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High-performance $\text{Fe}_a\text{Ti}_b\text{O}_x$ catalyst loaded on ceramic filter for $\text{NO}_x$ reduction

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Abstract

The $\text{Fe}_a\text{Ti}_b\text{O}_x$ catalyst was loaded into the pores of porous ceramic using impregnation method for removing nitrogen oxides with selective catalytic reduction (SCR) technology. The catalytic performance over $\text{Fe}_a\text{Ti}_b\text{O}_x$ catalyst was studied in detail. The $\text{Fe}_a\text{Ti}_b\text{O}_x$ catalyst displayed more than 95% $\text{NO}_x$ conversion within the range of $280 \degree \text{C}–400 \degree \text{C}$, and still maintained 97% $\text{NO}_x$ conversion when 300 ppm $\text{SO}_2$ and 10 vol.% water vapor were introduced at the testing temperature of 300 \degree \text{C}. The influence factors (including filtration velocity, $\text{NH}_3$/NO mole ratio and oxygen concentration) for $\text{NO}_x$ conversion over $\text{Fe}_6\text{Ti}_1\text{O}_x$ catalyst were also studied. The suitable $\text{NH}_3$/NO mole ratio and oxygen concentration was 0.9 and 6%, respectively. The XRD, $\text{N}_2$-BET, $\text{H}_2$-TPR, $\text{NH}_3$-TPD and XPS were employed to investigate physicochemical property of the $\text{Fe}_6\text{Ti}_1\text{O}_x$ catalyst. The results illustrated that $\text{Fe}_6\text{Ti}_1\text{O}_x$ catalyst has hematite $\text{Fe}_2\text{O}_3$ and $\text{TiO}_2$ structure, better redox properties and stronger surface acid.

1. Introduction

Industrial flue gas emission will result in seriously air pollution matters, such as photochemical smog, greenhouse effects, haze and so on [1, 2]. Particulates and nitrogen oxides usually co-exist in the flue gas. Porous ceramic filter usually applied for particulates removal in hot filtration [3, 4]. However, porous ceramic filter has no way in getting rid of nitrogen oxides. At present, $\text{NH}_3$-SCR technology was an efficient and economical way to diminish $\text{NO}_x$ emissions [5, 6]. De-NOx catalyst is very important for SCR technology. In order to removing particulates and $\text{NO}_x$ simultaneously, many researchers focus on combining de-NOx catalysts with porous ceramic filter.

Heidenreich et al [7] developed catalytic ceramic filter by integrating $\text{TiO}_2$-$\text{V}_2\text{O}_5$-$\text{WO}_3$ catalyst and ceramic filter. The effect of filtration velocity and operating temperature on catalytic performance were studied. Results showed that catalytic ceramic filter can achieve 98% NO conversion under the condition of $300 \degree \text{C}$ and 2 cm s$^{-1}$ filtration velocity. Choi et al [8] used rotational coating method to deposit $\text{V}_2\text{O}_5$-$\text{WO}_3$/$\text{TiO}_2$ catalyst on SiC porous ceramic. The experiment of $\text{V}_2\text{O}_5$ content and ball milling on NO conversion was carried out. The research result revealed that ball milling can reduce catalyst particle size, so that catalyst could go into pores of SiC ceramic filter easily. The best $\text{V}_2\text{O}_5$ content was 3% (M3V3), because M3V3 exhibited remarkable catalytic activity in reaction temperature range of $280 \degree \text{C}–320 \degree \text{C}$. Chen et al [9] prepared mullite ceramic filter with loaded $\text{MnO}_2$-$\text{CeO}_2$ catalyst. The effect of $\text{Mn}$/Ce ratio and deposited $\text{MnO}_2$-$\text{CeO}_2$ content upon NO conversion was studied. The suitable $\text{Mn}$/Ce ratio and catalyst loading was 6/4 and 4%, respectively. Catalytic filter can achieve over 90% NO conversion within reactive temperature of $120 \degree \text{C}–250 \degree \text{C}$.

