Article

The effect of Fe species distribution and acidity of Fe-ZSM-5 on the hydrothermal stability and SO2 and hydrocarbons durability in NH3-SCR reaction

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ABSTRACT

Fe-exchanged ZSM-5 catalysts prepared from Na+ and H+ forms of ZSM-5 were evaluated for the selective catalytic reduction of NOx by NH3 (NH3-SCR). Fe-H-ZSM-5 showed higher SCR activity than Fe-Na-ZSM-5 both when fresh and after hydrothermal aging at 750 °C in 5% H2O/air. The Fe species distribution and acidity of Fe-H-ZSM-5 and Fe-Na-ZSM-5 were found to be different. The dealumination of the zeolite framework of Fe-H-ZSM-5 during hydrothermal aging was found to be more severe compared with that of Fe-Na-ZSM-5. The durability of Fe-H-ZSM-5 and Fe-Na-ZSM-5 in NH3-SCR was compared using SO2 tolerance and hydrocarbon resistance experiments. The effect of water and SO2 on the activity of the two catalysts was similar, such that their activity decreased at low temperatures and increased at high temperatures. Fe-Na-ZSM-5 showed better propene resistance than Fe-H-ZSM-5. The SO2 and propene poisoning of the two Fe-ZSM-5 catalysts were found to be reversible.

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1. Introduction

The selective catalytic reduction (SCR) of NOx by NH3 is a well-proven process for the removal of NOx from stationary and mobile sources. A number of metal-exchanged zeolites (MFI, MOR, BEA, and FER), especially Cu- and Fe-based MFI-structured zeolites (ZSM-5), are active SCR catalysts and have been studied extensively [1,2]. Cu-ZSM-5 catalysts show high activity at low temperatures (< 300 °C), but their hydrothermal stability is limited [2,3]. Fe-ZSM-5 is more attractive for its nontoxic metal use, high activity at high temperature (> 300 °C) and better hydrothermal stability [2,4].

The NH4+, H+, and Na+ forms of ZSM-5 can be used as parent zeolites for Cu- and Fe-ZSM-5 preparation. The H+ and Na+ cations have been found to influence the catalytic behavior of Cu-zeolite catalysts [5-8]. The Cu location and the redox properties of Cu-zeolite catalysts (Cu-MOR and Cu-FAU) can be affected by co-cations. For example, the Cu in the Na+ form catalyst has been found to be more easily reduced than that in the protonic form [5,6]. Sultana et al. [7,8] reported that Cu-ZSM-5 prepared from a Na+ form precursor showed higher activity for NH3-SCR than those prepared from a H+ form precursor, owing to the existence of a larger number of Cu+ species and easily reducible Cu2+ species in the obtained Cu-NaZSM-5.

Controversial results have been reported for the effect of co-cations on the catalytic performance of Fe-ZSM-5 catalysts. Fe-ZSM-5 prepared from a Na-ZSM-5 precursor showed lower NO conversion in the NH3-SCR reaction compared with those

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prepared from H+ or NH4+ forms [9,10]. Pieterse et al. [11] pointed out that the removal of framework aluminium by steam-dealumination should be slowed in Fe-ZSM-5 owing to the replacement of protons with sodium. Contrarily, Brandenberger et al. [10] reported that hydrothermal deactivation at 800°C in 10% H2O/air resulted in a greater decrease in the NH3-SCR activity of Na-ZSM-5 exchanged Fe-ZSM-5 than H-ZSM-5 exchanged samples, but did not give further explanation.

Hydrothermal stability, hydrocarbon (HC) and SO2 tolerance are the challenges facing the practical application of de-NOx SCR catalysts in diesel engines. In this paper, Fe-ZSM-5 catalysts with different Fe species distribution and acidity were prepared from Na+ and H+ form ZSM-5 by liquid ion exchange, and their catalytic behavior in the NH3-SCR reaction was investigated. Temperature-programmed reduction with hydrogen (H2-TPR), UV-vis diffuse reflectance spectrometry (DRS), in situ diffuse reflectance infrared Fourier transform spectrometry (DRIFTS), nuclear magnetic resonance (NMR), and X-ray diffraction (XRD) were used to characterize the fresh and hydrothermally aged Fe-ZSM-5 catalysts. The hydrothermal stability, SO2 and HC resistance of Fe-NaZSM-5 and Fe-H-ZSM-5 in the NH3-SCR reaction were compared and discussed.

