

Article

Unraveling the Mechanism of High N₂ Selectivity in Ammonia Selective Catalytic Oxidation on Pt-V Tandem Catalyst

Yu Gao ^{1,*}, Pingshang Li ² and Wan Mei ²

¹ China Waterborne Transport Research Institute, Beijing 100083, China

² School of Environment, Beijing Jiaotong University, Beijing 100044, China; bjulps@163.com (P.L.); meiw177@126.com (W.M.)

* Correspondence: gaoyu@wti.ac.cn

Abstract: V_{0.5}/Pt/TiO₂ tandem catalysts exhibit both an outstanding low-temperature NH₃ conversion rate and high N₂ selectivity in NH₃-SCO reactions, but the mechanism of high N₂ selectivity remains unclear. In this work, V_x/Pt/TiO₂ tandem catalysts were synthesized through a two-step impregnation–deposition method. The modulating effect of the V loading amount on NH₃-SCO performance was evaluated, and the relevant reaction mechanism was explored systematically. The results demonstrated that the synergistic effect of tandem NH₃ oxidation and NH₃-SCR reactions could be regulated by changing the V loading amount, thereby modulating N₂ selectivity. Compared with other V_x/Pt/TiO₂ catalysts and previously reported SCO catalysts, the V_{0.5}/Pt/TiO₂ catalyst with a V loading amount of 0.5 wt.% exhibited outstanding NH₃-SCO performance, which achieved complete NH₃ conversion and >90% of N₂ selectivity within a range of 250–450 °C. XPS, NH₃-TPD, and O₂-TPD results suggested that the increase in the V loading amount from 0.1 wt.% to 0.5 wt.% was conducive to increasing the relative contents of Pt⁰ and V⁵⁺ species, as well as the amount of acid sites, oxygen species, and oxygen vacancies. Consequently, the synergistic effect of tandem NH₃ oxidation and NH₃-SCR reactions was significantly enhanced, enabling the catalyst to exhibit excellent N₂ selectivity. A further increase in the V loading amount from 0.5 wt.% to 0.9 wt.% would bring about the opposite effect to the above, resulting in a decline in catalytic performance. In situ DRIFTS results showed that a V loading amount of 0.5 wt.% was beneficial for -NH₂ species to participate in NH₃-SCO reactions, thereby boosting N₂ selectivity.

Keywords: Pt-V tandem catalyst; selective catalytic oxidation of NH₃; N₂ selectivity; V loading amount



Academic Editor: Benjamín Solsona

Received: 15 March 2025

Revised: 10 April 2025

Accepted: 11 April 2025

Published: 14 April 2025

Citation: Gao, Y.; Li, P.; Mei, W. Unraveling the Mechanism of High N₂ Selectivity in Ammonia Selective Catalytic Oxidation on Pt-V Tandem Catalyst. *Materials* **2025**, *18*, 1782. <https://doi.org/10.3390/ma18081782>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

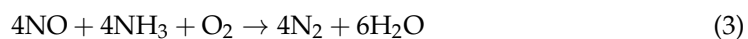
In response to increasingly stringent CO₂ emission reduction regulations, the international shipping industry is exploring the application of NH₃-fuel engines as the main engines for large merchant ships [1–3]. However, the serious environmental risks caused by NH₃ emissions from NH₃-fuel engines have become one of the main obstacles limiting the application of NH₃-fuel engines on board [3–8]. It is urgent to explore practical and efficient technologies for removing NH₃ from high-temperature flue gas to meet the needs of NH₃-powered ships. At present, the selective catalytic oxidation (SCO) technique is considered more promising than other techniques in meeting the above needs [9–11]. This

is because SCO technology can effectively convert NH_3 into N_2 through Equation (1) at relatively high temperatures and space velocities.



The NH_3 conversion performance of SCO technology mainly depends on the design of the catalyst. During the past several decades, numerous types of NH_3 -SCO catalysts have been reported, which can be mainly classified into noble metal catalysts and transition metal oxide catalysts. Noble metal catalysts exhibit an outstanding NH_3 conversion performance at low temperatures, which is attributed to their strong catalytic oxidation activity for NH_3 [11–15]. But noble metal catalysts are prone to excessively oxidizing NH_3 into NO_x , resulting in a low N_2 selectivity [13–15]. Transition metal oxide catalysts exhibit high N_2 selectivity due to their moderate catalytic oxidation activity for NH_3 , but this makes it difficult to achieve a good NH_3 conversion performance at low temperatures [15–17].

It is considered that the mainstream approach to designing SCO catalysts with excellent performance is to simultaneously pursue good NH_3 conversion performance and high N_2 selectivity over a broad temperature range. But this remains difficult to achieve at present. Aiming to synthesize SCO catalysts with excellent performance, the combination of transition metal oxides with a small amount of noble metal components was proposed as a strategy [18–23]. Its operation relies on an internal selective catalytic reduction (i-SCR) mechanism, which is mainly composed of the following two tandem reactions: Under catalysis of noble metal components, NH_3 is oxidized to NO by O_2 (Equation (2)). Subsequently, NO reacts with NH_3 under the action of transition metal oxide components through SCR reaction (Equation (3)).



For the design of catalysts employing the above strategy, the selection of suitable noble metal and transition metal components is deemed to be of great importance. In recent years, Pt-V tandem catalysts have received extensive attention due to their high potential for achieving good NH_3 conversion performance and high N_2 selectivity simultaneously. Byun et al. introduced 0.3 wt.% Pt into the $\text{V}_3\text{W}_2/\text{TiO}_2$ catalyst. The results showed that, within the temperature range of 330–380 °C, the $\text{Pt}_{0.3}\text{V}_3\text{W}_2/\text{TiO}_2$ catalyst could achieve complete conversion of NH_3 and the corresponding N_2 selectivity was higher than 90.0% [20]. The main reason for this was the synergistic effect between NH_3 -SCO and CO-SCR reactions. Kim et al. reported that the addition of 2 wt.% V into the $\text{Pt}_{0.1}/\text{TiO}_2$ catalyst could enhance the NH_3 -SCO performance. The $\text{Pt}_{0.1}/\text{V}_2/\text{TiO}_2$ catalyst derived through optimization completely converted NH_3 within the range of 250–350 °C, and the corresponding N_2 selectivity was ~81% [12].

In our previous work, a Pt-V tandem catalyst was synthesized by directly mixing and grinding a certain mass of the VW/TiO_2 catalyst with a small quantity of the $\text{Pt}/\text{Al}_2\text{O}_3$ catalyst [9]. Results of the experiments indicated that NH_3 -SCO and NH_3 -SCR reactions over the mixed catalysts displayed a synergistic effect, enabling them to exhibit excellent low-temperature redox performance. In situ DRIFTS results showed that NH_3 conversion reactions on the surface of mixed catalysts followed both the i-SCR mechanism and hydrazine mechanism. Moreover, authors synthesized a series of Pt-modified V/TiO_2 catalysts (0.04 wt.% Pt and 0.5 wt.% V) by using the impregnation–deposition method [22]. The effect of the V and Pt deposition sequence on NH_3 -SCO performance was explored. The results displayed that $\text{V}_{0.5}/\text{Pt}_{0.04}/\text{TiO}_2$, $\text{Pt}_{0.04}/\text{V}_{0.5}/\text{TiO}_2$, and $\text{Pt}_{0.04}\text{V}_{0.5}/\text{TiO}_2$ catalysts

all possessed outstanding NH_3 conversion performance. They could achieve complete NH_3 conversion at around 250°C . But the $\text{V}_{0.5}/\text{Pt}_{0.04}/\text{TiO}_2$ catalyst exhibited much better N_2 selectivity than the other two catalysts. However, the mechanism by which the $\text{V}_{0.5}/\text{Pt}_{0.04}/\text{TiO}_2$ tandem catalyst achieves high N_2 selectivity remains unclear. According to the i-SCR mechanism, N_2 selectivity is mainly determined by the V component. Thus, an exploration of the modulating effect of the V loading amount on NH_3 -SCO performance may be a promising approach to revealing the mechanism of the high N_2 selectivity of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ tandem catalyst. But similar studies have not been reported yet.

Herein, a series of $\text{V}_x/\text{Pt}/\text{TiO}_2$ tandem catalysts were prepared via a two-step impregnation–deposition process. The influence of the V loading amount on the NH_3 -SCO performance of the $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts was systematically investigated. The results showed that, compared with other $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts, the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst exhibited outstanding comprehensive SCO performance. It could completely remove 3000 ppm of NH_3 within the range of 250 – 450°C and corresponding N_2 selectivity was higher than 90%. Compared to previously reported NH_3 -SCO catalysts (Table S1), the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst also possessed a remarkable performance. The operating temperature window of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst was well-matched with the range of exhaust temperatures in NH_3 -fuel engines (280 – 450°C). In order to explore the mechanism underlying the excellent N_2 selectivity of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst, some characterization tests including N_2 adsorption–desorption, X-ray Diffraction (XRD), X-ray Photoelectron Spectroscopy (XPS), a High-Resolution Transmission Electron Microscope (HRTEM), Energy Dispersive X-Ray Spectroscopy (EDX), O_2 Temperature Programmed Desorption (O_2 -TPD), H_2 Temperature-Programmed Reduction (H_2 -TPR), and NH_3 Temperature-Programmed Desorption (NH_3 -TPD), and in situ Diffuse Reflection Infrared Fourier Transform Spectroscopy (in-situ DRIFTS) were carried out. The structure–efficiency relation and surface reaction pathways were discussed in depth based on characterization results. It is well known that for NH_3 -SCO catalysts, simultaneously achieving high NH_3 conversion efficiency and N_2 selectivity still remains a great challenge. This work is novel in uncovering the significant regulatory effect of V loading on N_2 selectivity of $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts, elucidating the relevant regulatory mechanism, and revealing the mechanism by which the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst achieves a high NH_3 conversion rate and N_2 selectivity simultaneously.

2. Experimental Section

2.1. Catalyst Preparation

Based on our previous research [22], the $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts with 0.04 wt.% Pt and x wt.% V were prepared using a two-step impregnation–deposition method. Different mass fractions of V ($x = 0.1, 0.3, 0.5, 0.7, 0.9$ wt.%) were incorporated via impregnation in the second step. The detailed preparation processes of $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts were given in the Supplementary Materials. The Pt/TiO_2 (0.04 wt.% Pt) and V/TiO_2 (0.5 wt.% V) catalysts were synthesized by the impregnation method for better benchmarking. The specific synthesis procedures can be found in the Supplementary Materials.

2.2. Catalyst Characterization

Various techniques including XRD, N_2 adsorption–desorption, XPS, HRTEM, EDX, NH_3 -TPD, O_2 -TPD, and H_2 -TPR were employed to characterize the prepared catalysts so as to reveal the physical and chemical properties. Additionally, in situ DRIFTS was used to investigate key intermediates in NH_3 -SCO reactions. Detailed information on catalyst characterization can be found in the Supplementary Materials.

