Fe$_2$O$_3$ enhanced high-temperature arsenic resistance of CeO$_2$–La$_2$O$_3$/TiO$_2$ catalyst for selective catalytic reduction of NO$_x$ with NH$_3$

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High-temperature arsenic resistance catalysts of CeLa$_{0.5}$Fe$_x$/Ti (x = 0, 0.1, 0.2, 0.3, 0.4, 0.5) series were prepared and measured under a simulation condition of arsenic poisoning. The as-prepared catalysts were characterized by XRD, SEM, TEM, and XPS. The specific surface area and pore size of the catalysts were measured. At x = 0.2, the catalyst shows the best arsenic resistance and catalytic performance. The active temperature range of the CeLa$_{0.5}$Fe$_{0.2}$/Ti catalyst is 345–520°C when the gas hourly space velocity is up to 225000 mL g$^{-1}$ h$^{-1}$. Compared with commercial vanadium-based catalysts, CeLa$_{0.5}$Fe$_{0.2}$/Ti shows much better catalytic performance. The introduction of Fe will improve the dispersion of CeO$_2$ and increase the concentration of Ce$^{3+}$ and unsaturated active oxygen on the surface. The NH$_3$-TPD and H$_2$-TPR results show that the CeLa$_{0.5}$Fe$_{0.2}$/Ti catalyst has more acidic sites and more excellent redox performance than CeLa$_{0.5}$Fe$_0$/Ti. The CeLa$_{0.5}$Fe$_{0.2}$/Ti catalyst might have application prospects in the field of selective catalytic reduction of NO$_x$ with NH$_3$.

1. Introduction

Nitrogen oxides (NO$_x$) are some of the main pollutants in the atmosphere, which can do great harm to the ecological environment and human health, such as, acid rain, photochemical smog, ozone depletion, etc.¹ Selective catalytic reduction (SCR) of NO$_x$ with ammonia is the most effective method to reduce NO$_x$ in flue gas of stationary sources. Currently, the most widely used commercial SCR catalyst is V$_2$O$_5$–WO$_3$(MoO$_3$)/TiO$_2$.²³ The vanadium-based catalyst has many advantages as well as some unavoidable problems, such as, strong biological toxicity of vanadium, narrow temperature window (300–400 °C), easy oxidation of SO$_2$ to SO$_3$, and low N$_2$ selectivity at high temperature.⁴ Recent reports have shown that CeO$_2$ is the most powerful substitute for V$_2$O$_5$ because of its non-toxicity, high reactivity, and excellent oxygen storage and release capabilities.⁵⁻⁷ However, the adaptability and anti-inactivation ability of CeO$_2$ in a complicated flue gas environment is still an urgent problem to be solved. Heavy metal arsenic, often existing in the form of volatile As$_2$O$_3$ or As$_2$O$_5$ in high-temperature flue gas, is toxic to commercial SCR catalysts.⁸ Early reports show that the arsenic poisoning of commercial catalysts is due to the coverage of the active sites on the surface of the catalyst by inactive As$_2$O$_3$ and the diffusion of arsenic oxides into the pores of the catalyst, which causes the blocking of the micropores in the catalysts.⁹⁻¹¹ The current widely accepted view is that chemical deactivation is the main reason, because arsenic of high oxidation state, As(V), can interact with the active site of vanadium to reduce the surface acid sites.¹²⁻¹⁴ In order to improve the arsenic resistance, commercial vanadium-based catalysts often need many additives, such as WO$_3$ and MoO$_3$. It has been found that MoO$_3$ has better resistance to arsenic poisoning than WO$_3$ because MoO$_3$ can further improve the dispersion of active sites of vanadium.¹⁵ Current literature on arsenic resistance mainly focuses on adding MoO$_3$ to commercial vanadium-based catalysts. However, the highest NO conversion of these catalysts after arsenic poisoning is less than 80%.¹⁶⁻¹⁷ It is also effective in improving the arsenic resistance of CeO$_2$-based catalysts by adding WO$_3$/MoO$_3$.¹⁸⁻²⁰ However the reported highest NO conversion of the CeO$_2$-based catalysts after arsenic poisoning is only 75%. So far, there is no report on the CeO$_2$-based catalyst by adding Fe$_2$O$_3$ as arsenic resistance catalyst. Recently, our research group has developed the CeO$_2$–La$_2$O$_3$/TiO$_2$ vanadium-free catalysts, which can be used at high temperature and are expected to replace commercial vanadium-based catalysts. Owing to its catalytic activity, sulfur resistance and porous properties, TiO$_2$ is an excellent catalytic carrier. La$_2$O$_3$ is a good auxiliary component for
active component of CeO\(_2\) because of the formation of Ce–O–La bond on the surface of CeO\(_2\), which increases the acidic sites of the catalyst and the adsorption of NH\(_3\) and NO. Because Fe-based catalysts have good deNO\(_x\) performance\(^{21,22}\) as well as good adsorption of arsenic owing to the formation of strong Fe–O–As chemical bond in the removal of the arsenic in the water treatment,\(^{23-26}\) it is expected that Fe\(_2\)O\(_3\) can be used as an arsenic resistance catalyst. In this paper, the Ce–La–Fe–Ti catalysts were obtained by an impregnation method, using anatase as the carrier and Ce–La–Fe oxides as the active component. The deNO\(_x\) activity of the as-prepared catalysts was measured. The as-prepared catalysts were characterized by XRD, SEM, TEM, and XPS. The reason for the arsenic resistance was discussed.