2. Experimental

2.1. Catalyst preparation

Na-ZSM-5 with SiO2/Al2O3 = 25 was obtained from Nankai University. The Na-ZSM-5 was mixed with 0.5 mol/L NH4NO3 aqueous solution and heated in a water bath at 80°C for 24 h, followed by washing and filtration. The resultant NH4-ZSM-5 was dried overnight at 110°C and then calcined at 550°C for 6 h in air to obtain H-ZSM-5. Fe-ZSM-5 catalysts were prepared by liquid ion exchange. Typically, 10 g ZSM-5 precursor was added to FeCl3•4H2O solution (17.8 g/L) with constant stirring under a continuous flow of N2 (200 mL/min) in a water bath at 80°C. After 24 h, the mixture was filtered and washed with deionized water. The resulting powder was dried overnight at 110°C and calcined at 600°C for 6 h in air to obtain Fe-NaZSM-5 and Fe-H-ZSM-5, which are hereafter denoted Fe-NaZ and Fe-HZ, respectively. The hydrothermal aging of Fe-NaZ and Fe-HZ was carried out at 750°C in 10% H2O/air for 12 h.

2.2. Catalytic characterization

H2-TPR experiments were performed with a Micromeritics AutoChem 2920 chemisorption analyzer equipped with a thermal conductivity detector (TCD). For the analysis, 100 mg of powdered sample was pre-treated in 20% O2 at 550°C for 20 min. After cooling to 30°C in Ar, the H2-TPR measurements were recorded in 10% H2/Ar (50 mL/min), with a heating rate of 20°C/min and a final temperature of 900°C.

UV-Vis DRS spectra were recorded with a Hitachi UV3010 (Japan). BaSO4 was used as the reference material. The Fe-ZSM-5 catalysts were diluted with BaSO4 at a ratio of 1:4.

The spectra were converted with the Kubelka-Munk (KM) function for comparison.

In situ DRIFTS experiments of NH3 adsorption over the Fe-ZSM-5 catalysts were performed on a Fourier transform infrared spectrometer (FTIR; Nicolet Nexus 670). Each sample was pretreated at 550°C in a flow of 20% O2/N2 for 20 min, then purged with pure N2 for 20 min and cooled to 140°C in N2. Then, the samples were exposed to a flow of 1% NH3/N2 and the spectra were recorded until NH3 adsorption saturation.

Powder XRD measurements were carried out on a Panalytical X-ray diffractometer (Netherlands, XPert PRO MPD) with a Cu Kα radiation source. The 2θ data from 5° to 60° were collected with a step size of 0.02°.

Solid state 27Al MAS NMR spectra were collected on a Brucker AVANCE III 400MHz WB Solid-State NMR spectrometer. All 27Al MAS NMR spectra were externally referenced to an aqueous solution of Al(NO3)3 at 0 ppm, and were obtained at a sample spinning rate of 10 kHz using 15° pulses and a 0.5 s recycle delay, a total of 12000 pulses being accumulated.

3. Results and discussion

3.1. Catalyst discussion

The elemental composition of the samples was analyzed using an inductively coupled plasma optical emission spectrometer (ICP-OES). Although the two catalysts were prepared by exactly the same procedure, the Fe loading of Fe-NaZ (1.62 wt%) was higher than that of Fe-HZ (1.27 wt%). Similar results have been reported and explained to be caused by the fact that the change in solution pH during the ion exchange process might be different for different precursors [9]. The residual Na content in Fe-NaZ was 0.61 wt%.

3.2. H2-TPR results

The H2-TPR profiles obtained from fresh and hydrothermally aged Fe-HZ and Fe-NaZ are shown in Fig. 1(a). A mechanical mixture of 5 wt% α-Fe2O3 with H-ZSM-5 was prepared and tested for comparison. The H2-TPR profile of 5 wt% α-Fe2O3/H-ZSM-5 showed broad reduction features between 325–650°C. This suggests that the reduction of iron oxide particles completed below 650°C, by the reduction of Fe2O3 to FeO and then reduction of FeO to Fe via FeO [10,12–16]. According to previous work on the H2-TPR of Fe-ZSM-5 catalysts, the first reduction peak corresponds to the reduction of
Fe³⁺ to Fe²⁺ [10,12–16]. When Fe³⁺ is located at ion-exchanged positions, further reduction of Fe²⁺ to Fe⁰ occurs at temperatures above 1000 °C owing to the collapse of the zeolite framework [10,12].