Iron-based de-NOx catalyst not only have good catalytic performance at medium-high temperature range, but also inexpensive and environmentally friendly [10, 11]. Titanium dioxide is extensively employed as a de-NOx catalyst supports in the SCR technology. As a result, most of researcher work based on $\text{Fe}_2\text{O}_3$ or $\text{TiO}_2$, like Fe-Ti [12], Fe-Fe-Ti [13], Fe-Fe-Nb-Fe [14], Fe-W-Zr [15], Fe-Ni-Ti [16], and Fe-W [17] composite oxides.
In this work, the FeaTibOx catalyst was loaded on ceramic filter by simple impregnation method. Porous ceramic filter has been developed in our previous work [18]. The de-NOx performance over FeaTibOx catalyst was studied in detail. And various characterizations associated with the physicochemical properties, reduction behavior and ammonia adsorption ability for catalyst were performed.

2. Experimental

2.1. Preparation of porous ceramic filter with FeaTibOx catalyst

Firstly, we prepared cylindrical porous ceramic filter. The ceramic short fibres, carboxymethyl cellulose, deionized water and glass powder were mixed together with stirring. After aging and pugging, the mixture was pressed into cylindrical green body (diameter = 22 mm, height = 10 mm) followed by sintering at 1150 °C for 1 h. The detailed preparation procedure of porous ceramic filter was described in our previous work [18]. Secondly, catalyst precursor solution was prepared by mixing TiOSO4·xH2SO4·xH2O (93%, Aladdin Reagent Co., Ltd.), Fe(NO3)3·9H2O (AR., Sinopharm Chemical Reagent Co., Ltd) in deionized water. Thirdly, the prepared ceramic filter was impregnated in the catalyst precursor solution for 10 min. The ceramic filter with loaded FeaTibOx catalyst was dried at 95 °C for 10 h and then sintered at 400 °C for 5 h. The preparation procedure was schematically shown in figure 1.
2.2. Measurement of catalytic activity

The catalytic performance of ceramic filter with loaded Fe₂Ti₁Oₓ catalyst was measured in the fixed-bed reactor (schematic of activity test system was shown in figure 2). The fixed-bed reactor was consisted of two quartz tubes (diameter = 22 mm and 38 mm). The feed stream was made up of 600 ppm NOₓ, 600 ppm NH₃, 6 vol.% O₂, 10 vol.% H₂O (when used), 300 ppm SO₂ (when used), and balance N₂. The mixed gas flow rate is 314 ml min⁻¹ in total. The filtration velocity was 1 m min⁻¹ (equal to GHSV of ∼50,000 h⁻¹). Cylindrical porous ceramic filter (diameter = 22 mm, height = 10 mm, mass = 3.6 g) with catalyst loading of 6% was put in the testing tube of diameter = 22 mm. The concentration of nitrogen oxides at the inlet and outlet of the reactor was detected by the gas analyzer (ECOM-D, RBR, Germany). Data was recorded after the reaction was stabilized. The NOₓ conversion was determined by following formula:

\[
\text{NO}_x \text{ conversion} = \frac{[\text{NO}_x]_{\text{in}} - [\text{NO}_x]_{\text{out}}}{[\text{NO}_x]_{\text{in}}} \times 100\%
\]

2.3. Characterizations

The crystal structure of catalyst was identified via x-ray diffraction (XRD) analysis (D Max/RB) with Cu Kα radiation. The scan speed was 10° min⁻¹ and the 2θ scans covered 10 ~ 80°. The morphology of the ceramic filter with catalyst was observed by scanning electron microscope (SEM, JSM-6510). The BET surface area and pore size distribution were tested by N₂ adsorption/desorption isotherms via surface-area analyzer (Micromeritics, 2020 M V3.00H). The TPD profiles of NH₃ (NH₃-TPD) was obtained on an automated chemisorption analyzer (Quantrachrome Instruments, CHEMBET-3000). Before the measurement, the catalyst was treated at 400 °C for 1 h with He gas, then cooled to 50 °C. The measure temperature was raised to 500 °C at 10 °C min⁻¹. The temperature programmed reduction of H₂ (H₂-TPR) test was executed on a Semiautomatic Micromeritics TPD/TPR 2900 instrument. Catalyst samples were preheated at 400 °C for 1 h in the pure Ar gas. Afterwards, the temperature was lowered to 50 °C and introducing 5% H₂/Ar. Finally, the test temperature was risen to 700 °C at 10 °C min⁻¹. The x-ray photoelectron spectroscopy (XPS) was performed by the PHI 5600 spectrometer with a Mg-Kα radiation source. The degree of vacuum in the XPS equipment was 10⁻⁷ Pa. The catalyst was dried at 80 °C for 24 h to eliminate moisture.
When NH3 catalyst was applicable, NOx conversion reached 62%. As the increase of NH3 mole ratio, NOx conversion was increased to 99%. However, compared with Fe6Ti1Ox catalyst, the NOx conversion in the temperature range of 240 °C–300 °C was decreased over Fe10Ti1Ox catalyst. The Fe6Ti1Ox catalyst exhibited best NOx conversion in the temperature range of 240 °C–400 °C. Therefore, the Fe10Ti1Ox catalyst was selected for the later study. Table 1 listed SCR result comparison with Fe-Ti catalyst.