### 2. Experimental

#### 2.1 Reagents and preparation

The Ce–La–Fe–Ti composite catalysts were prepared by an impregnation method. First, a certain volume of deionized water was added to a stainless steel reactor and heated to 60 °C. Then ammonia (25–28 wt%) and citric acid (analytical purity) were added to adjust the pH to 3–4 with stirring. After that, anatase pigment (TiO\(_2\), industrial grade), Ce(NO\(_3\))\(_2\)-6H\(_2\)O (industrial grade), La(NO\(_3\))\(_3\)-6H\(_2\)O (industrial grade), and (NH\(_4\))\(_2\)Fe(SO\(_4\))\(_2\)-6H\(_2\)O (analytical purity) were added according to the different weight ratios, CeLa\(_{0.5}\)Fe\(_{2}\)Ti (x = 0, 0.1, 0.2, 0.3, 0.4, 0.5), where 0.5 and x are the weight ratios of La (calculated as La\(_2\)O\(_3\)) and Fe (calculated as Fe\(_2\)O\(_3\)) to Ce (calculated as CeO\(_2\)). In all the Ce–La–Fe–Ti composite catalysts, the weight ratio of Ce–La–Fe to Ti (calculated as TiO\(_2\)) is 3 : 7. The suspension was stirred continuously for 2–3 h and evaporated by vacuum distillation for 1 h. Then the mixture was cooled to room temperature, ripen for 2 hours, dried at 105 °C for 12 h, and calcined at 500 °C in a muffle furnace for 5 h. Finally, the samples were used for the SCR activity test. For comparison, commercial vanadium-based catalysts obtained from the market were also used.

