Applicability of $V_2O_5$-WO$_3$/TiO$_2$ Catalysts for the SCR Denitrification of Alumina Calcining Flue Gas

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Abstract: $V_2O_5$-WO$_3$/TiO$_2$ catalysts with different $V_2O_5$ and WO$_3$ loadings were prepared by the impregnation method. H$_2$O and SO$_2$ resistance of the catalysts under high H$_2$O concentration (30 vol.%) was studied. Influence of various basic metal oxides, such as Al$_2$O$_3$, CaO, Na$_2$O, and K$_2$O on the catalytic performance was studied and compared. It is revealed that the inhibitory effect is in the sequence of K > Na > Ca > Al, which is consistent with their alkalinity. X-ray diffraction (XRD), N$_2$ physisorption (BET), temperature-programmed desorption of NH$_3$ (NH$_3$-TPD), H$_2$-temperature programmed reduction (H$_2$-TPR), X-ray photoelectron spectroscopy (XPS) and diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) were carried out, and the results were well-correlated with the catalytic studies.

Keywords: selective catalytic reduction; $V_2O_5$-WO$_3$/TiO$_2$; H$_2$O and SO$_2$ resistance; basic metals

1. Introduction

Nitrogen oxide (NO$_x$), one of the main precursors of photochemical smog and haze pollution, causes great harm to the ecosystem and human lives [1,2]. Many strategies have been developed for NO$_x$ abatements from the stationary emission sources, including selective catalytic reduction (SCR) [3,4], selective non-catalytic reduction (SNCR) [5,6], activated carbon denitration [7,8], and oxidation-absorption method [9,10]. Among those methods, SCR technology has attracted extensive attention for being the most efficient strategy for NO removal [11].

Accordingly, numerous SCR catalysts have been reported, such as V, Ce, Mn, Cu-based catalysts [12–15]. Hu et al. [16] found that the doping of Ce improved the catalytic activity and Na poisoning resistance of CeVWTi catalyst for NH$_3$-SCR. Although Mn-based catalyst has a good low temperature effect [17,18], it has poor sulfur and water resistance. Hong et al. [19] reported that the introduction of 5 wt.% W into Mn/Ce/Ti sharply increased the amount of Mn$^{4+}$ and Ce$^{3+}$, which accounted for the higher SCR activity and sulfur tolerance. Until now, $V_2O_5$-WO$_3$/TiO$_2$ catalyst has been most widely accepted in flue gas and has received an excellent effect [20,21].

Recently, in China, emission standards have become increasingly stringent, and NO$_x$ control has been generally recognized as a crucial step in environmental upgrades for non-electricity industries [22–24] such as the non-ferrous metal industry. The production of alumina is about 90 million tons in China, which accounts for more than half of the world’s production. In alumina
calcining flue gas, NOx concentrations are in the range of 200–600 mg/m³, whereas no mature denitrification technology has been employed. In the fluidized bed system of an alumina calciner, the flue gas temperature is 300–400 °C between the positions P02 and A02, as shown in Figure S1, and the temperature is suitable for the conventional V2O5-WO3/TiO2 catalysts. However, the water vapor concentration here reached 30%, and the dust in the flue gas was mainly Al2O3 with a high concentration at 30–100 g/m³. The unique properties make it necessary to investigate the SCR applications for alumina calcining flue gas.

Commonly, conventional SCR catalysts consist of 1% V2O5 and 5–10% WO3/MoO3 supported on antase TiO2, with the operation temperature range of 300–420 °C [25–27]. It has been widely employed in coal-fired flue gas due to its high stability and good H2O and SO2 resistance [28,29]. The anti-water performance has usually been studied with H2O concentrations below 15% [30–33], and almost no research has been conducted under conditions like alumina calcining flue gas (30% H2O). The metal-containing dust in alumina calcining flue gas is mainly composed of Al2O3 and traces of Al(OH)3, which distinguishes it from basic metal oxides, such as Na2O, K2O, and CaO, which are contained in coal-fired flue gas. The effect of basic metals on SCR performance in simulated coal-fired flue gas has been systematically evaluated, giving the results as follows: K2O > Na2O > CaO [34]. However, the influence of Al2O3 or Al(OH)3 on catalytic performance has not been reported.