2.3. Catalytic Performance Test

The NH₃-SCO performance of the V_x/Pt/TiO₂ catalysts was tested using a fixed-bed reactor (Ming Yang Company, Nanjing, China). A catalyst dosage of 0.2 mL was used in each test. Prior to testing, a N₂ stream was used to purge the catalyst at 150 °C for 1 h, removing any residual contaminants. The catalyst was then exposed to a reactant gas flow of 200 mL/min, consisting of 3000 ppm NH₃, 5 vol.% O₂, and N₂ as the balance gas. Then, reaction temperature was gradually increased from 200 to 450 °C at a rate of 2 °C/min. During this process, the concentrations of NH₃, NO, NO₂, and N₂O were monitored by using a FT-IR spectrometer (IGS, ThermoFisher Scientific, Waltham, MA, USA). Based on Equations (4) and (5), the NH₃ conversion efficiency and N₂ selectivity could be calculated:

$$\text{NH}_3 \text{ conversion} = \frac{\text{NH}_{3,\text{in}} - \text{NH}_{3,\text{out}}}{\text{NH}_{3,\text{in}}} \times 100\% \quad (4)$$

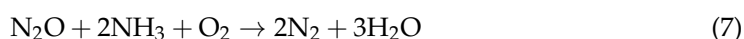
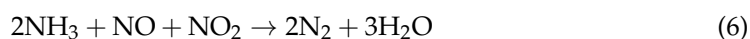
$$\text{N}_2 \text{ selectivity} = \frac{\text{NH}_{3,\text{in}} - \text{NH}_{3,\text{out}} - \text{NO}_{\text{out}} - \text{NO}_{2,\text{out}} - 2 \times \text{N}_2\text{O}_{\text{out}}}{\text{NH}_{3,\text{in}} - \text{NH}_{3,\text{out}}} \times 100\% \quad (5)$$

3. Results

3.1. NH₃-SCO Performance

The NH₃ conversion efficiencies of V_x/Pt/TiO₂ catalysts are illustrated in Figure 1a. It can be seen that with the reaction temperature increased from 200 to 250 °C, the NH₃ conversion efficiencies of the V_x/Pt/TiO₂ catalysts increased significantly. When the reaction temperature was 250 °C, the NH₃ conversion efficiencies of the V_{0.1}/Pt/TiO₂, V_{0.3}/Pt/TiO₂, and V_{0.5}/Pt/TiO₂ catalysts were 100%, while the NH₃ conversion efficiencies of the V_{0.7}/Pt/TiO₂ and V_{0.9}/Pt/TiO₂ catalysts were 89.2% and 83.5%, respectively. When the reaction temperature was further increased from 250 to 300 °C, the NH₃ conversion efficiencies of the V_{0.7}/Pt/TiO₂ and V_{0.9}/Pt/TiO₂ catalysts reached 100%. The above results indicate that, compared to V_{0.7}/Pt/TiO₂ and V_{0.9}/Pt/TiO₂ catalysts, the V_{0.1}/Pt/TiO₂, V_{0.3}/Pt/TiO₂, and V_{0.5}/Pt/TiO₂ catalysts exhibit better NH₃ catalytic conversion performance.

The N₂ selectivity of the V_x/Pt/TiO₂ catalysts within the temperature range of 200–450 °C is shown in Figure 1b. It can be observed that when the loading amount of V was increased from 0.1 wt.% to 0.5 wt.%, the N₂ selectivities of the V_x/Pt/TiO₂ catalysts were distinctly enhanced. It is noteworthy that, compared with other V_x/Pt/TiO₂ catalysts, the V_{0.5}/Pt/TiO₂ catalyst exhibited outstanding N₂ selectivity. The N₂ selectivity of the V_{0.5}/Pt/TiO₂ catalyst exceeded 90% across the entire temperature range. The above results imply that a moderate increase in the loading amount of V might be beneficial for enhancing NH₃-SCR reactions over V_x/Pt/TiO₂ catalysts, thereby promoting the generation of N₂ via Equations (3), (6) and (7)



When the V loading amount was further increased from 0.5 wt.% to 0.9 wt.%, the N₂ selectivity of the V_x/Pt/TiO₂ catalysts gradually decreased. According to previous studies [22–24], this might be related to the excessive catalytic oxidation of NH₃ by the V species.

The NH₃-SCO performance of Pt/TiO₂ (0.04 wt.% Pt) and V/TiO₂ (0.5 wt.% V) catalysts and the bare TiO₂ support were evaluated for benchmarking. The results are shown in Figure 1. It could be seen that the Pt/TiO₂ catalyst exhibited excellent NH₃ conversion performance. It could achieve complete conversion of 3000 ppm NH₃ within the tem-

perature range of 250–450 °C. Its NH_3 conversion performance was close to that of the $\text{V}_{0.1}/\text{Pt}/\text{TiO}_2$, $\text{V}_{0.3}/\text{Pt}/\text{TiO}_2$, and $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalysts, and was significantly better than that of the $\text{V}_{0.7}/\text{Pt}/\text{TiO}_2$ and $\text{V}_{0.9}/\text{Pt}/\text{TiO}_2$ catalysts. But the N_2 selectivity of the Pt/TiO_2 catalyst within the above temperature range was lower than 70%, which was significantly lower than that of the $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts. Compared with the $\text{V}_x/\text{Pt}/\text{TiO}_2$ and Pt/TiO_2 catalysts, the NH_3 conversion performance of the V/TiO_2 catalyst was relatively poor. It only shows the obvious NH_3 conversion performance when the reaction temperature was higher than 250 °C. However, the V/TiO_2 catalyst exhibited excellent N_2 selectivity, which exceeded 90% within the temperature range of 275–450 °C. The bare TiO_2 support did not show the catalytic activity within the whole temperature range.

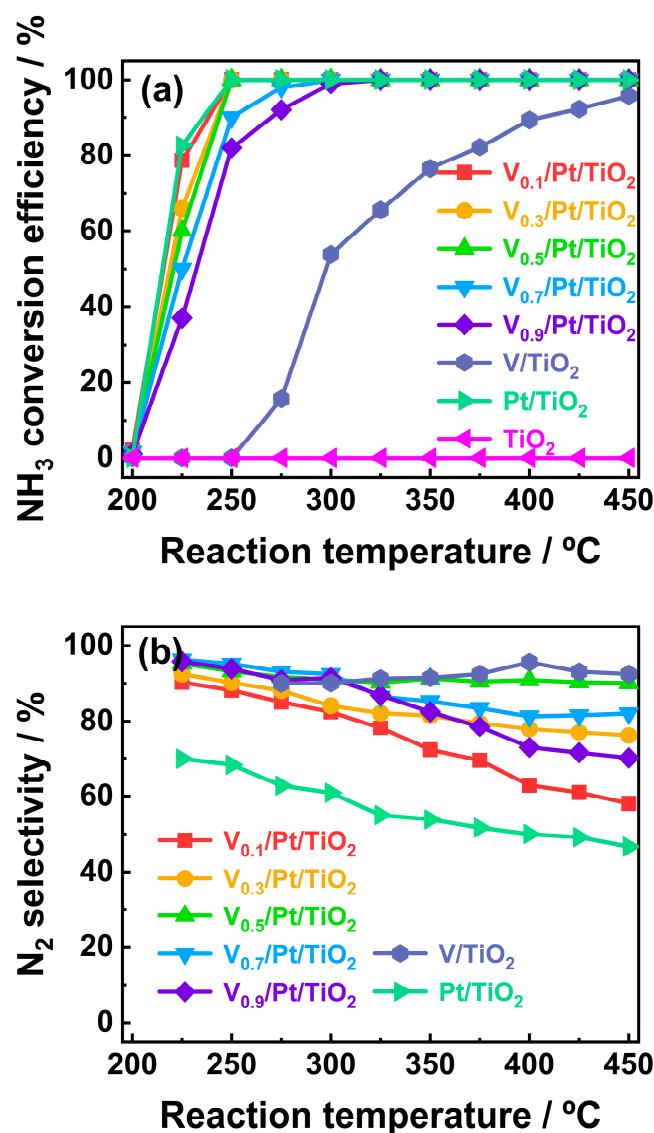


Figure 1. (a) NH_3 conversion efficiencies and (b) N_2 selectivities of prepared catalysts. **Reaction conditions:** $[\text{NH}_3]_{\text{in}} = 3000$ ppm, $[\text{O}_2]_{\text{in}} = 5$ vol%, Flowrate = 200 mL/min, N_2 balance gas.

In order to more intuitively display the influence of the V loading amount on the performance of the $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalyst, a summary schematic comparing the catalyst performance versus the V loading amount was drawn, which is shown in Figure 2. The reaction temperature corresponding to the schematic is 350 °C. As shown in Figure 2, with the V loading amount increased from 0.1 wt.% to 0.5 wt.%, the N_2 selectivity of the $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts significantly improved from 72.3% to 91.3%. When the V loading amount further

increased from 0.5 wt.% to 0.9 wt.%, the N_2 selectivity of the $V_x/Pt/TiO_2$ catalyst gradually decreased from 91.3% to 82.5%. During the process of increasing the V loading amount from 0.1 wt.% to 0.9 wt.%, the NH_3 conversion efficiency of the $V_x/Pt/TiO_2$ catalysts always remains at 100%. The above results indicated that, in this work, the $V_{0.5}/Pt/TiO_2$ catalyst with a V loading amount of 0.5 wt.% exhibited the best comprehensive SCO performance.

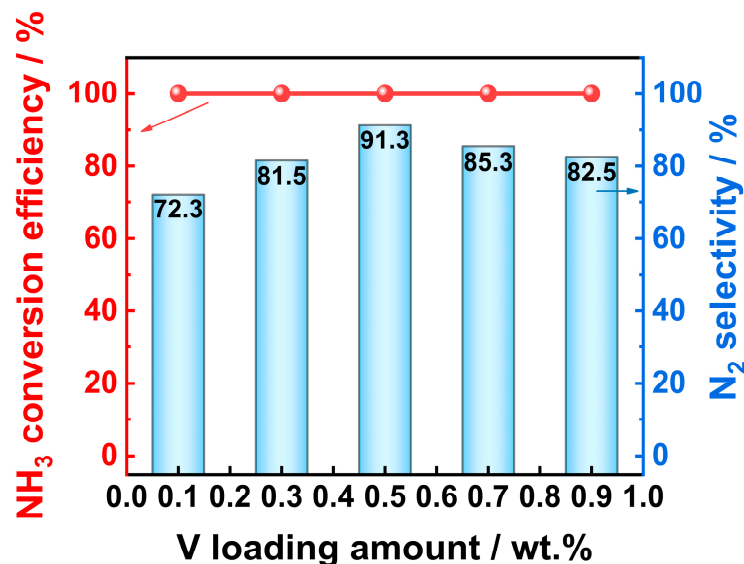


Figure 2. Change in NH_3 -SCO performance of $V_x/Pt/TiO_2$ catalysts with V loading amount. **Reaction conditions:** $[NH_3]_{in} = 3000$ ppm, $[O_2]_{in} = 5$ vol%, Flowrate = 200 mL/min, N_2 balance gas.