#### 2.2 Catalyst activity tests

First, 1 g as-prepared catalysts were ground in a planetary ball mill for 90 min and soaked in 25 mL 1 mg mL\(^{-1}\) arsenic standard solution (calculated as As\(_2\)O\(_3\)) for 3 h to simulate its arsenic poisoning. The water solvent was completely evaporated, thus the loading amount of As\(_2\)O\(_3\) on the catalyst was calculated to be about 2.5 wt%. Then the catalyst was adhered to an industrial honeycomb-shaped cordierite cylinder with size of \(20 \times 50\). After drying at 105 °C, the loaded cylinder was calcined in a closed tube furnace at 450 °C for 3 h. Then the loaded cylinder was put into a quartz tube furnace to test the activity of the catalyst. The loading amount of the catalyst is 0.8 g. The gas composition is 500 ppm NO, 500 ppm NH\(_3\), 300 ppm SO\(_2\), 3% O\(_2\), 5% H\(_2\)O, and N\(_2\) is used as the balance gas. The total gas flow is 3000 mL min\(^{-1}\), hence the corresponding gas hourly space velocity (GHSV) is calculated to be 225 000 mL g\(^{-1}\) h\(^{-1}\). The outlet gas concentrations of NO, NO\(_2\), SO\(_2\) were detected by the Germany Ecom flue gas analyzer and the N\(_2\)O concentration was detected by the KRM50 infrared flue gas analyzer. The temperature program was controlled by a computer. At each temperature, the experiment was kept for 30 min to stabilize before the data collection of the concentration of the outlet gas. The NO conversion and N\(_2\) selectivity were calculated according to the formula (1) and (2).

\[
\text{NO conversion (\%)} = \frac{\text{NO}_{\text{in}} - \text{NO}_{\text{out}}}{\text{NO}_{\text{in}}} \times 100\% \tag{1}
\]

\[
\text{N}_2 \text{ selectivity (\%)} = \frac{\text{H}_2 \text{consumption (1)} - \text{H}_2 \text{consumption (2)}}{\text{H}_2 \text{consumption (1)}} \times 100\% \tag{2}
\]

#### 2.3 Characterization

The Brunauer–Emmett–Teller (BET) specific surface area and pore volume of the samples were measured on the Micromeritics ASAP 2020 instrument. The morphology was observed on the Zeiss MERLIN compact field emission scanning electron microscope (FE-SEM) and a JEOL JEM 2100 plus transmission electron microscope (TEM). The X-ray diffraction (XRD) was performed on the Rigaku Ultima IV instrument, with a tube voltage of 40 kV, a tube current of 40 mA, and Cu K\(_\alpha\) radiation. X-ray photoelectron spectroscopy (XPS) was performed on the Thermo ESCALAB 250XI electronic energy spectrometer, with C1s binding energy (284.8 eV) for energy calibration, X-ray source voltage of 16 kV, current of 14.9 mA, beam diameter of 650 μm. The temperature programmed chemical adsorption/reduction (TPD/TPR) was performed on the AutoChem1 II 2920 instrument. For NH\(_3\)-TPD, the catalyst was pre-treated under argon atmosphere at 350 °C for 1 h, then cooled down to 50 °C and adsorbed NH\(_3\) to saturation. After that the temperature was raised to 100 °C and the catalyst was purged with Ar gas to desorb the physically adsorbed NH\(_3\). Finally the temperature was raised to 500 °C at a ramping rate of 10 °C min\(^{-1}\) and the outlet NH\(_3\) concentration was detected by the thermal conductivity detector (TCD). For H\(_2\)-TPR, the catalyst was pre-treated under Ar atmosphere at 350 °C for 1 h to remove the adsorbed gas on the surface, then cooled to room temperature. Then the catalyst was reduced in 10% H\(_2\)/Ar atmosphere from room temperature to 800 °C at a ramping rate of 10 °C min\(^{-1}\). The H\(_2\) consumption was detected by TCD.
3. Results and discussion

