2 consumption during the experiment was monitored by a TCD. NH3 temperature-programmed desorption (NH3-TPD) was performed on the same apparatus. Before the NH3-TPD experiment, the catalysts (150 mg) were purged at 300°C in a flow of N2 (30 mL/min) for 0.5 hr and cooled to 100°C under N2 flow. The samples were then exposed to a flow of NH3 at 100°C for 1 hr, followed by N2 purging for 0.5 hr. Finally, the reactor temperature was raised to 800°C in the N2 flow at a constant rate of 10°C/min.

1.3. Activity tests

The SCR activity measurements were carried out by a fixed-bed reactor where 4 mL samples in from 60°C to 460°C with a gas hourly space velocity (GHSV) of 24,000 hr⁻¹. The typical reactant gas consisted of 500 ppm NO, 500 ppm NH3, 200 ppm SO2 (if added), 10% H2O (if added), 5 vol.% O2 and balance N2. Water vapor was generated by passing N2 through a heated bottle containing deionized water. NO, NO2, SO2, and O2 were measured by a flue gas analyzer (MRU Vario Plus, Environmental Protection Technology Co. Ltd., Model MOT 400). The detect limit of NO, NO2, and SO2 is 1000 ppm and O2 is 25.0 vol.%, and the precision of NO, NO2, and O2 is ±1% of the full scale and O2 is less than ±0.2%. NH3 was analyzed with a portable NH3 analyzer (Nantong Water Environmental Protection Technology Co. Ltd., Model MOT 400). The detect limit of NH3 is 1000 ppm and the precision is ±2%. N2O was analyzed with a portable N2O analyzer (Medi-Gas G200, Bedfont Scientific Ltd., England). The detect limit of N2O is 1000 ppm and the precision is ±2%.

NOx conversion (%) = \frac{C_{\text{out}}^{\text{NO}} - C_{\text{in}}^{\text{NO}}}{C_{\text{in}}^{\text{NO}}} \times 100\%

N2 selectivity (%) = \left(1 - \frac{C_{\text{out}}^{\text{NO}} + 2C_{\text{out}}^{\text{N2O}}}{C_{\text{in}}^{\text{NO}} + C_{\text{in}}^{\text{N2O}} - C_{\text{out}}^{\text{N2}} - C_{\text{out}}^{\text{NH3}}} \right) \times 100\%
2. Results and discussion

2.1. Microstructure and morphology

The morphologies of CeO$_2$/TiO$_2$ and CeO$_2$@TiO$_2$ were investigated by TEM, HR-TEM and element mapping, and their images are shown in Fig. 1a–d. The nanoparticles in CeO$_2$/TiO$_2$ (Fig. 1a) were agglomerated, and no core–shell structure existed. However, it can be seen that the nanoparticles in the CeO$_2$@TiO$_2$ were spherical and well-dispersed from Fig. 1b. In these composite nanoparticles, about 108–136 nm CeO$_2$ nanoparticles (core) were encapsulated within a TiO$_2$ layer (shell) whose thickness was around 6 nm. The diffraction pattern (the insert picture of Fig. 1b) over a CeO$_2$@TiO$_2$ sphere shows a typical polycrystalline ring diffraction pattern which can be indexed to the (111), (200), (220) and (311) crystal planes of cubic CeO$_2$. From the HR-TEM image (Fig. 1c), clear lattice fringes could be observed for CeO$_2$@TiO$_2$. The spacing distances between the lattice planes were 0.312 nm and 0.276 nm matching with the (111) and (200) crystal planes of cubic CeO$_2$ (Corrêa et al., 2011), which were in agreement with the diffraction pattern. There were no significant lattice fringes of TiO$_2$ which meant that the TiO$_2$ might be amorphous. According to Fan et al. (2007), the formation process of the core–shell structures was based on the Kirkendall effect which includes two main stages. One is the generation of small Kirkendall voids via a bulk diffusion process; the other is the surface diffusion of the core material (CeO$_2$ nanoparticles) along the pore surface. And then, a newly-formed amorphous layer (TiO$_2$ shell layer) grew epitaxially on the surface of the CeO$_2$ spheres as the additive species (tetrabutyl titanate) hydrolysing under the solvothermal condition. From Fig. 1d, the element mapping of Ti and Ce reveals that the Ce element was completely covered up by the Ti element. This also showed the existence of the core–shell structure. Fig. 1e shows the TEM image of CeO$_2$, where the particles were not shaped well. Around 80–100 nm nanoparticles were formed in large random blocks, due to the particle agglomeration. From Fig. 1f, it is clear that a large number of homogeneous TiO$_2$ nanoparticles are synthesized by the hydrothermal method, with particle diameter ranged from 5 to 15 nm.