Table 1. SCR result comparison with Fe-Ti catalyst.

| Catalysts | Reaction condition | GHSV | NO conversion | References |
|-----------|--------------------|------|---------------|------------|
| Fe2TiO3   | [NO]=[NH3]=600ppm, [O2]=6% | ~50,000 h⁻¹ | >65% (320 °C–400 °C) | this work |
| Fe4TiO3   | [NO]=[NH3]=600ppm, [O2]=6% | ~50,000 h⁻¹ | >95% (280 °C–400 °C) | this work |
| Fe6Ti1Ox  | [NO]=[NH3]=600ppm, [O2]=6% | ~50,000 h⁻¹ | >90% (280 °C–400 °C) | this work |
| Fe4Ti0.5O0.5 | [NO]=[NH3]=500ppm, [O2]=5% | 50,000 h⁻¹ | >95% (225 °C–350 °C) | [1-2] |

3. Results and discussion

3.1. Catalytic performance

The catalytic performance over Fe5Ti6O15 serial catalysts (Fe/Ti mole ratio = 2:1, 6:1, 10:1) was demonstrated in figure 3(a). The Fe5Ti6O15 catalyst exhibited unsatisfactory catalytic performance within the whole temperature range, the maximum NOx removal efficiency was just 75% at the testing temperature of 360 °C. When the Fe/Ti mole ratio reached up to 6:1, the NOx removal efficiency overtook 95% within the testing temperature of 280 °C–400 °C. The NOx conversion was same in temperature range from 300 °C to 380 °C for Fe5Ti6O15 and Fe10Ti1Ox catalyst. However, compared with Fe5Ti6O15 catalyst, the NOx conversion in the temperature range of 240 °C–300 °C was decreased over Fe10Ti1Ox catalyst. The Fe5Ti6O15 catalyst exhibited best NOx conversion in the temperature range of 240 °C–400 °C. Therefore, the Fe5Ti6O15 catalyst was selected for the later study.

Table 1 listed SCR result of catalytic ceramic filter with Fe6Ti6O15 catalyst and Fe5Ti6O15 catalyst reported by [12]. The NOx conversion of catalytic ceramic filter with Fe6Ti6O15 catalyst was comparable to that of Fe5Ti6O15 catalyst ([1-2]).

In actual application of catalytic ceramic filter, different filtration velocity will change reaction time for SCR process. The influence of different filtration velocity on catalytic performance was showed in figure 3(b). When the filtration velocity was 0.5 m min⁻¹ (equal to GHSV of ~25,000 h⁻¹), the catalytic performance was best within temperature of 240 °C–400 °C. Fe5Ti6O15 catalyst achieved more than 95% NOx conversion in the temperature range of 260 °C–400 °C. With the increasing of filtration velocity, NOx conversion was decreased apparently at lower temperature range of 240 °C–300 °C. At high temperature range (320 °C–400 °C), this phenomenon is not obvious. The experiment results suggested that NOx conversion in the temperature range of 240 °C–300 °C was sensitive for higher filtration velocity.

It is generally acknowledged that ammonia acts a pivotal part in the catalytic reaction process. Figure 3(c) presented the influence of NH3 mole ratio on NOx conversion at the testing temperature of 300 °C. When NH3 mole ratio was 0.6, the NOx conversion was 62%. As the increase of NH3 mole ratio, the NOx conversion improved immediately. When NH3 mole ratio achieved 0.9, the NOx conversion reached 99%.
According to $4\text{NH}_3 + 4\text{NO} + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}$, oxygen concentrations will affect the NOx conversion of ceramic filter with Fe$_6$Ti$_1$O$_x$ catalyst. Figure 3(d) illustrated the influence of oxygen concentrations on the catalytic performance at the testing temperature of 300 $^\circ$C. The Fe$_6$Ti$_1$O$_x$ catalyst owned 75% NOx conversion with 0.5% O$_2$ concentration. As the elevating of O$_2$ concentration, the NOx conversion exhibited monotonic increase and then becoming steady. When oxygen concentrations achieved 6.0%, the NOx conversion reached maximum value (98%).