As shown in Fig. 1(a), the H₂-TPR profile of fresh Fe-HZ exhibited one main reduction peak at 370 °C, which can be assigned to the reduction of Fe³⁺ to Fe²⁺. No significant reduction peaks were observed from 550 °C to 900 °C in the profile of Fe-HZ, which indicates that most of the iron in Fe-HZ was located at exchange sites [13,14]. The first peak in the H₂-TPR profile of fresh Fe-NaZ can also be attributed to the reduction of Fe³⁺ at exchanged sites to Fe²⁺. The main peaks at 484 °C and the small shoulder at 435 °C should correspond to reduction of larger FeOₓ particles [10,12–16]. Fe species located at the same sites should show similar H₂ reduction temperatures. Therefore, the first reduction peak for Fe-NaZ could be assigned to the reduction of Fe species located in ion exchange sites, similar to that seen for the dominating Fe species in Fe-HZ.

After hydrothermal deactivation, the H₂ consumption peaks of the aged samples were shifted to higher temperatures, implying a decrease in the reducibility of active iron species in Fe-ZSM-5. Aged Fe-HZ showed a main peak at 405 °C while aged Fe-NaZ showed a main peak at 512 °C with a shoulder at 405 °C. According to Brandenberger et al. [10], the reduction peak of iron oxide clusters can shift to higher temperature with their size. The present H₂-TPR results indicate that the migration of Fe³⁺ from ion exchange sites and the formation of small FeOₓ particles took place during the hydrothermal aging. Deconvolution of the H₂ consumption peaks (Fig. 1(b)) revealed that the percentage area of the first peak with respect to the total area of the H₂ consumption peaks was around 34% for both fresh and aged Fe-NAZ. This suggests that the degree of migration of Fe ions in Fe-ZSM-5 is mainly decided by their location in the zeolites.

### 3.3. UV-vis DRS results

UV-vis DRS was used to study the distribution of Fe species in the Fe-ZSM-5 samples. The UV-Vis spectra of the fresh and aged Fe-ZSM-5 are compared in Fig. 2. Generally, the bands below 300 nm are assignable to isolated Fe³⁺ species located on ion exchange sites, while bands above 300 nm are assignable to oligomeric clusters (between 300–400 nm) and FeOₓ particles (above 400 nm) [17,18]. As shown in Fig. 2, the spectra of Fe-NAZ exhibited a significant intensity of bands above 400 nm. In contrast, most of the peak bands of Fe-HZ were below 400 nm. To estimate the Fe species distribution in the catalyst, the UV-vis spectrum of each sample was deconvoluted with \( r^2 > 0.999 \), and the results are summarized in Table 1. From these data we obtained a rough estimation of the percentage of iso-

| Table 1 |
|---------------------------------|
| Catalyst | \( I_1(\%) \) | \( I_2(\%) \) | \( I_3(\%) \) |
|-----------------|----------------|----------------|----------------|
| Fresh Fe-HZ     | 50.2           | 31.7           | 18.1           |
| Fresh Fe-NaZ   | 44.0           | 32.4           | 23.6           |
| Aged Fe-HZ      | 46.9           | 33.7           | 19.4           |
| Aged Fe-NaZ     | 40.6           | 34.1           | 25.3           |

\( I_1, I_2, \) and \( I_3 \) represent the percentage of isolated Fe³⁺ species (subbands at \( \lambda \leq 300 \) nm), oligomeric clusters (subbands at 300 nm < \( \lambda < 400 \) nm), and FeOₓ particles (subbands at \( \lambda > 400 \) nm), respectively.
lated Fe\(^{3+}\) species, oligomeric clusters, and FeO\(_x\) particles compared with the total Fe present in Fe-ZSM-5. The relative concentration of isolated Fe\(^{3+}\) species in Fe-HZ was found to be higher than that in Fe-NaZ, whereas Fe-NaZ contained more oligomeric FeO\(_x\) clusters and FeO\(_x\) particles. After hydrothermal aging, the intensity of the bands above 300 nm increased, which indicates that hydrothermal aging caused the migration of isolated Fe\(^{3+}\) species from iron exchange sites and the formation of small clusters of iron oxides, which confirms the H\(_2\)-TPR results.