2.2. XRD analysis of the catalysts

The XRD patterns of all the catalysts with different structures are shown in Fig. 2. The reflections of TiO$_2$ and CeO$_2$ nanoparticle catalyst showed typical diffraction patterns for anatase TiO$_2$ and cubic CeO$_2$ phase respectively. CeO$_2$/TiO$_2$ displayed the peaks both for anatase TiO$_2$ and cubic CeO$_2$ phase. The diffraction peaks of CeO$_2$@TiO$_2$ can be readily indexed to that of the face-centered cubic phase of CeO$_2$ structure (PDF ICDD. 34–0394) with lattice constant $a = 5.522$ Å (Fang and Liang, 2012). However, the signal of TiO$_2$ phase was not observed on CeO$_2$@TiO$_2$, which meant that the TiO$_2$ shell might be amorphous and were consistent with the information shown in the insert picture of Fig. 1b. No extra peaks due to the additive oxides or new-formed mixed phases are found, which is similar to the results reported before (Yu et al., 2011).

Fig. 1 – TEM image of CeO$_2$/TiO$_2$ (a), TEM, selected area electron diffraction and HR-TEM images of CeO$_2$@TiO$_2$ (b, c), element mapping of CeO$_2$@TiO$_2$ (d), TEM images of CeO$_2$ (e) and TiO$_2$ (f). TEM: transmission electron microscopy; HR-TEM: high-resolution transmission electron microscopy.
2.3. BET surface areas and pore structure

The N₂ adsorption–desorption was performed to determine the specific surface area and porosity of the catalysts. The specific surface area, pore volume, and pore size of CeO₂/TiO₂ and CeO₂@TiO₂ are summarized in Table 1. CeO₂@TiO₂ had a larger specific surface area, pore volume, and pore size of CeO₂/TiO₂ and CeO₂@TiO₂. CeO₂@TiO₂ had a larger specific surface area, pore volume, and pore size of CeO₂/TiO₂ and CeO₂@TiO₂. However, the BET surface area of CeO₂/TiO₂ (86.1 m²/g) was actually the mesopore, while the mean pore size of CeO₂/TiO₂ catalyst was larger than that in CeO₂@TiO₂. As illustrated in the inset of Fig. 3, the pore distribution of CeO₂/TiO₂ shows a pore size of around 6 nm which was actually the mesopore, while the mean pore size of CeO₂/TiO₂ of 10 nm. However, the BET surface area of CeO₂/TiO₂ catalyst was larger than that in CeO₂@TiO₂. As illustrated in the inset of Fig. 3, the pore distribution of CeO₂/TiO₂ shows a pore size of around 6 nm which was actually the mesopore, while the mean pore size of CeO₂/TiO₂ was about 10 nm. However, the BET surface area of CeO₂@TiO₂ (from Table 1) is determined to be 95.3 m²/g, higher than that of CeO₂/TiO₂ (86.1 m²/g). The larger specific surface area and special porous structures of CeO₂@TiO₂ catalyst could enhance the contact and interaction of active sites and reactants, resulting in its excellent catalytic performance.

2.4. XPS analysis

The atomic concentrations and chemical state for each element on the surface of CeO₂/TiO₂ and CeO₂@TiO₂ were investigated by XPS measurements. Fig. 4a-c illustrates the obtained XPS spectra of Ce 3d, Ti 2p, and O 1s, respectively.

The typical examples of the Ce 3d spectra are presented in Fig. 4a. Complex spectra of Ce 3d could be deconvoluted into eight components with a fitting procedure described previously (Gu et al., 2010; Wu et al., 2008). The XPS spectra revealed that Ce 3d was composed of two multiplets (v and u), denoted as u, v, v′, v″ respectively. The peaks labeled v were due to 3d½ spin-orbit states, and those labeled v′ were the corresponding 3d½ states. Among these peaks, u, v, v′, v″ were attributed to Ce⁴⁺ species, while u′ and v′ were assigned to Ce³⁺ species (Wu et al., 2008). From the figures, it could be seen that the Ce⁴⁺ oxidation state was predominant for both catalysts. The Ti 2p spectra shown in Fig. 4b indicated that titanium was mostly confined to its highest oxidation state (IV). There was no obvious difference in the oxidation states of Ce and Ti for both catalysts.