Hence, it is of great importance to research the applicability of V2O5-WO3/TiO2 catalysts for the SCR denitrification of alumina calcining flue gas. Herein, a series of V2O5-WO3/TiO2 catalysts are prepared and evaluated in simulated alumina calcining flue gas. The influence of Al on the catalyst surface is compared with those of K, Na, and Ca, respectively, by means of NH3-TPD, Diffuse Reflectance Infrared Fourier Dransform (DRIFT) spectroscopy, and X-ray photoelectron spectroscopy (XPS) characterizations.

2. Results and Discussion

2.1. Catalytic Studies of V-W/Ti Catalysts

In alumina calcining flue gas, the O2 concentration is 0.5–5% between sites P02 and A02, showing great variation for different calciners. Accordingly, the effect of O2 concentration on SCR activity over 1% V2O5/TiO2 was investigated. As shown in Figure S2, complete conversion of NO could be realized with the increase of temperature. At the same temperature, NO conversion increased with the improvement of O2 concentration. This is consistent with previous studies [35,36]. Noteworthy, the V-based catalyst still showed great applicability in the relatively oxygen-deficient flue gas, and 0.5% O2 concentration was constant in the following in this research.

Introduction of WO3 into the V2O5/TiO2 catalyst commonly increases its catalytic activity by strengthening its acidity on the catalyst surface [37]. To explore the influence of V2O5 and WO3 content on the catalytic activity, a series of (x)V-(y)W/Ti catalysts were prepared and evaluated. As shown in Figure 1a, the catalytic activity gradually increased, and the reaction temperature window was also broadened with the increase of V2O5 content. For (x)V-5W/Ti, the NO conversions increased from 43% to 92% at 250 °C, when the V2O5 content (x) was increased from 0.5% to 3%. It has been reported that a monolayer V2O5 structure can be formed on the surface of antase TiO2 when the V2O5 content is about 1% [38]. Further increasing the amount of V2O5 will not increase the surface V2O5, whereas the excess V2O5 trapped inside will not participate the catalytic cycle. For 1V-(y)W/Ti, the addition of WO3 apparently improved its catalytic performance, and 1V-5W/Ti showed almost comparable reactivity with that of 1V-10W/Ti, as shown in Figure 1b. Based on the results above, it could be concluded that the contents of 1% V2O5 and 5% WO3 would be appropriate for SCR applications in alumina calcining flue gas.
V-W/Ti was examined with H2O concentration variations at 10%, 20% and 30%, and the denitration efficiency of the catalyst was gradually improved. When the V2O5 content was 1%, the denitration efficiency of the catalyst was stabilized at 83% under the conditions of 30% H2O and 200 ppm SO2. Further increase of V2O5 content showed no apparent changes in catalytic performance. Then, 1V-5W/Ti was examined with H2O concentration variations at 10%, 20% and 30%, and the denitration efficiencies were 90%, 85%, and 83% in the presence of H2O and 200 ppm SO2, as shown in Figure 2a. The experiments for 1V(x)-yW/Ti with different WO3 loadings; (b) 1V-(x)W/Ti with different WO3 loadings. Reaction conditions: [NH3] = [NO] = 400 ppm, [O2] = 0.5%, balance N2, gas hourly space velocity (GHSV) = 30,000 h⁻¹.

V-W/Ti catalysts have been well demonstrated in SCR studies on the water and sulfur resistance of the catalyst [39,40]. Considering the alumina calcining flue gas temperature is between 300–400°C, the anti-water and sulfur tests for V-W/Ti catalysts were conducted to examine their catalytic stability. As show in Figure 2a, the experiments for 1V-5W/Ti (x = 0.5–3) were conducted under the conditions of temperature = 300°C, [H2O] = 30%, and [SO2] = 200 ppm. It could be seen that presence of H2O and SO2 led to the decrease of the NO conversions. With the increase of V2O5 content, the denitration efficiency of the catalyst was gradually improved. When the V2O5 content was 1%, the denitration efficiency of the catalyst was stabilized at 83% under the conditions of 30% H2O and 200 ppm SO2. Further increase of V2O5 content showed no apparent changes in catalytic performance. Then, 1V-5W/Ti was examined with H2O concentration variations at 10%, 20% and 30%, and the denitration efficiencies were 90%, 85%, and 83% in the presence of H2O and SO2 (Figure 2b).

Figure 1. NOx conversion versus temperature over different catalysts: (a) 1V(x)-yW/Ti with different V2O5 loadings; (b) 1V-(x)W/Ti with different WO3 loadings. Reaction conditions: [NH3] = [NO] = 400 ppm, [O2] = 0.5%, balance N2, gas hourly space velocity (GHSV) = 30,000 h⁻¹.