The NH_3 -SCO experimental results demonstrated that, compared with other $V_x/Pt/TiO_2$ catalysts, the $V_{0.5}/Pt/TiO_2$ catalyst exhibited excellent N_2 selectivity. In comparison with the NH_3 -SCO catalysts reported previously (Table S1), the performance of the $V_{0.5}/Pt/TiO_2$ catalyst was also quite outstanding. Therefore, the $V_{0.5}/Pt/TiO_2$ catalyst was selected for further study.

In order to evaluate the repeatability of the catalyst synthesis, three batches of the $V_{0.5}/Pt/TiO_2$ catalyst were, respectively, synthesized using the same process, and performance tests were carried out. The results are shown in Figure S1. The data of Test 1 in Figure S1 are the performance test data of the $V_{0.5}/Pt/TiO_2$ catalyst mentioned in the manuscript. The data of Test 2 and Test 3 are the performance test data of the other two batches of the $V_{0.5}/Pt/TiO_2$ catalyst synthesized under the same conditions. It can be seen from Figure S1 that the NH_3 conversion performances of the three batches of the $V_{0.5}/Pt/TiO_2$ catalyst in the temperature range of 200–450 °C are quite similar, and so is the N_2 selectivity. This indicated that the catalyst synthesis process has high reproducibility.

The common causes of catalyst aging or deactivation after long-term use include sintering of active components, changes in structure of active components, collapse of pore structure, and catalyst poisoning caused by external impurities [24–26]. The humid conditions may promote aging or deactivation of catalysts. This is because under certain conditions, H_2O molecules may react with active components, thus resulting in a reduction in catalytic activity or even deactivation [25,27]. H_2O molecules may also react with supports of the catalyst, resulting in collapse of the pore structure, thus leading to a decline in catalytic activity [28]. Since the combustion of NH_3 in NH_3 -fuel engines would produce H_2O vapor, it is advisable to conduct a preliminary test to obtain a brief understanding of the H_2O resistance of the $V_{0.5}/Pt/TiO_2$ catalyst. The H_2O resistance test was carried out under the following conditions: the concentration of the H_2O vapor was 10 vol.%, the reaction temperature was set at 300 °C, and the total experimental duration was 8 h. The

results are shown in Figure 3. It can be observed that the introduction of water vapor has no significant impact on the NH_3 conversion rate and N_2 selectivity of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst, indicating that the catalyst possessed good water resistance.

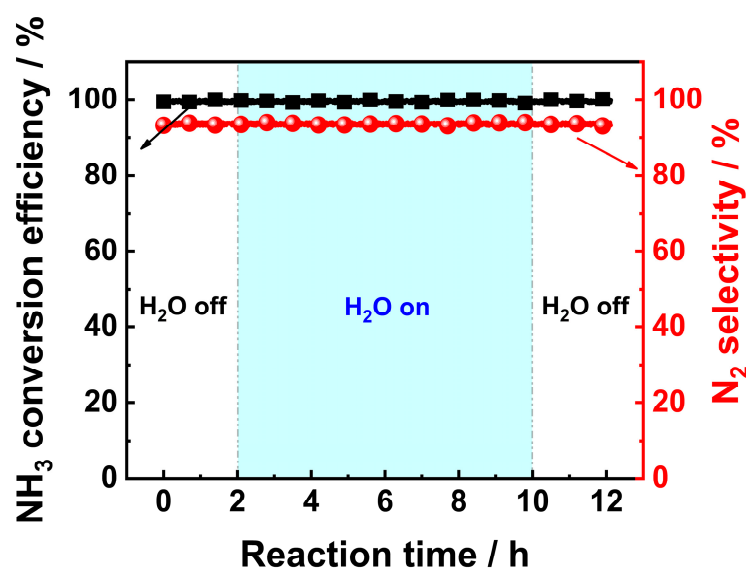


Figure 3. H_2O resistance test results of $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst. **Reaction conditions:** $[\text{NH}_3]_{\text{in}} = 3000$ ppm, $[\text{O}_2]_{\text{in}} = 5$ vol%, $[\text{H}_2\text{O}]_{\text{in}} = 10$ vol%, Flowrate = 200 mL/min, N_2 balance gas.

For the purpose of investigating the mechanism for outstanding N_2 selectivity of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst, some characterization techniques have been employed to characterize physicochemical properties of $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts. The results of the catalyst characterization tests will be presented below, and they will be discussed in detail.

3.2. N_2 Adsorption and Desorption

The specific surface area of a catalyst is usually closely related to the adsorption of reactants and the dispersion of active species on the catalyst surface, thereby having a significant impact on the performance of the catalyst [20,21]. Generally, a high specific surface area of the catalyst is conducive to adsorbing more NH_3 and O_2 , which is beneficial for promoting NH_3 -SCO performance [22,23]. A high specific surface area of the catalyst is also conducive to active species being more evenly dispersed on the catalyst surface, thereby enriching active sites and improving the NH_3 -SCO performance [24]. To characterize the surface physical properties of the $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts, N_2 adsorption and desorption experiments were performed, and the results are presented in Figure 4. Figure 4a shows the N_2 adsorption–desorption isotherms of the $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts. According to previous studies, the isotherms could be categorized as type IV(a) with H3 hysteresis loops, which implied the existence of a large number of mesopores on the surface of the tested catalysts [22–24]. It can be seen from Figure 4b that the surface pore sizes of the $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts were predominantly around 46 nm, which is in agreement with the results shown in Figure 4a. It can also be observed from Figure 4b that, compared with other $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts, the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst possessed more abundant 45 nm pores on the surface. As shown in Table S2, the specific surface area of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst was higher than those of other $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts. But there was little difference in surface pore volume and pore diameter between the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst and each of the other $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts. The results shown in Figure 4b and Table S2 indicate that 0.5 wt.% of the V loading amount might be conducive to the formation of mesopores on the surface of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst, thus resulting in a relatively higher specific surface area of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst. Generally, a higher specific surface area is conducive to

the dispersion of active metal components and the adsorption of reactants on the catalyst surface, thus improving the catalytic activity [29]. Thus, the relatively larger specific surface area of the $V_{0.5}/Pt/TiO_2$ catalyst contributed to its excellent NH_3 -SCO performance.

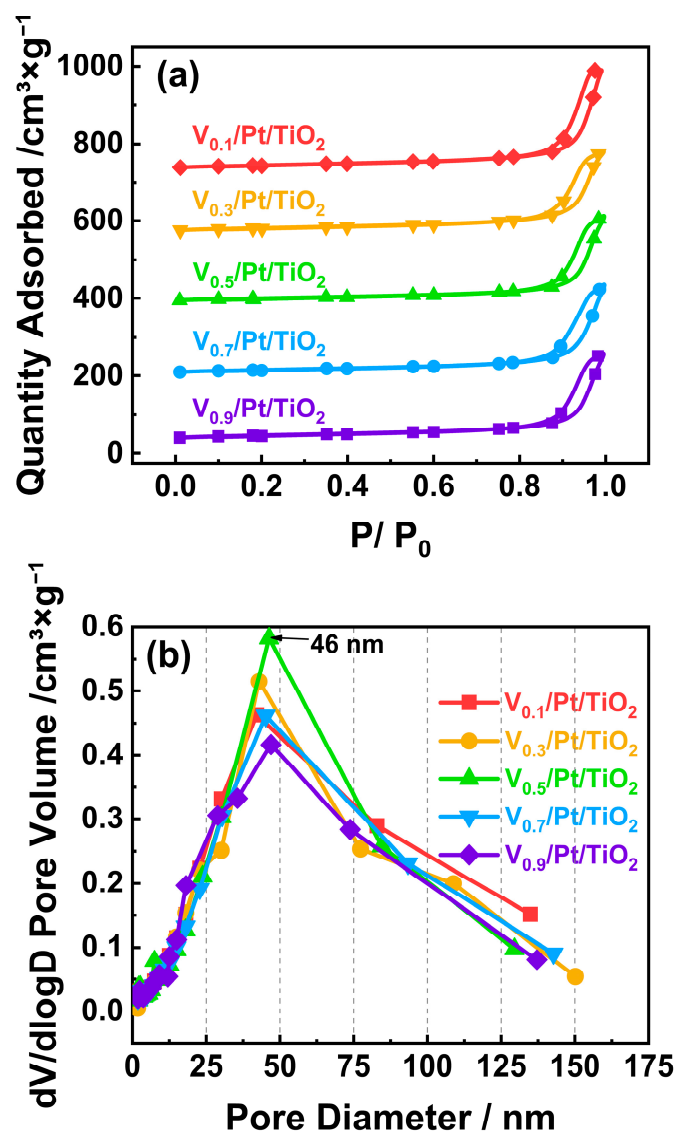


Figure 4. (a) N_2 adsorption–desorption isotherms and (b) pore size distribution curves of $V_x/Pt/TiO_2$ catalysts.

3.3. XRD

The crystal structures of active species and support are closely related to the performance of the catalyst. The XRD technique is considered a common technique for obtaining the above information. XRD tests were conducted on the $V_x/Pt/TiO_2$ catalyst, and the results are presented in Figure 5. Several obvious diffraction peaks can be observed in the XRD spectra of the $V_x/Pt/TiO_2$ catalysts. Diffraction peaks centered at 25.0° , 36.6° , 38.0° , 38.8° , 48.1° , 54.3° , 55.2° , 62.8° , 68.9° , 70.6° , and 75.3° could be attributed to anatase TiO_2 phases (ICDD #21-1276) [9,22,23]. The diffraction peak centered at 27.5° could be attributed to rutile TiO_2 phases (ICDD #21-1272) [24]. It can be seen from Figure 5 that there were no peaks attributed to the VO_x phase in the XRD spectra of the $V_{0.1}/Pt/TiO_2$, $V_{0.3}/Pt/TiO_2$, and $V_{0.5}/Pt/TiO_2$ catalysts. This suggested that the VO_x species over the above three catalysts were in a highly dispersed state or an amorphous state. As shown in Figure 5, a small diffraction peak (56.8°) emerged in each of the XRD spectra of the

$V_{0.7}/Pt/TiO_2$ and $V_{0.9}/Pt/TiO_2$ catalysts. These peaks were ascribed to the VO_x species (ICDD #19-1401), indicating that there were tiny VO_x crystals over the $V_{0.7}/Pt/TiO_2$ and $V_{0.9}/Pt/TiO_2$ catalysts [22–24]. The above results show that when the V loading amounts were 0.1 wt.%, 0.3 wt.%, and 0.5 wt.%, the VO_x species could be well dispersed on the catalyst surface. When the V loading amounts were 0.7 and 0.9 wt.%, the VO_x species on the surface of the catalyst agglomerated slightly. It can be seen from Figure 5 that no diffraction peaks that could be attributed to the Pt species appeared in the XRD spectra of the $V_x/Pt/TiO_2$ catalysts. This phenomenon could be primarily ascribed to the extremely low Pt contents in the $V_x/Pt/TiO_2$ catalysts.