3.2. Influence of SO$_2$ and water vapor on the catalytic performance

As the industrial flue gas always have water vapor and SO$_2$, water vapor and SO$_2$ in flue gas will influence the catalytic performance usually [19, 20]. The figure 4 displayed the NOx conversion over Fe$_6$Ti$_1$O$_x$ catalyst in the presence of SO$_2$ and water vapor at the testing temperature of 260 $^\circ$C, 280 $^\circ$C and 300 $^\circ$C. Before the introduction of water vapor and SO$_2$, the SCR process has been maintained for 0.5 h at testing temperature. When SO$_2$ and water vapor was injected at the testing temperature of 300 $^\circ$C, the NOx conversion maintained stable (97%). After removing SO$_2$ and water vapor, the catalytic activity regained to the first value (about 98%). At measuring temperature of 280 $^\circ$C and 260 $^\circ$C, the NOx conversion went down evidently after breathe into SO$_2$ and water vapor with same condition. The NOx removal efficiency maintained 85% and 65% at the testing temperature of 280 $^\circ$C and 260 $^\circ$C, respectively. When water vapor and SO$_2$ were removed, catalytic activity recovered to initial value. The decline of catalytic activity may be related with the formation of (NH$_4$)$_2$SO$_4$ or NH$_4$HSO$_4$, these metal sulfates deposited on catalyst surface readily and prevented the SCR reaction [21–23]. In a word, the Fe$_6$Ti$_1$O$_x$ catalyst has outstanding catalytic performance at the testing temperature of 300 $^\circ$C even though SO$_2$ and water vapor were existed.
3.3. Physicochemical properties

Figure 5(a) presented the XRD patterns of the Fe2Ti1Ox, Fe6Ti1Ox and Fe10Ti1Ox catalyst. The Fe6Ti1Ox catalyst showed the reflections for TiO2 and hematite Fe2O3 structure (2θ = 33.15°, 35.61°, 54.09°) (PDF 33-0664). The Fe10Ti1Ox catalyst displayed hematite Fe2O3 structure. Moreover, no TiO2 peaks were detected for Fe10Ti1Ox catalyst, this phenomenon may ascribe to lower TiO2 content or poorer crystallinity. Fe2Ti1Ox catalyst only provided TiO2 diffraction peak, no Fe2O3 peaks were detected. Figure 5(b) showed the cross section of ceramic filter with Fe6Ti1Ox catalyst. It can be seen that the ceramic fibers interconnected each other to construct the inner pores of ceramic filter and the Fe6Ti1Ox catalyst was coated on the ceramic fibers or the inner pore surface of ceramic filter.

The N2 adsorption-desorption isotherms over the Fe2Ti1Ox, Fe6Ti1Ox and Fe10Ti1Ox catalysts were demonstrated in figure 6(a). With the increasing of Fe content, the Fe2Ti1Ox, Fe6Ti1Ox and Fe10Ti1Ox catalysts showed type-IV, type-III and type-II pattern isotherms, respectively. In the region of P/P0 > 0.4, the Fe2Ti1Ox catalyst displayed H2 type hysteresis loop, which implying the existence of an ink-bottle-shaped pore. Both Fe6Ti1Ox and Fe10Ti1Ox catalysts showed H3 type hysteresis loop, it means the formation of slit-shape pore structure. The pore size distribution of three catalyst samples was showed in figure 6(b). Table 2 exhibited S\textsubscript{BET}, Pore volume and Pore diameter for Fe\textsubscript{a}Ti\textsubscript{b}O\textsubscript{x} catalysts. Fe6Ti1Ox and Fe10Ti1Ox catalyst owned larger pore

| Samples          | S\textsubscript{BET} (m\textsuperscript{2} g\textsuperscript{-1})\textsuperscript{a} | Pore volume (cm\textsuperscript{3} g\textsuperscript{-1})\textsuperscript{b} | Pore diameter (nm)\textsuperscript{c} |
|------------------|-----------------------------------|---------------------------------|----------------------------------|
| Fe2Ti1Ox catalyst | 69.165                            | 0.09733                         | 4.5784                           |
| Fe6Ti1Ox catalyst | 57.2332                           | 0.157397                        | 5.1616                           |
| Fe10Ti1Ox catalyst| 94                                | 0.2134                          | 6.6175                           |

\textsuperscript{a} BET surface area.
\textsuperscript{b} BJH desorption pore volume.
\textsuperscript{c} BJH desorption pore diameter.