Figure 2. Effect of H2O and SO2 on the NO conversion over the catalysts: (a) 1V(x)-yW/Ti with different V2O5 loadings; (b) effect of H2O concentration on 1V-5W/Ti catalyst. Reaction conditions: [NH3] = [NO] = 400 ppm, [O2] = 0.5%, [SO2] = 200 ppm, [H2O] = 10%, 20%, 30%, balance N2, GHSV = 30,000 h⁻¹, reaction temperature = 300°C.

2.2. Influence of Basic Metals (Al, Ca, Na, and K) on Catalytic Performance

Considering the high concentration of dust in the alumina calcining flue gas and its main component being Al2O3, the influence of Al2O3 on the activity of V-W/Ti catalysts was studied. Al-doped 1V-5W/Ti catalysts with different Al/V molar ratios were prepared using the impregnation method and evaluated in activity tests as well as the water and sulfur resistance tests. As shown in Figure 3a, with the increase of Al/V molar ratios, the activity of the catalysts gradually decreased. In the water and sulfur resistance tests (Figure 3b), the introduction of 30% H2O and 200 ppm SO2...
led to a decrease in the NO conversions for all catalysts. When the Al/V molar ratio was 0.5, the NO conversions could be stabilized around 75%. In the tests for the samples 1Al doped and 2Al doped, the NO conversions were gradually partially recovered when SO\textsubscript{2} was introduced. Similar phenomena have been observed in previous metal-poisoning studies, and it was ascribed to the generations of new acidic active sites [41,42].

**Figure 3.** Influence of Al on catalytic performance: (a) NO\textsubscript{x} conversion versus temperature over the catalysts with different contents of Al\textsubscript{2}O\textsubscript{3}; (b) effect of H\textsubscript{2}O and SO\textsubscript{2} on the NO conversion over the catalysts with different contents of Al\textsubscript{2}O\textsubscript{3}. Reaction conditions: [NH\textsubscript{3}] = [NO] = 400 ppm, [O\textsubscript{2}] = 0.5%, [SO\textsubscript{2}] = 200 ppm and [H\textsubscript{2}O] = 30% for (b), balance N\textsubscript{2}, GHSV = 30000 h\textsuperscript{-1}, H\textsubscript{2}O and SO\textsubscript{2} resistance test temperature = 300 °C.

The influence of Al\textsubscript{2}O\textsubscript{3} on the catalytic activity was compared with conventional basic metal oxides, such as K\textsubscript{2}O, Na\textsubscript{2}O and CaO. The same M/V molar ratio was adopted (being 1.0). As shown in Figure 4, the influence of Al\textsubscript{2}O\textsubscript{3} was far weaker than that of other basic metal oxides. Particularly at 300 °C, 1Al doped showed almost equal NO conversion with that of the fresh sample, whereas those of K, Na, and Ca doped were 19%, 45%, and 72%, respectively. The results revealed that the inhibitory effect of the metal oxides is in the sequence of K\textsubscript{2}O > Na\textsubscript{2}O > CaO > Al\textsubscript{2}O\textsubscript{3}, which is consistent with their alkalinity.

**Figure 4.** Comparison of catalyst deactivated by Al, Ca, Na, and K over NO conversion. Reaction conditions: [NH\textsubscript{3}] = [NO] = 400 ppm, [O\textsubscript{2}] = 0.5%, balance N\textsubscript{2}, GHSV = 30000 h\textsuperscript{-1}.

### 2.3. Catalyst Characterization

As shown in Figure 5, only anatase TiO\textsubscript{2} was detected in the XRD patterns, indicating the finely dispersed or amorphous existence of V\textsubscript{2}O\textsubscript{5}, WO\textsubscript{3} and all basic metal oxides, on the surface of antase TiO\textsubscript{2}. The surface area of the fresh and M (M = Al, Ca, Na, and K) doped catalysts are presented in
Table S1. It could be seen that doping of Al, Ca, Na, and K led to very slight changes of the surface area, revealing that BET surface area is not the prevailing reason for the catalyst deactivation.

The fresh (1V-5W/Ti) catalyst gave the largest NH$_3$ desorption amount. Among the basic metal doped catalysts, the decrease amount of the adsorption ammonia follows in the sequence of K > Na > Ca > Al, which is consistent with the catalytic results.