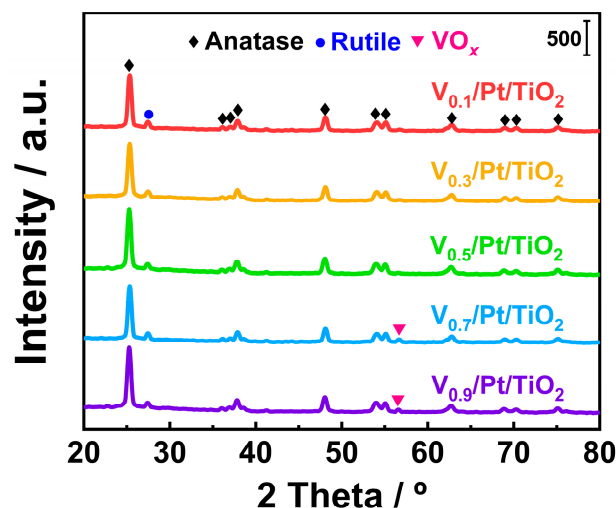


Figure 5. XRD spectra of $V_x/Pt/TiO_2$ catalysts.

3.4. XPS

The NH_3 -SCO performance of the catalyst is greatly influenced by the valence states and relative contents of the elements on the surface. XPS experiments were performed to analyze the valence states and relative contents of the main elements over the $V_x/Pt/TiO_2$ catalysts. The test results are presented in Figure 6 and Table S3. As shown in Figure 6a, the V 2p spectrum of each $V_x/Pt/TiO_2$ catalyst could be split into three sub-peaks. Sub-peaks centered at 515.6, 516.5, and 517.2 eV were attributable to the V^{3+} , V^{4+} , and V^{5+} species, respectively [22–24]. As shown in Table S3, with the V loading amount increasing from 0.1 wt.% to 0.5 wt.%, the $V^{5+}/(V^{3+}+V^{4+}+V^{5+})$ ratios of the $V_x/Pt/TiO_2$ catalysts increased from 28.20% to 32.65%. When the V loading amount was further increased from 0.5 wt.% to 0.9 wt.%, the $V^{5+}/(V^{3+}+V^{4+}+V^{5+})$ ratios of the $V_x/Pt/TiO_2$ catalysts gradually decreased from 32.65% to 25.22%. It has been reported that the V^{5+} species possesses good NH_3 -SCR catalytic activity [24]. Thus, the relatively high $V^{5+}/(V^{3+}+V^{4+}+V^{5+})$ ratio of the $V_{0.5}/Pt/TiO_2$ catalyst was conducive to promoting the generation of N_2 , enabling the $V_{0.5}/Pt/TiO_2$ catalyst to exhibit excellent N_2 selectivity.

The Pt 4f spectra of the $V_x/Pt/TiO_2$ catalyst are presented in Figure 6b. It can be seen that each of spectra could be resolved into four sub-peaks. As marked in Figure 6b, sub-peaks in the range of 73.6 to 77.9 eV could be ascribed to Pt^0 , Pt^{2+} , and Pt^{4+} species [27,28]. As shown in Table S3, when the V loading amount was increased from 0.1 wt.% to 0.5 wt.%, the $Pt^0/(Pt^0+Pt^{2+}+Pt^{4+})$ ratio of the $V_x/Pt/TiO_2$ catalyst increased from 35.56% to 37.66%. When the V loading amount was further increased from 0.5 wt.% to 0.9 wt.%, the $Pt^0/(Pt^0+Pt^{2+}+Pt^{4+})$ ratio of the $V_x/Pt/TiO_2$ catalyst decreased from 37.66% to 35.23%. This suggested that adopting a V loading amount of 0.5 wt.% was conducive to the generation of the Pt^0 species. Compared to the Pt^{2+} and Pt^{4+} species, the Pt^0 species possess much higher catalytic oxidation activity, which is mainly attributed to its high activity in O_2

dissociation [22,23]. Therefore, the existence of a relatively larger amount of Pt^0 species was beneficial for the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst to oxidize more NH_3 into NO_x , providing more reactants for the NH_3 -SCR reaction, thus promoting the generation of N_2 .

Figure 6c displays the O 1s spectra of the $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts. It can be seen that the spectrum of each $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalyst could be resolved into two sub-peaks. Sub-peaks centered at 531.2 eV and 529.8 eV could be ascribed to chemisorbed oxygen species (O_α) and lattice oxygen species (O_β), respectively. Table S3 shows that the $\text{O}_\alpha/(\text{O}_\alpha+\text{O}_\beta)$ ratio of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst is 15.23%, which is higher than those of other $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts. Compared with O_β species, the O_α species possess higher activity in the NH_3 oxidation reaction [29–32]. Thus, a relatively larger amount of O_α species was conducive to oxidation of more NH_3 into NO_x and N_2 . Subsequently, NO_x could be converted into N_2 through NH_3 -SCR reactions, enabling the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst to exhibit a good N_2 selectivity.

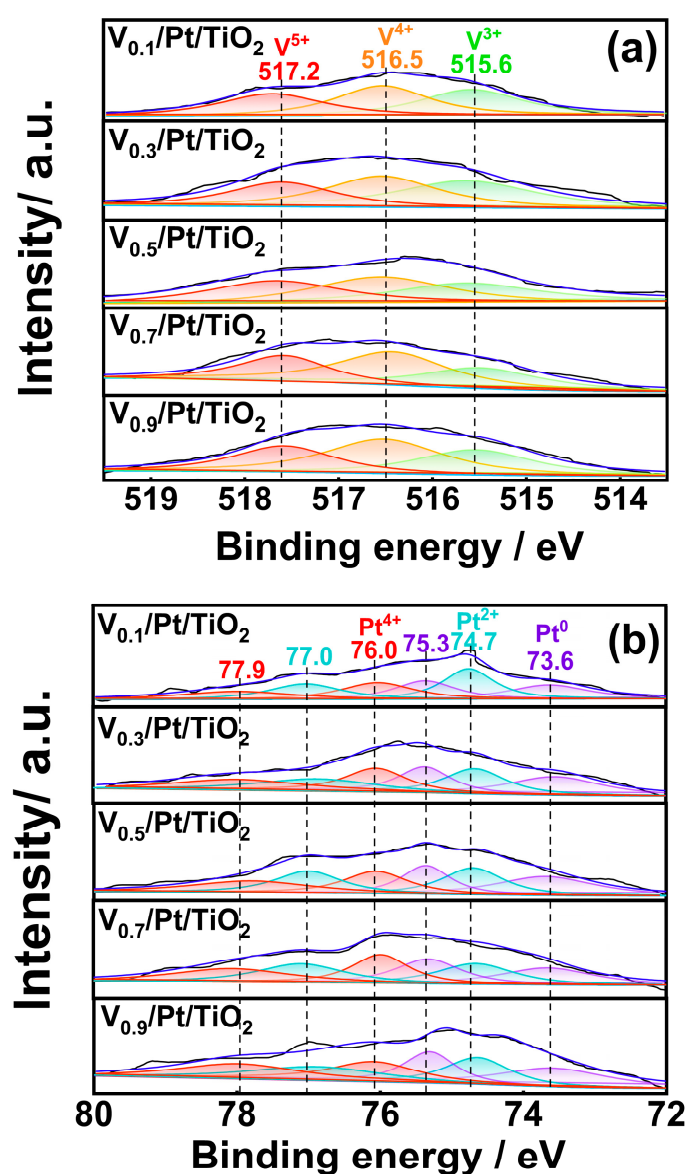


Figure 6. Cont.

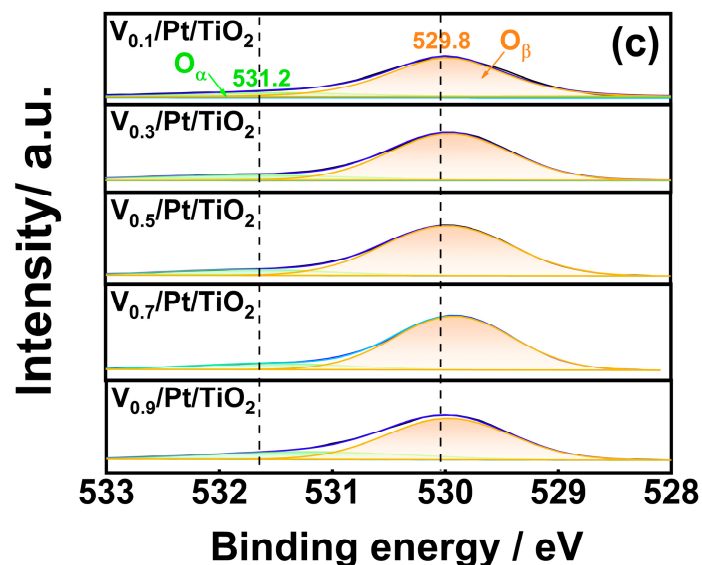


Figure 6. (a) V 2p, (b) Pt 4f, (c) O 1s XPS spectra of $V_x/\text{Pt}/\text{TiO}_2$ catalysts.

3.5. O_2 -TPD

The surface oxygen species can participate in NH_3 catalytic oxidation reactions, thereby influencing the SCO performance of the catalysts. For the purpose of characterizing the active oxygen species over the $V_x/\text{Pt}/\text{TiO}_2$ catalysts, O_2 -TPD experiments were performed, and the results are shown in Figure 7. Previous studies pointed out that O_2 desorption below 250 °C mainly resulted from the desorption of physically adsorbed oxygen [9,22,23]. O_2 desorption between 250 °C and 600 °C was mainly caused by the desorption of chemically adsorbed oxygen from oxygen vacancies. Desorption of O_2 between 600 °C and 900 °C was mainly related to the desorption of surface lattice oxygen.