3.1 Catalytic performance

Fig. 1 shows the catalytic performance of catalysts with different components, all the catalysts were treated by arsenic as described in Section 2.2 except “Fresh” catalysts. As temperature increases, the NO conversion first increases and then decreases. Influenced by the kinetics reason, the NO conversion will increase whereas the increasing trend will decrease with the increase of the temperature. If the temperature is too high (>450 °C), the NO conversion will decrease due to the decrease of the N₂ selectivity. At the same temperature, the NO conversion first increases and then decreases with the increase of the Fe content. When the Fe₂O₃ content x is 0.2, the NO conversion of CeLa₀.₅Fe₀.₂/Ti is the highest. The temperature range where the corresponding NO conversion is greater than 80% of CeLa₀.₅Fe₀.₂/Ti is 345–520 °C. Commercial vanadium-based catalyst shows much weaker arsenic resistance than CeLa₀.₅Fe₀.₂/Ti. On the one hand, Fe-based catalysts have good deNOₓ performance, on the other hand, Fe might form the bond of Fe–O–As with As, which makes Fe preferentially combine with As to protect the main active site of CeO₂. However, excessive loading of Fe₂O₃ is detrimental to the deNOₓ performance of the catalyst, which can be attributed to the fact that excessive Fe₂O₃ will cover the active sites of the CeO₂ on the catalyst surface. Above 350 °C, the NO conversion of the catalyst is maintained at a high level, which may be related to the enhanced oxidation of CeO₂. The introduction of La increases the surface unsaturated oxygen on the surface and the dispersibility of CeO₂. From Fig. 1(b), it can be found that the commercial vanadium-based catalyst is significantly poisoned in arsenic environment, while CeLa₀.₅Fe₀.₂/Ti catalyst is slightly affected in arsenic environment. The NO conversion of the CeLa₀.₅Fe₀.₂/Ti is obviously better than commercial vanadium-based catalyst with regard to the arsenic resistance. In Fig. 1(c), the N₂ selectivity of the CeLa₀.₅Feₓ/Ti (x = 0, 0.1, 0.2, 0.3, 0.4, 0.5) catalysts is much better than that of commercial vanadium-based catalyst and CeLa₀.₅Fe₀.₂/Ti shows the best N₂ selectivity (99.08–100%). In Fig. 1(d), the N₂O concentration of vanadium-based catalysts increases quickly whereas the N₂O concentration of CeLa₀.₅Feₓ/Ti (x = 0, 0.1, 0.2, 0.3, 0.4, 0.5) increase slowly. This arsenic poisoning of vanadium-based catalysts is consistent with the results reported in the literature.

3.2 XRD

Fig. 2 shows the XRD pattern of CeLa₀.₅Feₓ/Ti (x = 0, 0.1, 0.2) series. The main phase of the three catalysts is anatase TiO₂ (JCPDS no. 99-0008). The broad diffraction peaks indicate that
the anatase is a nano-particle, which is consistent with the following SEM and TEM results. There are weaker cubic fluorite CeO2 peaks (JCPDS no. 43-1002) near 28.6°, 33°, etc. The full width at half maximum (FWHM) of CeO2 is wider than that of anatase, showing that the grain size of CeO2 is much smaller than that of TiO2. However, there is no phase related to the La2O3, indicating that La2O3 is highly dispersed on the catalyst surface in an amorphous state, which is similar to the literature.32 The XRD peak of Fe2O3 (~33.15°, JCPDS no. 33-0664) is very weak and very wide, which indicates the Fe2O3 is amorphous. The FWHM of the (111) peak of the CeO2 at 28.5° becomes wider with the increase of the Fe content, which means the addition of Fe decreases the CeO2 grain size. Since CeO2 is the main catalyst, small crystal size is beneficial to increase its catalytic activity. In addition, the peak of CeO2 at 28.5° (after Gaussian fitting) moves towards higher angle direction, which might be caused by the formation of the solid solution of CeO2–Fe2O3. This is because the radius of Ce4+ (eight-coordinated, 0.97 Å) is larger than that of Fe3+ (eight-coordinated, 0.78 Å). It is worth noting that although there are reports in the literature that anatase will transform into rutile at ~500 °C,33 the rutile phase cannot be found in the catalysts, showing that the catalysts have good thermal stability.

3.3 SEM

Fig. 3 is the SEM images of the CeLa0.5Fex/Ti (x = 0, 0.1, 0.2) series. According to the reports, the catalysts with the size of nano-particles can show high catalytic activity.34 As can be seen, the active components are highly dispersed on the surface of the catalysts.
catalysts and the nano-particles form agglomerates with the size of sub-microns. The number of particles increases with the increase of the Fe content, which means that the addition of Fe may enhance the dispersion of CeO₂ on the surface of TiO₂. This is consistent with the XRD results.