The first step of this SCR reaction is the catalyst ammonia adsorption [43,44]. Hence, it is essential to investigate the adsorption ability of the fresh and doped catalysts. As shown in Figure 6, each curve can be divided into two peaks, peak 1 at around 200 °C and peak 2 at around 320 °C, which correspond to the weakly and strongly bound ammonia. The weakly bound ammonia can be assigned to the Brønsted acid sites and the strongly bound ammonia can be assigned to the Lewis acid sites [45]. The fresh (1V-5W/Ti) catalyst gave the largest NH$_3$ desorption. Low Al/V molar ratio (≤0.5) has little effect on the adsorption ability of the catalysts. When the molar ratio of Al/V is 2, the NH$_3$ desorption decreases distinctly. After the introduction of different basic metals, the NH$_3$ desorption amount decreases distinctly. Among the basic metal doped catalysts, the decrease amount of the adsorption ammonia follows in the sequence of K > Na > Ca > Al, which is consistent with the catalytic results.

In addition to the acid sites on the catalyst surface, the redox ability of vanadium species is also considered as another key property for SCR reaction. Therefore, the reducibility of vanadium and tungsten species was measured, and the results were presented in Figure 7. Three apparent reduction peaks, centered at 325 °C, 450 °C and 728 °C, were observed on fresh 1V-5W/Ti catalyst, which could be assigned to the reduction of adsorbed oxygen species, V$^{5+}$ to V$^{3+}$, and W$^{6+}$ to W$^{0}$, respectively [37,46]. However, it is clear that the main reduction peaks of basic metal doped catalysts shift to higher temperatures. This means the reducibility of vanadium and tungsten species is...
weakened. This phenomenon can be explained by basic metals entering the $V_2O_5$ and $WO_3$ lattice to form strong chemical bonds. This results in the decrease of lattice oxygen concentration, or inhibits the release of lattice oxygen, leading to the vanadium and tungsten species being harder to reduce.

Considering the $H_2$-TPR results above, the redox properties of vanadium and tungsten species are influenced along with the addition of different basic metals, which is correlated to the surface oxygen. Therefore, the state of surface oxygen was analyzed and the ratio $O_\alpha/O_\alpha + O_\beta$ was calculated due to its importance in the catalytic oxidation reaction [47]. As shown in Figure 8, the O1s peaks could be fitted into two peaks assigned to lattice oxygen (denoted as $O_\beta$) at 530.0–530.4 eV and surface chemisorbed oxygen (denoted as $O_\alpha$) at 531.1–531.5 eV [48]. The fresh 1V-5W/Ti catalyst contributed the highest $O_\alpha/(O_\alpha + O_\beta)$ ratio at 43.9%, and it decreased in the sequence of fresh > 1Al doped > 1Ca doped > 1Na doped > 1K doped (Table 1), which is in accordance with the variation of SCR activity. These changes can be explained by the formation of strong bonds between the surface oxygen center and basic metals, resulting in a decrease in the reducibility ability of the surface species. Figure 8b presents the $V$ 2p XPS spectra of different catalysts. The $V$ 2p XPS spectra could be divided into two peaks related to $V^{5+}$ and $V^{4+}$ [49]. As illustrated in Figure 8b, the fractionate peaks appearing at 515.8 and 516.9 eV could be ascribed to $V^{4+} 2p_{3/2}$ and $V^{5+} 2p_{3/2}$, respectively. The $V^{5+}/(V^{5+} + V^{4+})$ of the fresh catalyst was 47.5%, and doping of basic metals led to an increase in the value, and the redox ability was accordingly influenced.

It is believed that basic metals could be easily adsorbed on the acid sites to deactivate the catalysts [45]. Hence, diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) measurements of $NH_3$ adsorption were carried out to clarify the effect of different basic metals on the acid sites over V-W/Ti catalysts, and the results are presented in Figure 9. The broad band in the range of 3100–3400 cm$^{-1}$, 1100–1300 cm$^{-1}$ and peaks at ~1600 cm$^{-1}$ belonged to $NH_3$ adsorption on the Lewis acid sites, whereas peaks at around 1700 cm$^{-1}$ and 1450 cm$^{-1}$ could be assigned to $NH_4^+$ on the Brønsted acid sites [50,51]. With the increase of the temperature, the peaks become less intense for all samples, revealing that the adsorption of ammonia is weakened. The results for the fresh and 1M doped catalysts ($M = Al, Ca, Na, and K$) at 300 °C were illustrated in Figure 9b, it was clear that the intensity of the main peaks in fresh catalyst that assigned to the Brønsted acid sites and the Lewis acid sites were more intense than those in 1M doped catalysts ($M = Al, Ca, Na, and K$), indicating that the presence of basic metals was disadvantageous to the ammonia adsorption on both the Brønsted and Lewis acid sites, showing a similar tendency with the catalytic results.
Table 1. XPS data of fresh 1V-5W/Ti and 1 M doped catalysts (M = Al, Ca, Na, and K).