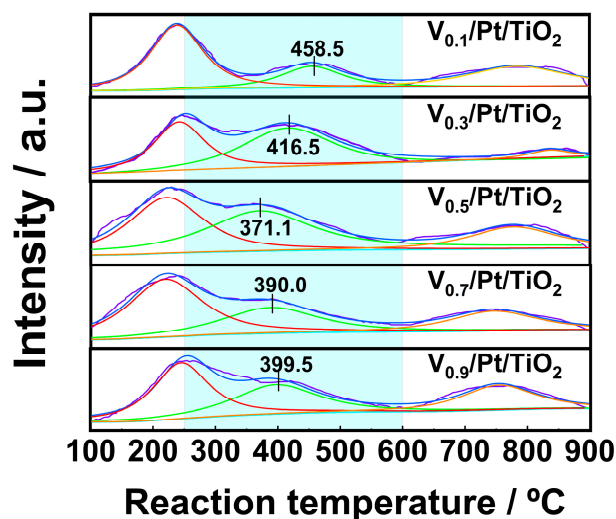


Figure 7. O_2 -TPD profiles of $V_x/\text{Pt}/\text{TiO}_2$ catalysts.

It can be seen from Figure 7 that for the O_2 -TPD profile of each $V_x/\text{Pt}/\text{TiO}_2$ catalyst, there is a single peak within the range of 100–250 °C, which implies that a great amount of physically adsorbed oxygen desorbed from the surface of the $V_x/\text{Pt}/\text{TiO}_2$ catalyst in this temperature range. As shown in Figure 7, each of the O_2 -TPD profiles of the $V_x/\text{Pt}/\text{TiO}_2$ catalysts had one peak in the range of 250 to 600 °C. The peak of the $V_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst within the above temperature range was centered at 371.1 °C, which was significantly lower than the peak temperatures of the other $V_x/\text{Pt}/\text{TiO}_2$ catalysts. This indicates that,

compared with other $V_x/\text{Pt}/\text{TiO}_2$ catalysts, the oxygen vacancies on the surface of the $V_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst exhibit higher activity within the range of 250 to 600 °C [33]. This was beneficial for the $V_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst to adsorb and activate O_2 , enabling it to exhibit excellent NH_3 -SCO performance.

3.6. Redox Performance

The NH_3 -SCO performance of the catalysts is strongly associated with their redox performance. In order to investigate the redox performance of the $V_x/\text{Pt}/\text{TiO}_2$ catalysts, H_2 -TPR tests were carried out over a temperature range of 100 to 800 °C, and the results are shown in Figure 8. The H_2 -TPR profiles of each $V_x/\text{Pt}/\text{TiO}_2$ catalyst contained three reduction peaks. The reduction peaks at 268.7, 230.0, 188.7, 226.9, and 262.7 °C were attributed to the reduction processes of the Pt^{2+} and V^{5+} species. During these processes, Pt^{2+} was reduced to Pt^0 and V^{5+} was reduced to V^{4+} [31–34]. The reduction processes of the V^{4+} species to the V^{3+} species and subsequent reduction in the V^{3+} species accounted for reduction peaks at 505.9, 416.0, 375.0, 479.8, and 430.1 °C [31–35]. As TiO_2 was difficult to react with H_2 under 600 °C, reduction peaks at 746.9, 728.9, 688.3, 742.1, and 727.8 °C were attributed to the reduction in the TiO_2 species [34].

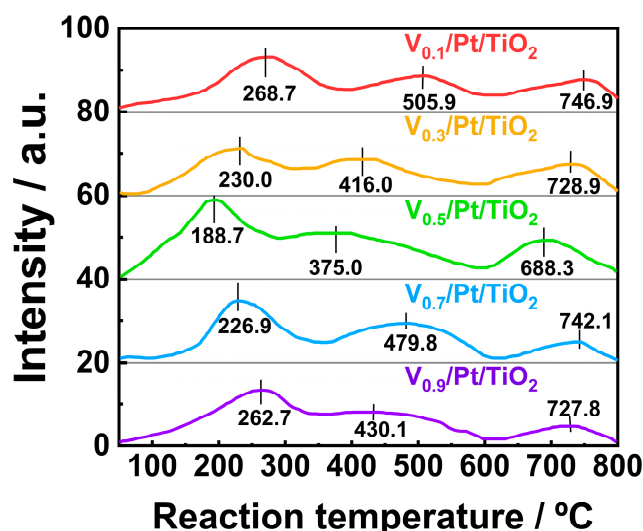


Figure 8. H_2 -TPR profiles of $V_x/\text{Pt}/\text{TiO}_2$ catalysts.

It is worth noting that the temperatures corresponding to three reduction peaks in the H_2 -TPR profile of the $V_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst were lower than those of the other $V_x/\text{Pt}/\text{TiO}_2$ catalysts. This might be ascribed to the strong interaction between the active components and TiO_2 support [36]. The above results indicate that throughout the entire temperature, the $V_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst exhibited better redox performance compared to other $V_x/\text{Pt}/\text{TiO}_2$ catalysts. In addition, as shown in Table S4, the H_2 consumption value (0.75 mmol/g) of the $V_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst was higher than those of other $V_x/\text{Pt}/\text{TiO}_2$ catalysts. This indicated that compared with other $V_x/\text{Pt}/\text{TiO}_2$ catalysts, there were more abundant reducible species on the surface of the $V_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst. Generally, outstanding redox performance and abundant reducible species are beneficial for the catalyst to exhibit excellent activity in the NH_3 -SCR reaction. Thus, the $V_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst could achieve higher N_2 selectivity via the i-SCR mechanism.

3.7. NH_3 -TPD

Surface acidity played a pivotal role in facilitating adsorption and activation of NH_3 on the catalyst surface, which was critical for the NH_3 -SCO reaction. The surface acidity of the $V_x/\text{Pt}/\text{TiO}_2$ catalysts was tested through NH_3 -TPD experiments, and the results

are displayed in Figure 9. Figure 9a displays the NH_3 -TPD profiles of the $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts. Based on previous studies, the NH_3 -TPD profiles in the temperature range of 50 to 200 °C were ascribed to NH_3 desorption from weak acid sites. NH_3 -TPD profiles between 200 and 350 °C were attributed to the desorption of NH_3 from medium acid sites [36–38]. The NH_3 -TPD profiles in the temperature range of 350 to 500 °C were ascribed to the NH_3 desorption from strong acid sites [39–41]. The quantities of acid sites on the surface of $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts were calculated by integrating the areas of sub-peaks in NH_3 -TPD profiles, and the results are shown in Figure 9b. It can be seen that with the V loading amount increasing from 0.1 wt.% to 0.5 wt.%, the total acid quantities of $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts gradually increased from 4.2 to 5.2 mmol/g. When the V loading amount was further increased from 0.5 wt.% to 0.9 wt.%, the total acid quantities of $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts decreased from 5.2 to 3.2 mmol/g. This suggested that compared with other $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts, the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst had more abundant acid sites on its surface. It can be seen from Figure 9b that the quantities of the weak and medium acid sites on the surface of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst were higher than those of other $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts. This was conducive to the adsorption and activation of NH_3 on the surface of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst [34–46], enabling the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst to exhibit excellent N_2 selectivity.

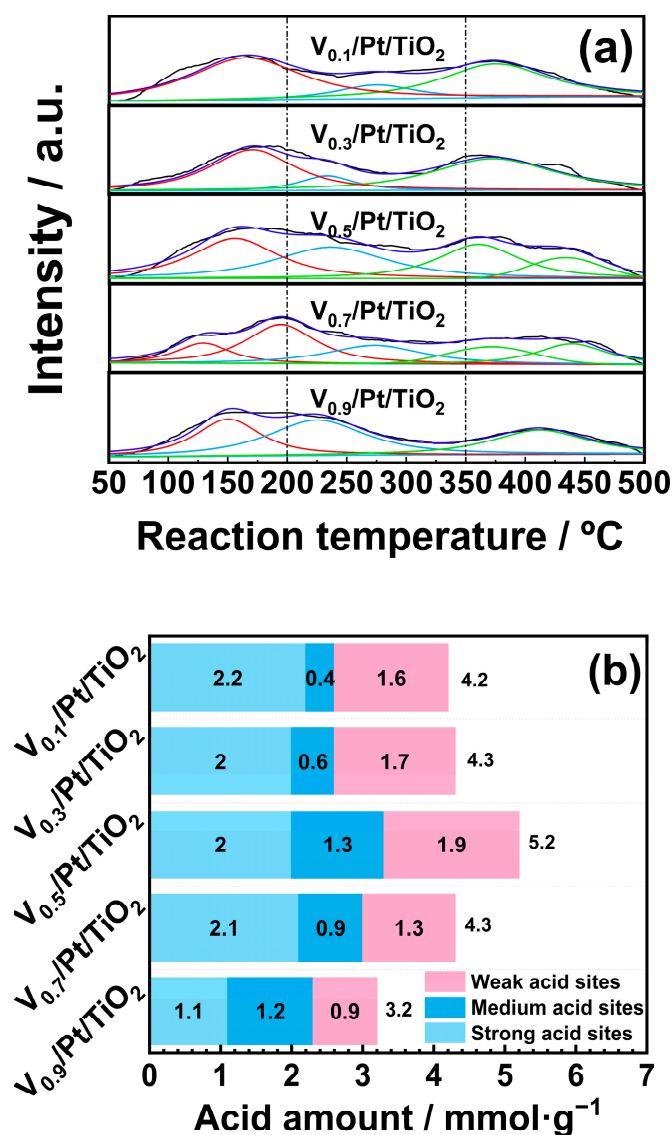


Figure 9. (a) NH_3 -TPD profiles and (b) acid sites quantities of $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts.

3.8. HRTEM and EDX

HRTEM tests were conducted on $V_x/\text{Pt}/\text{TiO}_2$ catalysts, and EDX tests were carried out on the $V_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst. The results are shown in Figures 10 and 11. It can be seen from Figure 10 that the $V_x/\text{Pt}/\text{TiO}_2$ catalysts all exhibited a granular microscopic morphology, with a particle size of approximately 20–50 nm. This was mainly because in this work, P25 TiO_2 nanoparticles were used as the catalyst support. It could be observed that distinct lattice fringes existed in the highly magnified images. As marked in Figure 10, these fringes could be attributed to anatase TiO_2 species (ICDD 21-1276), rutile TiO_2 species (ICPD 21-1272), the Pt species (ICDD 43-1100), and the V_2O_5 species (ICDD 19-1401) [27,46]. This indicated that there were nanocrystals of the above-mentioned species on the surface of the catalysts.