3.4 TEM

Fig. 4 shows the TEM image, elemental mapping, and energy dispersive spectra (EDS) of CeLa₀.₅Fe₀.₂/Ti. The morphology in Fig. 4(a) clearly shows that the crystal size of the catalyst is tens of nanometers. In the HR-TEM image (Fig. 4(b)), the stripe spacing of 0.357 nm corresponds to the (101) plane of anatase TiO₂, and the stripe spacing about 0.318 nm corresponds to the (111) plane of CeO₂. The elemental mapping pictures of Ti, Ce, Fe, La, and O (Fig. 4(d–h)) show that the La, Ce, Fe and Ti elements are uniformly distributed in the catalysts. The EDS result in Fig. 4(i) shows that the main elements are Ti, La, Ce, Fe, and Cu, where Cu is caused by the Cu grid used to support the sample.

3.5 XPS

Fig. 5 is the XPS spectra of CeLa₀.₅Feₓ/Ti (x = 0, 0.1, 0.2). The peaks of Ce, La, Ti, Fe and C can be found in the survey spectra in Fig. 5(a). The Ce3d XPS spectra (Fig. 5(b)) can be fitted to nine peaks, named V₁ (≈ 880.7 eV), V₂ (≈ 882.3 eV), V₃ (≈ 885.8 eV), V₄ (≈ 888.6 eV), V₅ (≈ 898.3 eV), U₁ (≈ 900.8 eV), U₂ (≈ 903 eV), U₃ (≈ 907.3 eV), U₄ (≈ 916.7 eV). All V peaks correspond to Ce3d₅/₂ spin orbits, and all U peaks correspond to Ce3d₃/₂ spin orbits. The peaks of V₁, V₂, and U₁ correspond to Ce³⁺, while the peaks of V₃, V₄, V₅, U₁, U₂, and U₄ correspond to Ce⁴⁺. From the peak area, the Ce³⁺ content on the CeO₂ surface increases significantly as the Fe content increases. Because of the different electrovalence of Fe³⁺ and Ce⁴⁺, in order to maintain charge balance, the oxygen vacancy defects on the CeO₂ surface also increase as the Fe content increases, which are beneficial to the improvement of the catalytic activity.

The XPS of O₁s (Fig. 5(c)) can be fitted into two peaks: O₁ (surface unsaturated oxygen, ≈ 530.6 eV) and O₂ (lattice oxygen, ≈ 528.7 eV). Calculated by the fitted peak area, the O₁/(O₁ + O₂) fractions of CeLa₀.₅Fe₀Ti, CeLa₀.₅Fe₀.₁Ti, CeLa₀.₅Fe₀.₂/Ti Catalysts are 43.30%, 43.73%, and 43.78%, respectively. Because the surface unsaturated oxygen O₁ of CeO₂ has a higher mobility and a stronger catalytic performance than the lattice oxygen O₂, CeLa₀.₅Fe₀.₂/Ti catalyst shows the best catalytic performance. In Fig. 5(d), the peaks of Fe₂p correspond to Fe₂p₁/₂ (724 eV),
Fe$_{2p3/2}$ (711 eV) and satellite peaks. The peaks of Fe$_{2p3/2}$ are fitted by two peaks of Fe$^{2+}$ (710.0 eV) and Fe$^{3+}$ (712.8 eV).

The CeLa$_{0.5}$Fe$_x$/Ti and CeLa$_{0.5}$Fe$_{0.1}$/Ti catalysts have no obvious differences in shape and positions, showing that the valences of Fe in the two samples are the same or similar. No obvious satellite peak and asymmetric peak are observed at 715 eV, and the peak positions of 2p$_{3/2}$, satellite, and 2p$_{1/2}$ are close to that of Fe$^{3+}$. However the existence of Fe$^{2+}$ must be considered because Fe$^{2+}$ can be fitted in the curve. Therefore, it can be concluded that Fe$^{3+}$ is the major valence while Fe$^{2+}$ is the minor valence on the surface.