<table>
<thead>
<tr>
<th>Sample</th>
<th>$O_\alpha/(O_\alpha + O_\beta)%$</th>
<th>$V^{5+}/(V^{5+} + V^{4+})%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh</td>
<td>43.9</td>
<td>47.5</td>
</tr>
<tr>
<td>1Al doped</td>
<td>37.4</td>
<td>60.7</td>
</tr>
<tr>
<td>1Ca doped</td>
<td>35.7</td>
<td>61.9</td>
</tr>
<tr>
<td>1Na doped</td>
<td>32.4</td>
<td>65.6</td>
</tr>
<tr>
<td>1K doped</td>
<td>28.6</td>
<td>70.7</td>
</tr>
</tbody>
</table>

Figure 8. X-ray photoelectron spectroscopy (XPS) spectrum of O 1s (a) and V 2p (b) of fresh (1V-5W/Ti) and 1M doped catalysts (M = Al, Ca, Na, and K).

It is believed that basic metals could be easily adsorbed on the acid sites to deactivate the catalysts [45]. Hence, diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) measurements of NH3 adsorption were carried out to clarify the effect of different basic metals on the acid sites over V-W/Ti catalysts, and the results are presented in Figure 9. The broad band in the range of 3100–3400 cm$^{-1}$, 1100–1300 cm$^{-1}$ and peaks at ~1600 cm$^{-1}$ belonged to NH3 adsorption on the Lewis acid sites, whereas peaks at around 1700 cm$^{-1}$ and 1450 cm$^{-1}$ could be assigned to NH$_4^+$ on the Brønsted acid sites [50,51]. With the increase of the temperature, the peaks become less intense for all samples, revealing that the adsorption of ammonia is weakened. The results for the fresh and 1M doped catalysts (M = Al, Ca, Na, and K) at 300 °C were illustrated in Figure 9b, it was clear that the intensity of the main peaks in fresh catalyst that assigned to the Brønsted acid sites and the Lewis acid sites were more intense than those in 1M doped catalysts (M = Al, Ca, Na, and K), indicating that the presence of basic metals was disadvantageous to the ammonia adsorption on both the Brønsted and Lewis acid sites, showing a similar tendency with the catalytic results.

Figure 9. NH3-DRIFTS spectra of (a) fresh 1V-5W/Ti and (b) 1 M doped catalysts (M = Al, Ca, Na, and K).
3. Materials and Methods

3.1. Catalyst Preparation

All catalysts were prepared by the impregnation method. NH$_4$VO$_3$ and [NH$_4$]$_6$W$_7$O$_{24}$.6H$_2$O were selected as precursors of V$_2$O$_5$ and WO$_3$, and the support was anatase TiO$_2$. The slurry was then stirred for 4 h, dried at 110 °C for 12 h and calcined at 500 °C for 4 h in air. The fresh catalyst was then ground and sieved within 40–80 meshes for evaluation. (x)%V$_2$O$_5$-(y)%WO$_3$/TiO$_2$ are recorded as (x)V-(y)W/Ti. The basic metal oxides doped catalysts were prepared by wet impregnation using Al(NO$_3$)$_3$, Ca(NO$_3$)$_2$, NaNO$_3$, and KNO$_3$ as the precursors for Al$_2$O$_3$, CaO, Na$_2$O, and K$_2$O, respectively. Various basic metal loadings are calculated by molar ratio of M/V (M = Al, Ca, Na, K). The doped catalysts were then stirred for 4 h, dried at 110 °C for 12 h and calcined at 500 °C for 4 h in air. The Al doped catalysts were prepared with Al/V molar ratio of 0.2, 0.5, 1, 2. For comparison, Ca/V, Na/V, and K/V molar ratios were determined to be 1.

3.2. Catalyst Characterizations

The powder X-ray diffraction (XRD) patterns were determined by Rigaku (Japan electronics corporation, Tokyo, Japan) D/Max-2500/PC diffractometer, operating at 40 kV and 40 mA using CuK$\alpha$ radiation. The diffraction patterns were taken in the 2$\theta$ range of 10°–90° at a scan speed of 10° min$^{-1}$ and a resolution of 0.02°.