3.4. \(\text{NH}_3\) adsorption

The in situ DRIFTS spectra of various samples measured after saturated \(\text{NH}_3\) adsorption are shown in Fig. 3. The bands related to \(\text{NH}_3\)-adsorbed species appear at 3500–1400 cm\(^{-1}\) after \(\text{NH}_3\) adsorption over Fe-ZSM-5. The bands related to \(\text{NH}_3\) adsorbed species appearing at 3500–250 cm\(^{-1}\) can be assigned to the N–H stretching vibration of adsorbed \(\text{NH}_3\) [14]. The band at 1480 cm\(^{-1}\) is assigned to the symmetric bending vibration of \(\text{NH}_4^+\) chemisorbed onto Brønsted acid sites [14,17–20]. The negative band at 3610 cm\(^{-1}\) can be assigned to the OH stretch of Brønsted acid sites resulting from the interaction of surface hydroxyls with \(\text{NH}_3\), which may reflect the relative concentration of Brønsted acid sites on the Fe-ZSM-5 [10,19–21]. The intensity of the band at 3610 cm\(^{-1}\) was higher for Fe-HZ than Fe-NaZ. A magnification of the 3610 cm\(^{-1}\) band is inset in Fig. 3. No IR bands corresponding to Brønsted acid sites were observed for Na-ZSM-5. Protonic sites can be introduced into Na-ZSM-5 by the ion exchange process [10,11]. The same bands were observed for fresh Fe-NaZ after \(\text{NH}_3\) adsorption, but the intensity was lower compared with those observed for fresh Fe-HZ. After hydrothermal aging, the intensity of the negative band at 3610 cm\(^{-1}\) and the intensity of the bands of \(\text{NH}_3\) adsorption species over Fe-HZ and Fe-NaZ were significantly decreased.

3.5. XRD and NMR results

Figure 4 shows the XRD patterns of the fresh and hydrothermally aged Fe-HZ and Fe-NaZ catalysts, and of a mechanical mixture of 5% \(\alpha\)-FeO\(_x\) with H-ZSM-5 for comparison. The aged Fe-HZ and Fe-NaZ exhibited little change compared with those of the fresh samples. This indicates that the crystalline zeolite structure was retained after hydrothermal aging. The typical XRD peaks of \(\alpha\)-FeO\(_x\) were observed at 33.1°, 35.6°, 40.9°, and 49.5° [14,22,23]. Low intensity peaks of \(\alpha\)-FeO\(_x\) were detected in the XRD patterns of fresh and aged Fe-NaZ. This confirmed the presence of FeO\(_x\) particles in Fe-NaZ.

The \(^27\)Al MAS NMR spectra of fresh and hydrothermally aged Fe-HZ and Fe-NaZ are shown in Fig. 5. The fresh Fe-ZSM-5 samples showed a strong signal at around 55 ppm, attributed to tetrahedrally coordinated aluminum, and a weak signal at around 0 ppm, assignable to octahedrally-coordinated aluminum (extra-framework) [10,24,25]. After hydrothermal aging, the intensity of the peak at 55 ppm was decreased owing to the removal of the aluminum from the tetrahedral zeolite framework. The intensity of the octahedral aluminum peak at 0 ppm was also decreased in the spectra of the aged samples. These results indicate that the aluminum removed from the tetrahedral zeolite framework was converted into distorted “NMR invisible” Al species [10,24]. The intensity of the tetrahedral
aluminum peak in aged Fe-HZ more significantly was reduced than that of aged Fe-NaZ. The integrated peak area of the tetrahedral Al$^{3+}$ ions in the aged samples was around 53% in Fe-NaZ and 26% in Fe-HZ. This indicates that the zeolite framework of Fe-NaZ was more stable during hydrothermal aging than that of Fe-HZ.