Figure 7. X-ray photoelectron spectra of (a) Fe 2p, (b) Fe 2p 3/2, (c) O 1s and (d) Ti 2p for Fe\textsubscript{a}Ti\textsubscript{b}O\textsubscript{x} catalyst.

3.3. Physicochemical properties

Table 2. Physicochemical properties for different catalyst.
volume and pore diameter compared with Fe₂Ti₁Oₓ catalyst. For Fe₆Ti₁Oₓ catalyst, slit-shape pore structure, larger pore volume and pore diameter was beneficial to the diffusion of SCR reactive gas.

3.4. Redox behavior

The x-ray photoelectron spectra were conducted to investigate the atomic concentrations and chemical states for FeₐTiₐOₓ catalysts. Figure 7 presented the XPS results of Fe 2p, Fe 2p₃/₂, O 1s and Ti 2p. The content of each element and iron with different valence was determined and presented in table 3. In figure 7(a), the peaks of Fe 2p₃/₂ and Fe 2p₁/₂ were detected for all catalyst samples. The appeared peaks of Fe 2p₃/₂ and Fe 2p₁/₂ indicated that Fe³⁺ was the major valence state for three catalysts [24, 25]. From figure 7(b), the Fe 2p₃/₂ spectrum was fitted with two peaks, the peak turned up at higher binding energies can be ascribed to Fe³⁺, the lower one could be owned to Fe²⁺ [26, 27]. The content of Fe³⁺/(Fe²⁺ + Fe³⁺) on the surface of FeₐTiₐOₓ catalyst was listed in table 3. For the most part, Fe³⁺ possessed stronger oxidative ability than Fe²⁺, which was contributed to the oxidation process of NO to NO₂. And it could promote the ‘fast SCR’ process:

\[
2\text{NH}_3 + \text{NO} + \text{NO}_2 \rightarrow 2\text{N}_2 + 3\text{H}_2\text{O} [28–30].
\]

The higher content of Fe³⁺/(Fe²⁺ + Fe³⁺) provide a guarantee for better redox properties in the selective catalytic reduction reaction. The O 1s spectra could be deconvoluted into two peaks. In figure 7(c), the peak emerged at higher binding energies was surface adsorbed oxygen species (marked as Oₓ), in the shape of O²⁻ or O⁻ with regard to defect-oxide or hydroxyl-like group; another peak arise at lower binding energies was allocated to the lattice oxygen O²⁻ (marked as Oᵧ) [31, 32]. In figure 7(d), intensity of Ti 2p₁/₂ and Ti 2p₁/₂ peak decreased from Fe₂Ti₁Oₓ to Fe₁₀Ti₁Oₓ catalyst. Fe₁₀Ti₁Oₓ catalyst only showed Ti 2p₁/₂ peak. Combining with XRD pattern, the missing of Ti 2p₁/₂ peak for Fe₁₀Ti₁Oₓ catalyst may ascribe to higher Fe amount.

With regard to the NH₃-SCR process, the reduction ability was one of the most significant factors for the catalyst. The H₂-TPR profiles of FeₐTiₐOₓ catalyst was illustrated in figure 8(a). The Fe₂Ti₁Oₓ and Fe₁₀Ti₁Oₓ catalyst provided a broad reduction peaks appeared at 488 °C and 398 °C. Fe₆Ti₁Oₓ catalyst showed different H₂ reduction peaks (located at 378 °C, 412 °C and 530 °C, separately). Compared with Fe₂Ti₁Oₓ and Fe₁₀Ti₁Oₓ catalyst, Fe₆Ti₁Oₓ catalyst has a lower temperature H₂ consumption peaks (378 °C), indicated that the reduction of Fe₆Ti₁Oₓ catalyst was better than the reduction of other two catalysts. Clear broad reduction peaks appeared within the temperature range of 350 °C–500 °C, indicating that Fe³⁺ was reduced to Fe²⁺ [33]. Another large broad peak turned up around 530 °C for Fe₆Ti₁Oₓ catalyst, suggesting that part of Fe²⁺ species may be further reduced to metallic Fe⁰ [34].