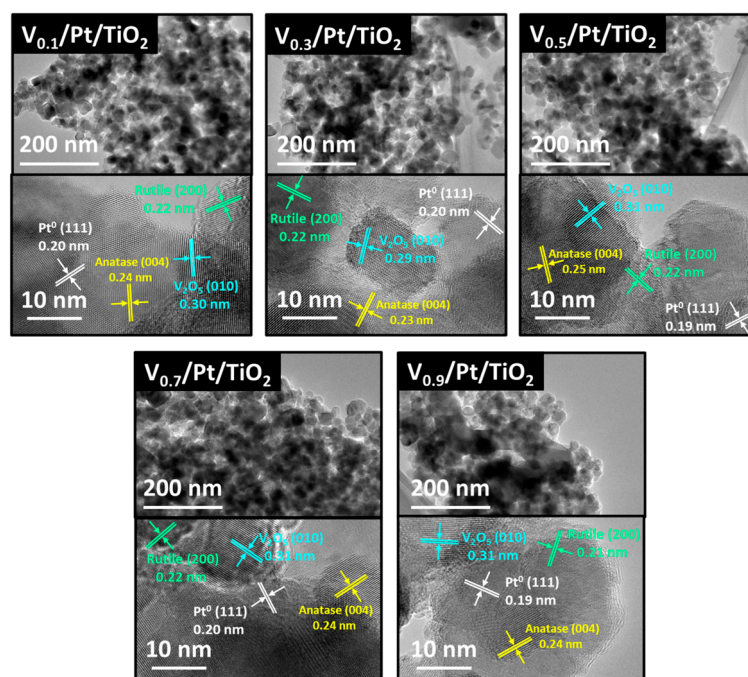


Figure 10. HRTEM images of $V_x/\text{Pt}/\text{TiO}_2$ catalysts.

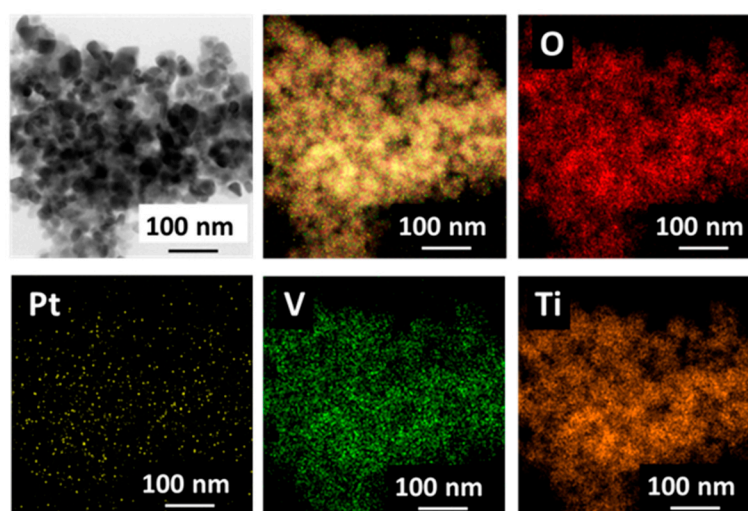


Figure 11. EDX mappings of $V_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst.

The EDX test was employed to characterize the dispersion state of O, Pt, V, and Ti elements on the surface of the $V_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst, and the results are shown in Figure 11.

The results suggested that O, Pt, V, and Ti elements were uniformly distributed on the surface of the $V_{0.5}/Pt/TiO_2$ catalyst. Pt and V elements were in intimate contact with one another, which contributed to facilitating the interaction between the Pt and V species.

3.9. In Situ DRIFTS

The surface reaction pathways of NH_3 -SCO catalysts are closely related to their N_2 selectivity. With the aim of exploring reaction pathways over $V_x/Pt/TiO_2$ catalysts, in situ DRIFTS experiments were carried out for the reaction between NH_3 and O_2 at 350 °C, and the results are shown in Figure 12. The results of in situ DRIFTS experiments have been discussed as follows. Detailed information about in situ DRIFTS experiments is presented in the Supplementary Materials.

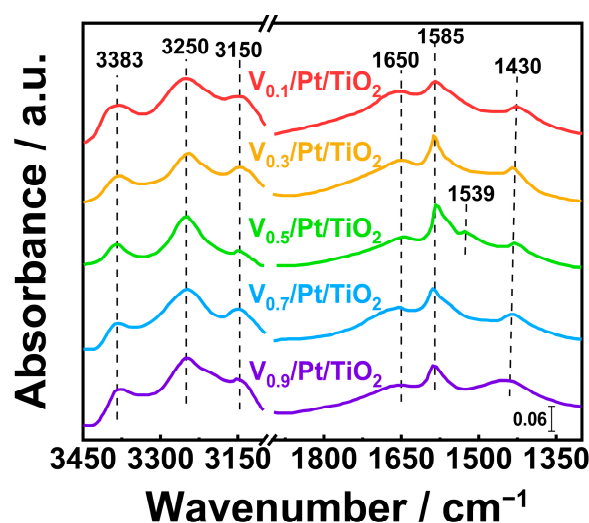


Figure 12. In situ DRIFT spectra of NH_3 and O_2 co-adsorbed over $V_x/Pt/TiO_2$ catalysts at 350 °C for 30 min.

As shown in Figure 12, the NH_3 species (3383 , 3150 cm^{-1}), NH_3 species coordinated at Lewis acid sites (3250 cm^{-1}), NO_2 species (1650 cm^{-1}), bidentate nitrate species (1585 cm^{-1}), and NH_4^+ species coordinated at Brønsted acid sites (1436 cm^{-1}) on the surface of $V_x/Pt/TiO_2$ catalysts were capable of taking part in the NH_3 -SCO reaction [47–53]. It can be seen from Figure 12 that when both NH_3 and O_2 were introduced into reaction cell, a distinct signal of $-NH_2$ species (1539 cm^{-1}) appeared in the in situ DRIFTS spectrum of the $V_{0.5}/Pt/TiO_2$ catalyst [35]. But during the same reaction process, the signal of the $-NH_2$ species did not appear in the in situ DRIFTS spectra of other $V_x/Pt/TiO_2$ catalysts. This implied that the $-NH_2$ species could be involved in the NH_3 -SCO reaction over the $V_{0.5}/Pt/TiO_2$ catalyst. Since the $-NH_2$ species was a key intermediate in the i-SCR mechanism [53,54], the appearance of the $-NH_2$ species over the $V_{0.5}/Pt/TiO_2$ catalyst might be associated with the promotion of the i-SCR reaction. This facilitated the formation of N_2 , consequently enhancing the N_2 selectivity.

4. Discussion

HRTEM, EDX, XRD, XPS, and H_2 -TPR results indicated that there were Pt^0 and V_2O_5 nanocrystals on the surface of the $V_{0.5}/Pt/TiO_2$ catalyst. The Pt^0 species had a strong ability for catalytic oxidation of NH_3 . V_2O_5 species possessed remarkable catalytic performance for NH_3 -SCR reactions. Thus, both NH_3 -SCO and NH_3 -SCR reactions existed on the surface of the $V_x/Pt/TiO_2$ catalyst, as shown in Figure 13. This enabled NH_3 to be converted into N_2 through the i-SCR mechanism. XPS and H_2 -TPR results implied that the valence states of the V and Pt species could be regulated by varying the V loading amount, thereby

regulating the synergistic effect between NH_3 -SCO and NH_3 -SCR reactions. When the V loading amount was 0.5 wt.%, there were abundant Pt^0 and V^{5+} species on the surface of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst. This was beneficial for making the synergistic effect between NH_3 -SCO and NH_3 -SCR reactions more efficient, thus enabling the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst to exhibit excellent N_2 selectivity. N_2 adsorption–desorption, NH_3 -TPD, O_2 -TPD, and in situ DRIFTS results suggested that the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst possessed a higher specific surface area, abundant surface acid sites, and oxygen vacancies, as well as better reaction pathways. This also contributed to enabling the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst to exhibit excellent N_2 selectivity.

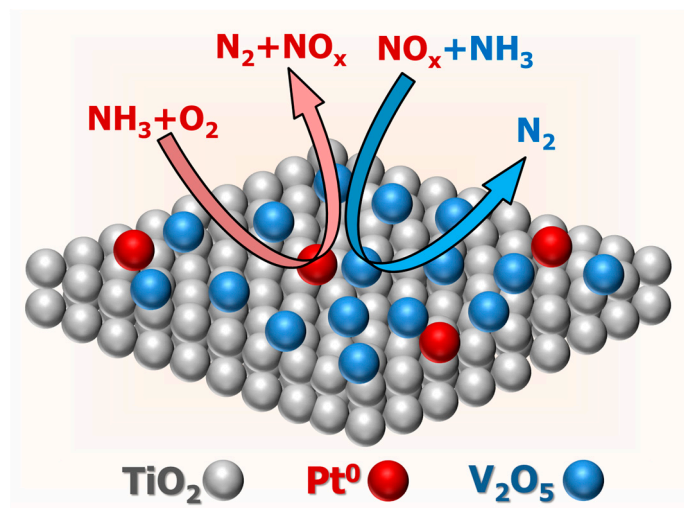


Figure 13. Schematic diagram of reaction pathways on the surface of $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts.

Due to the limitation of the article length, a systematic exploration of hydrothermal aging characteristics of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst has not been carried out in this work. In future work, the NH_3 -SCO performance of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst under different hydrothermal aging conditions will be systematically explored. The influence mechanism of the hydrothermal aging process on the catalytic performance will be analyzed, and corresponding strategies for improving the catalytic performance will be proposed.

5. Conclusions

In this work, the $\text{V}_x/\text{Pt}/\text{TiO}_2$ tandem catalysts were synthesized for SCO of NH_3 by the two-step impregnation–deposition method. The synergistic effect of NH_3 -SCO and NH_3 -SCR reactions over $\text{V}_x/\text{Pt}/\text{TiO}_2$ tandem catalysts could be regulated by changing the V loading amount, thereby modulating the N_2 selectivity. When the Pt loading was 0.5 wt.%, there were relatively abundant Pt^0 species and V^{5+} species on the surface of the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst. These two species, respectively, possessed excellent NH_3 catalytic oxidation performance and NH_3 -SCR performance, thus enabling NH_3 -SCO and NH_3 -SCR reactions to achieve highly efficient synergy. In addition, the $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst had a relatively high specific surface area, abundant surface acid sites, good redox properties, and reaction pathways that are more favorable for the generation of N_2 , which are also the reasons for its excellent N_2 selectivity.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/ma18081782/s1>, Figure S1: (a) NH_3 conversion efficiencies and (b) N_2 selectivities of $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst in the repeatability test.; Table S1: NH_3 -SCO performance comparison for $\text{V}_{0.5}/\text{Pt}/\text{TiO}_2$ catalyst and other catalysts in previous work; Table S2: Specific surface areas and average pore sizes of $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts; Table S3: XPS results of $\text{V}_x/\text{Pt}/\text{TiO}_2$ catalysts;

Table S4: H₂ consumption values of V_x/Pt/TiO₂ catalysts. References [55–62] are cited in the Supplementary Materials.