3.6. Catalytic activity

We conducted a comparative study of the effect of hydrothermal deactivation, and the presence of SO$_2$ and C$_3$H$_6$ on the SCR activity of the Fe-HZ and Fe-NaZ catalysts. Figure 6(a) shows NO$_x$ conversion as a function of reaction temperature at 190–550 °C over fresh and hydrothermally aged Fe-HZ and Fe-NaZ catalysts. The fresh Fe-HZ showed higher SCR activity than the fresh Fe-NaZ within the whole reaction temperature range. Hydrothermal aging resulted in a significant decrease in NO$_x$ conversion over the Fe-ZSM-5 catalysts, especially at low temperatures. The aged Fe-HZ also showed higher SCR activity than the aged Fe-NaZ.
The effect of SO₂ on the Fe-ZSM-5 catalysts is shown in Fig. 6(b). When 100 ppm SO₂ was added into the flue gas, a decline in NOₓ conversion at low temperatures (below 350 °C) and a slight increase in NOₓ conversion at high temperatures (>350 °C) were observed. The SO₂ durability (100 ppm) of Fe-HZ and Fe-NaZ was investigated at 325 °C with the copresence of 5% water (Fig. 6(d)). The SCR reaction was left to stabilize for 1 h before adding SO₂ and water. A sharp decline in the NOₓ conversion of both the Fe-HZ and Fe-NaZ catalysts was observed upon addition of the SO₂ and water to the gas flow. The NOₓ conversion of Fe-HZ was decreased from ca. 80% to ca. 55%, while that of Fe-NaZ was decreased from ca. 65% to ca. 45% after 20 h of reaction.

Figure 6(c) shows the NOₓ and C₃H₆ conversions over Fe-HZ and Fe-NaZ in the presence of 500 ppm C₃H₆. The presence of C₃H₆ in the feed gas stream was found to result in an apparent decrease in the NOₓ conversion ability of both of the catalysts. Fe-NaZ exhibited higher NOₓ conversion than Fe-HZ in the presence of C₃H₆. Fig. 6(e) shows the C₃H₆ durability of Fe-HZ and Fe-NaZ at 350 °C. After the SCR reaction had been stable for about 1 h, 500 ppm C₃H₆ was added to the reaction gas flow. The decrease in SCR activity caused by adding C₃H₆ was rapid in the first few minutes and then became slower in the time that followed. After 5 h reaction, the NOₓ conversion of Fe-HZ decreased from 82% to 40% while that of Fe-NaZ decreased from 79% to 44%. It seems that the impact of C₃H₆ on the SCR activity was more significant for Fe-HZ than Fe-NaZ. When C₃H₆ was removed from the feed gas, the NOₓ conversion of Fe-NaZ recovered within 20 min, while the NOₓ conversion of Fe-HZ recovered slowly.

The SO₂-poisoned and C₃H₆-poisoned samples were regenerated after the durability tests by heating at 550 °C in air for 30 min. The regenerated catalysts were tested in the standard SCR reaction and the results were compared with those obtained for the fresh samples. As shown in Fig. 7, the NOₓ conversions of the poisoned samples were partly recovered after the heat treatment. This indicates that the SO₂ and C₃H₆ poisoning of Fe-ZSM-5 was reversible. A better recovery of activity was observed for Fe-NaZ under the present regeneration conditions than Fe-HZ.

3.7. Discussion

The acidity and redox properties of Fe-ZSM-5 are two important parameters for the SCR reaction. The Brønsted acid sites of Fe-ZSM-5 are important for activating NH₃ species and are assumed to have a promoting effect for the SCR reaction at low temperatures [21,26]. Fe active sites are involved in the NO oxidation to NO₂, which is considered the slow step of the SCR reaction [22,27]. Among the various types of Fe species coexisting in the Fe-ZSM-5 catalysts, the isolated Fe³⁺ species are considered to contribute to the SCR reaction at low temperatures (< 300 °C) [23,28,29]. Therefore, the higher SCR activity of Fe-HZ might be mainly attributed to the higher amount of active Fe³⁺ ions and the greater number of Brønsted acid sites in this catalyst compared with those in Fe-NaZ.

The characterization results showed that hydrothermal aging of Fe-ZSM-5 catalysts led to the dealumination of the framework, the migration of Fe ions to form Fe₂O₃ clusters, and a significant decrease in acidity, in accordance with previous reports [10,30]. Protons remaining on zeolites are well known to accelerate the process of steam-induced aluminum loss [10,11,15]. Fe-NaZ contained fewer protonic sites than Fe-HZ, so the dealumination of the zeolite framework by hydrothermal deactivation occurred to a much lesser extent for Fe-NaZ. The Brønsted acid sites of aged-Fe-HZ and aged-Fe-NaZ were significantly decreased to the point of almost completely disappearing. Therefore, the higher SCR activity of aged Fe-HZ should be attributed to the greater number of residual Fe³⁺ species located in the ion-exchanged sites of this catalyst. The loss of redox active Fe sites, rather than dealumination of zeolite framework, should be responsible for the decrease in SCR activity.