### Table 3. XPS results of the different catalyst samples.

| Samples     | Fe   | Ti   | O    | C    | \(A_{Oₓ}/(A_{Oₓ}+A_{Oᵧ})\) (%) | \(A_{Fe³⁺}^{AO⁺}/(A_{Fe²⁺}^{AO⁺}+A_{Fe³⁺}^{AO⁺})\) (%) |
|-------------|------|------|------|------|---------------------------------|--------------------------------------------------------|
| Fe₂Ti₁Oₓ    | 11.26| 4.29 | 58.55| 25.9 | 72.5                            | 49.7                                                   |
| Fe₆Ti₁Oₓ    | 20.23| 2.14 | 51.28| 25.81| 58.7                            | 59.7                                                   |
| Fe₁₀Ti₁Oₓ   | 21.79| 1.36 | 53.18| 23.67| 55.3                            | 55                                                     |

Figure 8. (a) H₂-TPR and (b) NH₃-TPD for Fe₂Ti₁Oₓ, Fe₆Ti₁Oₓ and Fe₁₀Ti₁Oₓ catalyst.
3.5. Surface acidity (NH3-TPD)
It is noteworthy for NH3 adsorption capacity over the different catalysts in the SCR process. The surface acidity for Fe2Ti1Ox, Fe6Ti1Ox and Fe10Ti1Ox catalyst was evaluated by the NH3-TPD analysis, the results were displayed in figure 8(b). Well known to us all, the position of the NH3 desorption peak is correlated with the strength of acid sites [35]. It is evident that the temperature of the NH3 desorption peak for Fe6Ti1Ox catalyst was higher than that of other two catalyst. It means that Fe6Ti1Ox catalyst has stronger surface acid than the other two catalyst; the NH3 desorbed at higher temperature may be associated with the chemisorbed ammonia [36]. Wherefore, the higher SCR activity for Fe6Ti1Ox catalyst may be assigned to its stronger surface acid.

3.6. Summary
Fe6Ti1Ox catalyst exhibited the best catalytic performance in testing temperature range (240 °C–400 °C). For three catalysts, Fe6Ti1Ox catalyst has stronger surface acid than the other two catalysts, which was beneficial for NH3 adsorption on the surface of catalyst. Moreover, by combining XRD result and catalytic performance of three catalysts, hematite Fe2O3 and TiO2 may exist an important synergetic effect for the improvement of catalytic performance. As the main catalytic active species, hematite Fe2O3 has better oxidative ability and the content of Fe3+/Fe2+ of Fe6Ti1Ox catalyst was higher than the other two catalysts. H2-TPR result showed that Fe6Ti1Ox catalyst has the best redox property. The predominant catalytic performance of Fe6Ti1Ox catalyst may be owned to its hematite Fe2O3 and TiO2 structure, superior redox properties and strong surface acid.

4. Conclusions
In this study, high-performance Fe6Ti1Ox catalyst was prepared for selective catalytic reduction of NOx with NH3. The Fe6Ti1Ox catalyst enjoyed outstanding catalytic activity, more than 95% NOx removal efficiency was obtained at measuring temperature from 280 to 400 °C. When the filtration velocity was 0.5 m min⁻¹, Fe6Ti1Ox catalyst obtained exceed 95% NOx conversion in the temperature range of 260 °C–400 °C. The suitable O2 concentration and NH3/NO mole ratio should maintain about 0.9 and 6%, respectively. Furthermore, the Fe6Ti1Ox catalyst has attractive catalytic activity when SO2 and water vapor were existed at the testing temperature of 300 °C. The NOx conversion maintained 97% when 300 ppm SO2 and 10 vol.% water vapor were introduced. A series of characterization result showed that Fe6Ti1Ox catalyst presented a higher catalytic activity depending on hematite Fe2O3 and TiO2 structure, excellent redox properties and strong surface acid.

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Data availability statement
All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of interest
There are no conflicts to declare.

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