Author Contributions: Conceptualization, Y.G.; methodology, Y.G. and W.M.; investigation, Y.G. and W.M.; writing—original draft preparation, Y.G.; writing—review and editing, Y.G. and P.L.; funding acquisition, P.L. and W.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the “National Key Research and Development Program of China”, grant number 2021YFB2601601 and the “Fundamental Research Funds for China Waterborne Transport Research Institute”, grant number 72404.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article and Supplementary Materials. Further inquiries can be directed to the corresponding author.

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

References

1. Lagouvardou, S.; Psaraftis, H.N.; Zis, T. Impacts of a bunker levy on decarbonizing shipping: A tanker case study. *Transp. Res. Part D Transp. Environ.* **2022**, *106*, 103257. [\[CrossRef\]](#)
2. Liu, J.; Cavagnaro, R.J.; Deng, Z.D.; Shao, Y.; Kuo, L.J.; Nguyen, M.T.; Glezakou, V. Renewable ammonia as an energy fuel for ocean exploration and transportation. *Mar. Technol. Soc. J.* **2020**, *54*, 126–136. [\[CrossRef\]](#)
3. Kanberoğlu, B.; Kökkülünk, G. Assessment of CO₂ emissions for a bulk carrier fleet. *J. Clean. Prod.* **2021**, *283*, 124590. [\[CrossRef\]](#)
4. Dimitriou, P.; Javaid, R. A review of ammonia as a compression ignition engine fuel. *Int. J. Hydrogen Energy* **2020**, *45*, 7098–7118. [\[CrossRef\]](#)
5. Reiter, A.J.; Kong, S.C. Combustion and emissions characteristics of compression-ignition engine using dual ammonia-diesel fuel. *Fuel* **2011**, *90*, 87–97. [\[CrossRef\]](#)
6. Niki, Y. Reductions in unburned ammonia and nitrous oxide emissions from an ammonia-assisted diesel engine with early timing diesel pilot injection. *J. Eng. Gas Turbines Power* **2021**, *143*, 091014. [\[CrossRef\]](#)
7. Niki, Y.; Nitta, Y.; Sekiguchi, H.; Hirata, K. Diesel fuel multiple injection effects on emission characteristics of diesel engine mixed ammonia gas into intake air. *J. Eng. Gas Turbines Power* **2019**, *141*, 061020. [\[CrossRef\]](#)
8. Cui, J.; Chen, W.; Wang, B.; Fan, Y.; Tian, H.; Long, W.; Liu, X. Effects of relative position of injectors on the performance of ammonia/diesel two-stroke engines. *Energy* **2024**, *309*, 133085. [\[CrossRef\]](#)
9. Gao, Y.; Han, Z.; Cheng, S.; Xu, D.; Pan, X. A mixed catalyst prepared by mechanically milling VW/TiO₂ and low content of Pt/Al₂O₃ for SCO of high-concentration NH₃. *New J. Chem.* **2022**, *46*, 20108–20119. [\[CrossRef\]](#)
10. Gao, F.; Liu, Y.; Sani, Z.; Tang, X.; Yi, H.; Zhao, S.; Yu, Q.; Zhou, Y. Advances in selective catalytic oxidation of ammonia (NH₃-SCO) to dinitrogen in excess oxygen: A review on typical catalysts, catalytic performances and reaction mechanisms. *J. Environ. Chem. Eng.* **2021**, *9*, 104575. [\[CrossRef\]](#)
11. Lan, T.; Zhao, Y.; Deng, J.; Zhang, J.; Shi, L.; Zhang, D. Selective catalytic oxidation of NH₃ over noble metal-based catalysts: State of the art and future prospects. *Catal. Sci. Technol.* **2020**, *10*, 5792–5810. [\[CrossRef\]](#)
12. Kim, G.J.; Kwon, D.W.; Shin, J.H.; Kim, K.W.; Hong, S.C. Influence of the addition of vanadium to Pt/TiO₂ catalyst on the selective catalytic oxidation of NH₃ to N₂. *Environ. Technol.* **2019**, *40*, 2588–2600. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Wang, F.; Ma, J.; He, G.; Chen, M.; Zhang, C.; He, H. Nanosize effect of Al₂O₃ in Ag/Al₂O₃ catalyst for the selective catalytic oxidation of ammonia. *ACS Catal.* **2018**, *8*, 2670–2682. [\[CrossRef\]](#)
14. Qu, Z.; Wang, H.; Wang, S.; Cheng, H.; Qin, Y.; Wang, Z. Role of the support on the behavior of Ag-based catalysts for NH₃ selective catalytic oxidation (NH₃-SCO). *Appl. Surf. Sci.* **2014**, *316*, 373–379. [\[CrossRef\]](#)
15. Kim, J.; Kim, D.H.; Kwon, D.W.; Lee, K.Y.; Ha, H.P. Unveiling the traits of rare earth metal (RM)-substituted bimetallic Ce_{0.5}RM_{0.5}V₁O₄ phases to activate selective NH₃ oxidation and NO_x reduction. *Appl. Surf. Sci.* **2020**, *518*, 146238. [\[CrossRef\]](#)
16. Li, B.; Wang, X.; Wang, Y.; Wang, W.; Zhou, S.; Zhang, S.; Li, W.; Li, S. Revealing the promotional effect of Ce doping on the low-temperature activity and SO₂ tolerance of Ce/FeVO₄ catalysts in NH₃-SCR. *J. Environ. Chem. Eng.* **2022**, *10*, 107588. [\[CrossRef\]](#)
17. Liang, C.; Li, X.; Qu, Z.; Tade, M.; Liu, S. The role of copper species on Cu/γ-Al₂O₃ catalysts for NH₃-SCO reaction. *Appl. Surf. Sci.* **2012**, *258*, 3738–3743. [\[CrossRef\]](#)

18. Wang, F.; Zhu, Y.; Li, Z.; Shan, Y.; Shan, W.; Shi, X.; Yu, Y.B.; Zhang, C.B.; Li, K.; Ning, P.; et al. Promoting effect of acid sites on NH₃-SCO activity with water vapor participation for Pt-Fe/ZSM-5 catalyst. *Catal. Today* **2021**, *376*, 311–317. [\[CrossRef\]](#)
19. Chang, S.; Harle, G.; Ma, J.; Yi, J. The effect of textural properties of CeO₂-SiO₂ mixed oxides on NH₃-SCO activity of Pt/CeO₂-SiO₂ catalyst. *Appl. Catal. A-Gen.* **2020**, *604*, 117775. [\[CrossRef\]](#)
20. Byun, S.W.; Lee, S.J.; Kim, M.; Bae, W.B.; Shin, H.; Hazlett, M.J.; Kang, D.; Tesfaye, B.; Park, P.W.; Kang, S.B. High N₂ selectivity of Pt-VW/TiO₂ oxidation catalyst for simultaneous control of NH₃ and CO emissions. *Chem. Eng. J.* **2022**, *444*, 136517. [\[CrossRef\]](#)
21. Liu, W.; Long, Y.; Zhou, Y.; Liu, S.; Tong, X.; Yin, Y.; Li, X.; Hu, K.; Hu, J. Excellent low temperature NH₃-SCR and NH₃-SCO performance over Ag-Mn/Ce-Ti catalyst: Evaluation and characterization. *Mol. Catal.* **2022**, *528*, 112510. [\[CrossRef\]](#)
22. Gao, Y.; Han, Z.; Lu, S.; Pan, X. Influence of deposition order of dual active components on the NH₃-SCO performance of the bimetallic Pt-V system supported on TiO₂. *New J. Chem.* **2023**, *47*, 11143–11155. [\[CrossRef\]](#)
23. Kwon, D.W.; Lee, S.M.; Hong, S.C. Influence of attrition milling on V/Ti catalysts for the selective oxidation of ammonia. *Appl. Catal. A-Gen.* **2015**, *505*, 557–565. [\[CrossRef\]](#)
24. Shen, M.; Li, C.; Wang, J.; Xu, L.; Wang, W.; Wang, J. New insight into the promotion effect of Cu doped V₂O₅/WO₃-TiO₂ for low temperature NH₃-SCR performance. *RSC Adv.* **2015**, *5*, 35155–35165. [\[CrossRef\]](#)
25. Lian, Z.; Liu, L.; Lin, C.; Shan, W.; He, H. Hydrothermal aging treatment activates V₂O₅/TiO₂ catalysts for NO_x abatement. *Environ. Sci. Technol.* **2022**, *56*, 9744–9750. [\[CrossRef\]](#)
26. Wang, Y.; Shen, G.; Wang, C.; Gao, F.; Wang, J.; Shen, M. Mechanistic insights into the deactivation of Pd/BEA methane combustion catalysts by hydrothermal aging. *Mol. Catal.* **2024**, *558*, 114027. [\[CrossRef\]](#)
27. Liu, Z.; Liu, K.; Yang, X.; Chen, X.; Shen, X.; Li, Y.; Fang, Y.; Liu, Y.; Zhao, J.; Yang, X.; et al. In-situ formed stable Pt nanoclusters on ceria-zirconia solid solutions induced by hydrothermal aging for efficient low-temperature CO oxidation. *Chem. Eng. J.* **2024**, *498*, 155427. [\[CrossRef\]](#)
28. Liu, S.R.; Luo, S.T.; Wu, X.D.; Wang, T.J.; Ran, R.; Weng, D.; Si, Z.; Liu, S. Application of silica-alumina as hydrothermally stable supports for Pt catalysts for acid-assisted soot oxidation. *Rare Met.* **2023**, *42*, 1614–1623. [\[CrossRef\]](#)
29. Song, D.; Shao, X.; Yuan, M.; Wang, L.; Zhan, W.; Guo, Y.; Lu, G. Selective catalytic oxidation of ammonia over MnO_x-TiO₂ mixed oxides. *RSC Adv.* **2016**, *6*, 88117–88125. [\[CrossRef\]](#)
30. Guo, J.; Yang, W.; Zhang, Y.; Gan, L.; Fan, C.; Chen, J.; Peng, Y.; Li, J. A multiple-active-site Cu/SSZ-13 for NH₃-SCO: Influence of Si/Al ratio on the catalytic performance. *Catal. Commun.* **2020**, *135*, 105751. [\[CrossRef\]](#)
31. Sun, M.; Liu, J.; Song, C.; Ogata, Y.; Rao, H.; Zhao, X.; Xu, H.D.; Chen, Y. Different reaction mechanisms of ammonia oxidation reaction on Pt/Al₂O₃ and Pt/CeZrO₂ with various Pt states. *ACS Appl. Mater. Interfaces* **2019**, *11*, 23102–23111. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Liao, W.M.; Liu, Y.R.; Zhao, P.P.; Cen, B.H.; Tang, C.; Jia, A.P.; Lu, J.; Luo, M.F. Total oxidation of propane over Pt-V/SiO₂ catalysts: Remarkable enhancement of activity by vanadium promotion. *Appl. Catal. A-Gen.* **2020**, *590*, 117337. [\[CrossRef\]](#)
33. Tian, Y.; Han, Z.; Zhou, Z.; Zhao, H.; Zeng, Q.; Li, Y.; Ma, D. Synthesis of Cu/CeTiO_x tandem catalyst with dual-function sites for selective catalytic oxidation of ammonia. *Chem. Eng. J.* **2025**, *503*, 158212. [\[CrossRef\]](#)
34. Jabłońska, M. TPR study and catalytic performance of noble metals modified Al₂O₃, TiO₂ and ZrO₂ for low-temperature NH₃-SCO. *Catal. Commun.* **2015**, *70*, 66–71. [\[CrossRef\]](#)
35. Góra-Marek, K.; Brylewska, K.; Tarach, K.A.; Rutkowska, M.; Jabłońska, M.; Choi, M.; Chmielarz, L. IR studies of Fe modified ZSM-5 zeolites of diverse mesopore topologies in the terms of their catalytic performance in NH₃-SCR and NH₃-SCO processes. *Appl. Catal. B-Environ.* **2015**, *179*, 589–598. [\[CrossRef\]](#)
36. Wang, Z.; Sun, Q.; Wang, D.; Hong, Z.; Qu, Z.; Li, X. Hollow ZSM-5 zeolite encapsulated Ag nanoparticles for SO₂-resistant selective catalytic oxidation of ammonia to nitrogen. *Sep. Purif. Technol.* **2019**, *209*, 1016–1026. [\[CrossRef\]](#)
37. Hua, Z.; Xin, Q.; Ren, W.; Zheng, Z.; Zhou, F.; Liu, S.; Yang, Y.; Gao, X. Enhanced performance of Nb₂O₅ decorated RuO₂/Sn_{0.2}Ti_{0.8}O₂ for selective catalytic oxidation of ammonia. *Process Saf. Environ. Prot.* **2022**, *160*, 948–957. [\[CrossRef\]](#)
38. Macina, D.; Opiola, A.; Rutkowska, M.; Basag, S.; Piwowarska, Z.; Michalik, M.; Chmielarz, L. Mesoporous silica materials modified with aggregated transition metal species (Cr, Fe and Cr-Fe) in the role of catalysts for selective catalytic oxidation of ammonia to dinitrogen. *Mater. Chem. Phys.* **2017**, *187*, 60–71. [\[CrossRef\]](#)
39. Lin, M.; An, B.; Takei, T.; Shishido, T.; Ishida, T.; Haruta, M.; Murayama, T. Features of Nb₂O₅ as a metal oxide support of Pt and Pd catalysts for selective catalytic oxidation of NH₃ with high N₂ selectivity. *J. Catal.* **2020**, *389*, 366–374. [\[CrossRef\]](#)
40. Im, H.G.; Lee, M.J.; Kim, W.G.; Kim, S.J.; Jeong, B.; Ye, B.; Lee, H.; Kim, H.D. High-Dispersed V₂O₅-CuO_x Nanoparticles on h-BN in NH₃-SCR and NH₃-SCO Performance. *Nanomaterials* **2022**, *12*, 2329. [\[CrossRef\]](#)
41. Jiang, L.; Liu, Q.; Ran, G.; Kong, M.; Ren, S.; Yang, J.; Li, J. V₂O₅-modified Mn-Ce/AC catalyst with high SO₂ tolerance for low-temperature NH₃-SCR of NO. *Chem. Eng. J.* **2019**, *370*, 810–821. [\[CrossRef\]](#)
42. Li, X.; Han, Z.; Wang, X.; Yang, S.; Liu, G.; Gao, Y.; Li, C. Acid treatment of ZrO₂-supported CeO₂ catalysts for NH₃-SCR of NO: Influence on surface acidity and reaction mechanism. *J. Taiwan Inst. Chem. Eng.* **2022**, *132*, 104144. [\[CrossRef\]](#)