### 3.6 N$_2$ adsorption and desorption

The BET specific surface area, pore volume and pore diameter of CeLa$_{0.5}$Fe$_x$/Ti ($x = 0, 0.1, 0.2$) series were measured by N$_2$ adsorption and desorption experiments. The results were shown in Table 1. Because the main components of the catalysts are TiO$_2$, CeO$_2$ and La$_2$O$_3$, and the content of Fe$_2$O$_3$ is very little, the change of Fe content has little effect on the specific surface area of the catalyst. The specific surface area increases and the pore size increases slightly. The reason may be that the introduction of Fe inhibits the growth rate of ceria grains and reduces the ceria grain size. This is consistent with the results of the XRD and SEM images.

### 3.7 NH$_3$-TPD and H$_2$-TPR

NH$_3$-TPD result reflects the acidity of the catalysts. Fig. 6(a) shows the NH$_3$-TPD curves of the CeLa$_{0.5}$Fe$_x$/Ti ($x = 0, 0.1, 0.2, 0.3$) catalysts. As can be seen, the CeLa$_{0.5}$Fe$_0$/Ti catalyst has two desorption peaks at about 350 °C and 290 °C. It is generally believed that the peak above 450 °C is related to the Lewis acid site (strong acid site) associated with the NH$_3$ molecule, and the peak near 300 °C is related to the Bronsted acid site (weak acid site) associated with NH$_4^+$ ions.

From the peak area, the quantity of the Bronsted acid sites on the surface of the catalyst increases with the increase of Fe content up to $x = 0.2$, which helps to increase the catalytic activity. This is consistent with the catalytic performance in Fig. 1.

H$_2$-TPR result reflects the redox characteristics of the catalysts. Fig. 6(b) shows the H$_2$-TPR curves of the CeLa$_{0.5}$Fe$_x$/Ti ($x = 0, 0.1, 0.2, 0.3$) catalysts. The strong peaks of the four catalysts in the range of 450-580 °C correspond to the reduction process from Ce$^{4+}$ to Ce$^{3+}$, which are closely related to the catalytic activity of the catalysts.

With the increase of Fe content $x$ up to $x = 0.2$, the peak position shifts towards lower temperature direction from 577 °C to 473 °C, which means that the introduction of Fe makes the reduction of the surface oxygen on CeO$_2$ by H$_2$ more easy. However, when the Fe content increases to $x = 0.3$, the reduction peak changes from 473 °C to 515 °C, which means that the reduction of CeO$_2$ on the catalyst surface becomes more difficult. From the peak area, the H$_2$...
consumption is CeLa0.5Fe0.2/Ti > CeLa0.5Fe0.3/Ti > CeLa0.5Fe0.1/Ti > CeLa0.5Fe/Ti, showing that the surface oxygen on CeO2 increases with the increase of Fe content, which is consistent with the XPS results. Based on the NH3-TPD and H2-TPR curves, it can be concluded that CeLa0.5Fe0.2/Ti catalyst has the most acidic sites and strongest redox performance.

4. Conclusions

An anti-arsenic SCR denitration catalyst with anatase as the carrier, CeO2, as the main active components, and La2O3, Fe2O3 as the main auxiliary agent was prepared by the impregnation method. The optimized CeLa0.5Fe0.2/Ti catalyst exhibits better catalytic performance under arsenic environment than the commercial vanadium-based catalysts. After the introduction of the Fe2O3, the Ce3+ concentration, surface unsaturated oxygen, CeO2 dispersibility, specific surface area, and acidic sites are all improved, which improves the catalytic activity in the arsenic environment. CeLa0.5Fe0.2/Ti catalyst has high NO conversion efficiency, excellent N2 selectivity and arsenic resistance, which might be a candidate for SCR denitrification applications in the arsenic flue gas environment.

Conflicts of interest

There are no conflicts to declare.

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