The peak of O 1s (Fig. 4c) could be well fitted as a combination of O₁ (peak at about 531.2 eV) and O₂ (peak at about 531.2 eV) (Kang et al., 2007). O₁ was lattice oxygen, attributed to Ti–O in TiO₂ crystal lattice, while O₂ was chemisorbed oxygen or hydroxyl groups, ascribed to the Ti–OH on the surface or the adsorbed H₂O on the catalyst surface (Wu et al., 2011). It can be clearly seen that the binding energy for O₁ and O₂ shifted to higher values (O₁: 0.3 eV, O₂: 0.6 eV) over CeO₂/TiO₂ sample. A higher binding energy indicates a new stable covalent bond produced (Shen et al., 2013). According to the XPS analysis, the percentage of O₂ species on the CeO₂@TiO₂ surface are much higher than that of CeO₂/TiO₂, indicating a higher content of active surface oxygen species (Zhang et al., 2014), which benefits for the SCR reaction (Shen et al., 2013).

2.5. NH₃-TPD analysis

The chemisorption and activation of NH₃ on the surface acid sites of catalysts are generally regarded as the primary process in the NH₃-SCR of NOₓ (Zhang et al., 2014), and are closely associated with the acidity properties of catalysts, which were analyzed by NH₃-TPD, shown in Fig. 5. It can be

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**Table 1 – BET results of the two catalysts.**

<table>
<thead>
<tr>
<th>Catalysts</th>
<th>BET surface Area (m²/g)</th>
<th>Pore volume (×10⁻² cm³/g)</th>
<th>Average pore Diameter (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CeO₂/TiO₂</td>
<td>86.0804</td>
<td>17.3481</td>
<td>8.06135</td>
</tr>
<tr>
<td>CeO₂@TiO₂</td>
<td>95.2958</td>
<td>12.7019</td>
<td>5.33156</td>
</tr>
</tbody>
</table>

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*Fig. 2 – XRD patterns of all the catalysts. XRD: X-ray diffraction.*

*Fig. 3 – N₂ adsorption–desorption isotherms and corresponding pore size distribution curves (inset) of the catalysts. Line a: CeO₂/TiO₂; line b: CeO₂@TiO₂.*
seen that a broad peak around 160°C attributed to the NH3 desorbed from weak acid sites could be observed for CeO2@TiO2. And the peak area was large which can be deduced that it had more acid sites which resulted in high catalyst activity. The desorption peaks centered at 600 and 700°C could be ascribed to the Brønsted and Lewis acid, respectively (Lónyi et al., 1996). At the temperature around 750°C, the strong peak observed was probably due to the N2 desorption (Wang, 2006). However, these peaks could not be seen for CeO2/TiO2 sample. The strong acidity on CeO2@TiO2 would lead to a significant increase in the adsorption capacity of NH3, improving the SCR reaction greatly (Lietti et al., 1999). While for CeO2/TiO2, the low-temperature desorption peak centered at 160 and 300°C attributed to the NH3 desorbed by weak and medium acid sites. There was only a weak broad peak between 600 and 700°C observed at high temperature, indicating that the Brønsted and Lewis acid sites of CeO2/TiO2 were very weak.

### 2.6. H2-TPR analysis

TPR was used to investigate the redox capabilities of the catalysts. As illustrated in Fig. 6, the H2-TPR profiles of both samples present two distinct H2 consumption peaks. It was found that the reduction peaks of the surface-capping oxygen and the bulk oxygen of CeO2 were centered at 500 and 800°C, respectively (Zhu et al., 2004). The reduction peaks of the two Catalysts are similar, and the reduction temperature of CeO2 decreases to 770°C greatly due to the Ce–Ti interaction in the catalysts. For CeO2@TiO2, the reduction peak shifted to higher temperature which indicated that it had slightly weaker redox capability at low-temperature. However, it can be seen that the peak area of CeO2@TiO2 at 770°C was larger than that of CeO2/TiO2 from the patterning, which speculates that CeO2@TiO2 had a better redox capability as the temperature rises.