The impact of SO₂ on the SCR activity of Fe-ZSM-5 was different at low and high temperatures, in agreement with previous studies [31–33]. Long et al. [33] suggested that the formation of surface iron sulfate on Fe-ZSM-5 increased the surface acidity of the catalyst and resulted in enhancement of its high temperature activity. At low temperatures (< 325 °C), the formation of ammonium sulfate might occur and cover some iron active sites, resulting in a decrease in SCR activity.

![Fig. 7. SCR performance of fresh and regenerated Fe-ZSM-5. (a) After SO₂ durability test; (b) After C₃H₆ durability test.](image-url)
The recovery of low temperature activity of Fe-ZSM-5 after regeneration can be explained as caused by the decomposition of these surface ammonium sulﬁte/sulfate species at high temperature.

Unburned hydrocarbons are always present in real exhaust gas. Zeolite SCR catalyst can be deactivated by hydrocarbons as a result of active site poisoning and pore blockage [35–39].

4. Conclusions

Fe-ZSM-5 catalysts prepared from H-ZSM-5 and Na-ZSM-5 showed differences in SCR activity, hydrothermal stability, and C₃H₆/SO₂ resistance owing to their different acidity and distributions of Fe species. The predominant Fe species in Fe-HZ was Fe³⁺ in ion exchanged sites, while Fe-NaZ contained a certain amount of Fe₂O₃ particles. The stability of these Fe³⁺ ions in Fe-ZSM-5 was mainly decided by their location. The zeolite structure of Fe-NaZ was more stable during hydrothermal aging than that of Fe-HZ. The presence of SO₂ and H₂O resulted in a decrease in the low temperature activity and an increase in the high temperature activity of both Fe-HZ and Fe-NaZ. Fe-NaZ showed better HC resistance than Fe-HZ, owing to less extensive hydrocarbon coking. Fe-HZ and Fe-NaZ deactivated by SO₂ or C₃H₆ was well regenerated by heating in air at 550 °C, although a better recovery of activity was observed for Fe-NaZ. According to the present results, to obtain better hydrothermal stability and hydrocarbon/SO₂ resistance, Fe-ZSM-5 catalysts should be prepared with greater quantities of Fe³⁺ species in ion exchanged sites and fewer residual protonic sites.

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NH$_3$-SCR反应中Fe-ZSM-5的Fe物种分布和酸性位对其水热稳定性及抗硫和抗碳氢性能的影响

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摘要: 以Na$^+$型和H$^+$型ZSM-5为载体制备了Fe-ZSM-5催化剂并用于氨选择性催化还原(NH$_3$-SCR)氮氧化物。Fe-H-ZSM-5在新鲜时和750℃含10%水的空气中老化后, 其SCR活性均优于Fe-Na-ZSM-5。表征结果显示, Fe-H-ZSM-5和Fe-Na-ZSM-5的Fe物种分布和酸性位有所不同。高温水热老化后Fe-H-ZSM-5分子筛骨架的脱铝较Fe-Na-ZSM-5严重。水和硫的存在对Fe-H-ZSM-5和Fe-Na-ZSM-5的SCR活性的影响相似, 即降低了低温活性, 略提高了高温活性。Fe-Na-ZSM-5表现出比Fe-H-ZSM-5更好的抗硫抗碳氢中毒性能。这两种催化剂的SO$_2$和碳氢中毒是可逆的。

关键词: 铁-ZSM-5; 氨选择性催化还原; 催化物化学; 抗硫性能; 水热稳定性

Graphical Abstract

The effect of Fe species distribution and acidity of Fe-ZSM-5 on the hydrothermal stability and SO$_2$ and hydrocarbons durability in NH$_3$-SCR reaction

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Fe-ZSM-5 prepared from Na-ZSM-5 is more stable against hydrothermal deactivation and shows better SO$_2$ and C$_3$H$_6$ poisoning resistance than Fe-ZSM-5 prepared from H-ZSM-5.

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