The BET surface areas of the catalysts were measured with Quantachrome instruments (Boynton Beach, FL, USA). Prior to the BET measurements, each sample was degassed under vacuum conditions for 4 h at 350 °C.

X-ray photoelectron spectroscopy (XPS) measurements were performed on a Thermo Scientific (Waltham, MA, USA) ESCALAB 250 electron spectrometer. The photoelectrons were excited using monochromatic Al K$\alpha$ X-ray (1486.6 eV) as a radiation source at 150 W. The chamber pressure was 2 × 10$^{-10}$ mbar under testing conditions.

Temperature-programmed desorption of NH$_3$ (NH$_3$-TPD) was collected on a Fourier Transform infrared spectrometer (FTIR) (Thermo Fisher, Boston, MA, USA). For NH$_3$-TPD, 100 mg samples were pretreated at 400 °C in N$_2$ for 1 h before testing, and then exposed to a 2500 ppm NH$_3$/N$_2$ gas flow (200 mL/min) for 1 h at 100 °C, and purged in N$_2$ for 1 h, then desorbed under a N$_2$ gas flow (200 mL/min) at a rate of 10 °C/min up to 600 °C.

Temperature-programmed reduction of H$_2$ (H$_2$-TPR) were carried out by a Quantachrome instrument chemisorption analyzer. For H$_2$-TPR, the samples were pretreated at 500 °C in Ar for 1 h before testing. It was carried out under 5% H$_2$ in Ar (50 mL/min) from 50 °C to 950 °C at a rate of 10 °C /min. Diffuse reflectance infrared Fourier transform spectroscopy of NH$_3$ (NH$_3$-DRIFTS) was recorded on a Thermo Scientific Nicolet 6700 spectrometer, which was equipped with a Harrick IR cell and an MCT detector cooled by liquid N$_2$. Prior to the experiment, catalysts were firstly purged at 350 °C for 1 h under N$_2$ gas (total flow rate 100 mL/min), and the background spectrum at desired temperature was collected NH$_3$ was adsorbed at 50 °C with 400 ppm NH$_3$/N$_2$ flow for 1 h, and then flushed in N$_2$ for 1 h. Before scanning, samples were kept for 30 min at the desired temperature and the DRIFT spectra were collected by accumulating 64 scans at a resolution of 4 cm$^{-1}$.

3.3. Catalyst Activity Measurements

SCR activity measurements were conducted in the fixed-bed reactor containing 800 mg of catalysts (40–80 meshes). The feed gas mixture contained 400 ppm NO, 400 ppm NH$_3$, 0.5% O$_2$, 10–30 vol % H$_2$O (when added), 200 ppm SO$_2$ (when added) and N$_2$ as the balance gas. The total gas flow rate was 400 mL/min. Detection of gas content was obtained by Fourier transform infrared spectrometer (FTIR spectrometer). The measurement was performed between 100–400 °C in intervals of 25 °C.
Each temperature point is stable for 50 min. The catalytic activities were evaluated by NO conversion (\%) according to the following equation:

\[
\text{NO conversion (\%) = } \left( \frac{[\text{NO}]_{\text{inlet}} - [\text{NO}]_{\text{outlet}}}{[\text{NO}]_{\text{inlet}}} \right) \times 100\%.
\] (1)

4. Conclusions

In this work, V-W/Ti catalysts were synthesized with different V\(_2\)O\(_5\) and WO\(_3\) loadings. High H\(_2\)O and SO\(_2\) resistance of V-W/Ti catalysts were studied, and it was illustrated that 1% V\(_2\)O\(_5\) and 5% WO\(_3\) would be appropriate for the catalyst used in alumina calcining flue gas. Meanwhile, the influence of various basic metals (Al, Ca, Na, and K) on SCR activity was investigated on V-W/Ti catalysts. The results revealed that the inhibitory effect of the metal oxides are in the sequence of K > Na > Ca > Al, which is consistent with their alkalinity. The adsorption of basic metals on the acid sites resulted in a significant decrease of Brønsted acid sites for V\(_2\)O\(_5\)-WO\(_3\)/TiO\(_2\) catalysts.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4344/9/3/220/s1, Figure S1: Alumina calcining process flow chart, Figure S2: Evaluation of different oxygen concentration of 1V/Ti catalyst, Table S1: Surface areas of various catalysts.

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Conflicts of Interest: The authors declare no conflict of interest.

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