43. Zhang, X.; Zhang, X.; Yang, X.; Chen, Y.; Hu, X.; Wu, X. CeMn/TiO₂ catalysts prepared by different methods for enhanced low-temperature NH₃-SCR catalytic performance. *Chem. Eng. Sci.* **2021**, *238*, 116588. [\[CrossRef\]](#)
44. Yu, Y.; Wei, D.; Tong, Z.; Wang, J.; Chen, J.; He, C. Rationally engineered ReO_x-CuSO₄/TiO₂ catalyst with superior NH₃-SCO efficiency and remarkably boosted SO₂ tolerance: Synergy of acid sites and surface adsorbed oxygen. *Chem. Eng. J.* **2022**, *442*, 136356. [\[CrossRef\]](#)
45. Zhai, G.; Han, Z.; Wu, X.; Du, H.; Gao, Y.; Yang, S.; Song, L.; Dong, J.; Pan, X. Pr-modified MnO_x catalysts for selective reduction of NO with NH₃ at low temperature. *J. Taiwan Inst. Chem. Eng.* **2021**, *125*, 132–140. [\[CrossRef\]](#)
46. Gao, Y.; Han, Z.T.; Cheng, S.S.; Lu, S.J.; Pan, X.X. The enhancement effect of Cu modification on N₂ selectivity of V_{0.5}/Pt_{0.04}/TiO₂ catalyst for selective catalytic oxidation of NH₃. *J. Taiwan Inst. Chem. Eng.* **2023**, *149*, 104947. [\[CrossRef\]](#)
47. Song, K.; Zhao, S.; Li, Z.; Li, K.; Xu, Y.; Zhang, Y.; Cheng, Y.; Shi, J.W. Zinc and phosphorus poisoning tolerance of Cu-SSZ-13 and Ce-Cu-SSZ-13 in the catalytic reduction of nitrogen oxides. *J. Colloid Interface Sci.* **2023**, *629*, 243–255. [\[CrossRef\]](#)
48. Han, Z.; Du, H.; Xu, D.; Gao, Y.; Yang, S.; Song, L.; Dong, J.; Pan, X. Fe and Mn mixed oxide catalysts supported on Sn-modified TiO₂ for the selective catalytic reduction of NO with NH₃ at low temperature. *New J. Chem.* **2022**, *46*, 1621–1636. [\[CrossRef\]](#)
49. Wang, F.; Ma, J.; He, G.; Chen, M.; Wang, S.; Zhang, C.; He, H. Synergistic effect of TiO₂-SiO₂ in Ag/Si-Ti catalyst for the selective catalytic oxidation of ammonia. *Ind. Eng. Chem. Res.* **2018**, *57*, 11903–11910. [\[CrossRef\]](#)
50. Gao, Y.; Han, Z.; Zhai, G.; Song, L.; Dong, J.; Yang, S.; Pan, X. Mechanistic insight into the promoting effect of partial substitution of Mn by Ce on N₂ selectivity of MnTiO_x catalyst for NH₃-SCR of NO. *J. Taiwan Inst. Chem. Eng.* **2022**, *133*, 104269. [\[CrossRef\]](#)
51. Jabłońska, M.; Wolkenar, B.; Beale, A.M.; Pischinger, S.; Palkovits, R. Comparison of Cu-Mg-Al-O_x and Cu/Al₂O₃ in selective catalytic oxidation of ammonia (NH₃-SCO). *Catal. Commun.* **2018**, *110*, 5–9. [\[CrossRef\]](#)
52. Peng, Y.; Si, W.; Li, X.; Luo, J.; Li, J.; Crittenden, J.; Hao, J. Comparison of MoO₃ and WO₃ on arsenic poisoning V₂O₅/TiO₂ catalyst: DRIFTS and DFT study. *Appl. Catal. B-Environ.* **2016**, *181*, 692–698. [\[CrossRef\]](#)
53. Yao, H.; Chen, Y.; Wei, Y.; Zhao, Z.; Liu, Z.; Xu, C. A periodic DFT study of ammonia adsorption on the V₂O₅ (001), V₂O₅ (010) and V₂O₅ (100) surfaces: Lewis versus Brönsted acid sites. *Surf. Sci.* **2012**, *606*, 1739–1748. [\[CrossRef\]](#)
54. Zhang, X.; Wang, H.; Jiang, X.; Sun, H.; Qu, Z. Study of synergistic effect between CuO and CeO₂ over CuO@CeO₂ core-shell nanocomposites for NH₃-SCO. *Catal. Sci. Technol.* **2019**, *9*, 2968–2981. [\[CrossRef\]](#)
55. Shrestha, S.; Harold, M.P.; Kamasamudram, K.; Yezerets, A. Selective oxidation of ammonia on mixed and dual-layer Fe-ZSM-5+Pt/Al₂O₃ monolithic catalysts. *Catal. Today* **2014**, *231*, 105–115. [\[CrossRef\]](#)
56. Sun, M.; Wang, S.; Li, Y.; Wang, Q.; Xu, H.; Chen, Y. Promotion of catalytic performance by adding Cu into Pt/ZSM-5 catalyst for selective catalytic oxidation of ammonia. *J. Taiwan Inst. Chem. E.* **2017**, *78*, 401–408. [\[CrossRef\]](#)
57. Sun, M.; Wang, S.; Li, Y.; Xu, H.; Chen, Y. Promotion of catalytic performance by adding W into Pt/ZrO₂ catalyst for selective catalytic oxidation of ammonia. *Appl. Surf. Sci.* **2017**, *402*, 323–329. [\[CrossRef\]](#)
58. Wang, F.; He, G.; Zhang, B.; Chen, M.; Chen, X.; Zhang, C.; He, H. Insights into the activation effect of H₂ pretreatment on Ag/Al₂O₃ catalyst for the selective oxidation of ammonia. *ACS Catal.* **2019**, *9*, 1437–1445. [\[CrossRef\]](#)
59. Zhang, Q.; Wang, H.; Ning, P.; Song, Z.; Liu, X.; Duan, Y. In situ DRIFTS studies on CuO-Fe₂O₃ catalysts for low temperature selective catalytic oxidation of ammonia to nitrogen. *Appl. Surf. Sci.* **2017**, *419*, 733–743. [\[CrossRef\]](#)
60. Gang, L.; Van Grondelle, J.; Anderson, B.G.; Van Santen, R.A. Selective low temperature NH₃ oxidation to N₂ on copper-based catalysts. *J. Catal.* **1999**, *186*, 100–109. [\[CrossRef\]](#)
61. Long, R.Q.; Yang, R.T. Selective catalytic oxidation of ammonia to nitrogen over Fe₂O₃-TiO₂ prepared with a sol-gel method. *J. Catal.* **2002**, *207*, 158–165. [\[CrossRef\]](#)
62. Lee, J.Y.; Kim, S.B.; Hong, S.C. Characterization and reactivity of natural manganese ore catalysts in the selective catalytic oxidation of ammonia to nitrogen. *Chemosphere* **2003**, *50*, 1115–1122. [\[CrossRef\]](#) [\[PubMed\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.