### 2.7. Catalytic activity

The activity of the catalysts under different temperature is presented in Fig. 7a. It can be seen that the NOx conversion over all the catalysts increased with the increasing temperature. Among the catalysts, CeO2@TiO2 and CeO2/TiO2 showed higher catalytic activity compared with the TiO2 or CeO2 nanoparticle catalysts for the SCR of NOx with NH3. The catalytic activity of CeO2@TiO2 was lower than that of CeO2/TiO2 below 210°C. The slightly lower catalyst activity of CeO2@TiO2 below 210°C was owing to the weaker redox capability at low-temperature confirmed by H2-TPR results in Fig. 6. What’s more, the catalytic activity of CeO2@TiO2 was higher than CeO2/TiO2 with the increasing of temperature (from 210°C), which was again proved by H2-TPR results. However, the catalytic activity of CeO2@TiO2 remained 100% from 280 to
460°C while the catalytic activity of CeO2/TiO2 decreased from 400°C. The plot of N2 product selectivity over CeO2@TiO2 as a function of temperature is also shown in Fig. 7a. The N2 selectivity remained 100% throughout the whole experiment and there was no by-product (N2O) formed. The stability of CeO2@TiO2 at 220°C is shown in Fig. 7b. It can be seen that the NOx conversion reached a stable level of about 93.5% and could last for more than 10 hr. Therefore, it could be concluded that CeO2@TiO2 had good stability and high N2 selectivity as well as high SCR activity.

2.8. Influence of SO2

The effects of SO2 on SCR performances of CeO2@TiO2 and CeO2/TiO2 catalysts are illustrated in Fig. 8. When 200 ppm SO2 was added to the system, the NOx conversion over CeO2@TiO2 could maintain 100% for 2.25 hr while the NOx conversion over CeO2/TiO2 only sustained the original state (92.6%) for 1.25 hr at 280°C. After 5 hr, the catalytic activity of CeO2@TiO2 and CeO2/TiO2 dropped to 75.8% and 55% respectively, verifying that SO2 had poisoning effects on SCR activity of the two catalysts. After being cut off of the SO2, the NOx conversion over CeO2@TiO2 gradually recovered to 96.2% and tended to be stable in 2 hr. It is indicated that the decrease of activity by SO2 may result from the competing adsorption of SO2 (Qi et al., 2004). The NOx conversion over CeO2/TiO2 kept falling in 0.5 hr after withdrawing SO2 from flue gas and then recovered. Finally, it became constant at about 50%. This indicated that CeO2/TiO2 was deactivated to a certain degree. Therefore, it is obvious that CeO2@TiO2 has better resistance to SO2 than CeO2/TiO2 nanoparticle. Considering the similarities of raw materials, their ratio and preparation method, the difference between their SO2 resistances might originate from the core–shell structure. The TiO2 shell protects the CeO2 active center from the erosion of SO2 as anticipated before. It can be concluded that the catalyst containing core–shell structure had good resistance to SO2.

2.9. Influence of H2O

It was reported that the H2O in the exhaust emission can also induce the deactivation of catalysts (Chen et al., 2015; Skalska...
et al., 2010). Therefore, the effect of H₂O on NOx conversion by CeO₂@TiO₂ and CeO₂/TiO₂ at 220°C was investigated. When 10% H₂O was added to the system, the NOx conversion over CeO₂/TiO₂ decreased from 89% to 83% in 1.5 hr and recovered to original level when H₂O was removed (Fig. 9). However, the NOx conversion over CeO₂@TiO₂ almost kept constant with the addition of H₂O. This result indicated that the decrease in activity caused by H₂O was reversible and might be on account of its competitive adsorption with the reactant on the active sites over the catalyst surface. What’s more, the TiO₂ shell of CeO₂@TiO₂ might prevent the adsorption of H₂O.

3. Conclusions

In summary, we have successfully fabricated a novel porous CeO₂@TiO₂ core-shell nanostructure as high-performance NH₃-SCR catalyst via a two-step hydrothermal method. Over 210°C, it showed higher activity, higher stability and superior SO₂ and H₂O tolerance for low-temperature SCR of NOx with NH₃. The unique porous structures provide a larger surface area and more active sites to adsorb and activate reagents, resulting in the high catalytic activity. NH₃-TPD results showed that the catalyst provided a better NH₃ chemisorption ability resulting in the improvement of SCR activity. Moreover, the H₂-TPR investigation verified that it did not have excellent redox activity which improved the catalyst oxygen storage capacity and facilitated the oxygen mobility over catalysts at low-temperature. Although its catalytic activity was a little lower than CeO₂/TiO₂ at low temperature, the special core-shell structure obtained from hydrothermal method endowed the CeO₂@TiO₂ catalyst better SO₂ and H₂O tolerance. Therefore, the simple and scalalble synthesis approach in the present study can be extended to fabricate other promising mixed metal oxides with core-shell structures on the nanoscale for various applications.

Acknowledgments

The work is financially supported by the National Natural Science Foundation of China (No. 51508281), and the Natural Science Foundation of Jiangsu Province (No. BK20130907), the Research Startup Funds Program for High Level Talent of Nanjing Normal University (No. 2013105XGQ0056).

References


temperature NOx reduction with NH3. J. Rare Earths 30 (7), 676–682.