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H₂-SCR at high water concentrations with *in situ* generated NH₃ for efficient removal of NO_x from H₂ engines

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The two main challenges of application of Pd-based catalysts in H₂-SCR are catalytic performance and water resistance. In this study, oxide supports (TiO₂ and ZrO₂) were employed and experimentally demonstrated to exhibit higher catalytic activities than the SSZ-13 zeolite-supported catalyst. Furthermore, doping Mn into Pd/TiO₂ further increased the maximum NO conversion to 61% compared to 44% for undoped Pd/TiO₂. Comprehensive characterization techniques, including XRD, STEM, XPS, CO-DRIFTS, and H₂-reduction experiments, were used to investigate the catalysts' physicochemical properties and hydrogen spillover behavior. Pd/MnTiO₂ not only retained the strong metal–support interaction observed in Pd/TiO₂ but also significantly optimized the surface electronic structure. A higher proportion of metallic Pd facilitated H₂ dissociation and enhanced hydrogen spillover, leading to improved catalytic activity. Water resistance tests, at 5% and up to 12% water vapor, revealed that the zeolite-supported catalyst exhibited superior tolerance to water. Although the oxide-supported catalysts were more sensitive to water, they still retained significantly higher catalytic activity overall. Notably, Pd/MnTiO₂ exhibited the largest formation of NH₃. Finally, since NH₃ was identified as a major byproduct during H₂-SCR over Pd/MnTiO₂, a novel NO_x removal strategy was developed by adding a downstream Cu-SSZ-13 monolith to establish an integrated H₂-SCR and NH₃-SCR reaction system. This configuration successfully increased the maximum NO conversion to 78%, with N₂ and N₂O as the only detected products, achieving a nitrogen selectivity of 76%.

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Introduction

Hydrogen, as an alternative energy source, has garnered widespread attention in recent years. It has been reported that while internal combustion engines (ICEs) using fossil fuels contribute 25% of the world's power, they are also responsible for more than 10% of global greenhouse gas emissions (GHGs).¹ In addition, conventional ICEs not only produce GHGs (CO₂, N₂O, *etc.*) but also other harmful gases (CO, NO_x, *etc.*) and particulate matter, which need to be removed *via* catalytic techniques. Therefore, clean hydrogen can play an important role in utilizing internal combustion engines.^{2–4} Although the combustion of hydrogen produces water, the combustion process is accompanied by a small amount of NO_x emissions because air, rather than pure oxygen is used in ICEs. The development of hydrogen internal combustion engines (H₂-ICEs) has made selective catalytic reduction of NO_x using hydrogen (H₂-SCR) an attractive alternative to conventional NH₃-SCR catalysts in exhaust after-treatment systems. This is

because hydrogen is already available onboard as fuel in emerging H₂-ICE platforms, such as the Cummins X15H heavy-duty engine, MAN hydrogen-powered trucks, and the JCB hydrogen-fueled off-road machinery engine, as described in their webpages.

In many studies, Pt and Pd are considered the active centers for H₂-SCR under lean-burn conditions, offering high potential for low-temperature emission reductions.^{5,6} Our previous study showed that NO reduction with hydrogen can also occur at high temperatures using an Ir catalyst, which covers a wide temperature window with combinations of catalysts.⁷ Pd showed a moderately active temperature window and a relatively high N₂ selectivity. However, one challenge in developing Pd-based catalysts for H₂-SCR is their lower activity compared to Pt catalysts.^{8–10} To address this, researchers have applied some effective strategies. Deutschmann and co-workers successfully boosted the activity of Pd-based catalysts for H₂-SCR by using a combination of oxides and zeolite (20% TiO₂/HY and 5% V₂O₅/20% TiO₂-Al₂O₃) supports.¹¹ Liu *et al.* added Mn as a dopant to modify Pd/TiO₂-Al₂O₃, which not only enhanced activity but also remarkably increased N₂ selectivity above 150 °C. They revealed that new active nitrogen oxides formed on MnO_x, which are unstable and more active.¹² Yang's group

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investigated the effect of a nickel additive on Pd/TiO₂ for H₂-SCR, revealing the synergistic effects between Pd and Ni promoted catalytic activity and N₂ selectivity.¹³ They also noted that adding Ni altered the profiles of H₂ adsorption and spillover from Pd/TiO₂. As a part of the H₂-SCR process, hydrogen spillover effects (HSPEs) have been reported to be an interfacial phenomenon that plays a crucial role.^{14–18} Peng *et al.* demonstrated that enhanced hydrogen spillover could effectively eliminate the ‘volcano-type’ behavior of NO_x conversion *vs.* temperature in H₂-SCR over Pd-based catalysts.¹⁹ Despite this, many scholars have noted that a comprehensive understanding of HSPEs is still lacking, leading to debates about non-reducible oxide supports. Precious metals (Pt and Pd) are considered the most effective catalysts for the HSPE.²⁰ Additionally, researchers have found that hydrogen spillover is influenced by particle size, the distribution of the noble metal, the type of support, and the interaction between the metal and support.

Apart from the intrinsic performance of the catalyst, the high water content in the exhaust of hydrogen-powered vehicles presents a significant challenge that cannot be overlooked in the development of after-treatment catalysts. Water is the main combustion product, and its concentration in the exhaust depends on the air-fuel ratio (λ). It has been reported that at $\lambda = 1$, the molar fraction of water is 34% for H₂-ICES.^{21,22} This elevated water concentration has a significant impact on catalyst aging. Water has been proven to have a divergent influence on the reaction by researchers. Costa *et al.* found a promoting effect of H₂O on Pt/MgO–CeO₂, because the dissociation of H₂O contributes to an increased H-reservoir and facilitates hydroxylation of the surface. As a result, N₂ selectivity was improved with more active NO_x species formed on the hydrated surface.^{23–25} Xu *et al.* claimed a positive effect of H₂O on a Co-Al_{1.95}Pd_{0.05}O₄ catalyst, as the H_{ads} dissociated by H₂O could assist NO dissociation, improving N₂ formation.²⁶ However, it has also been reported that water has a strong inhibitory effect on N₂ selectivity when 5% H₂O is added to the NO/H₂/O₂ feed on Pt/SiO₂ and Pt/Al₂O₃ catalysts due to the competitive chemisorption of NO and H₂O on the active site.²⁷ The inhibition and deactivating effect of H₂O was reported to be both reversible and irreversible, depending on the conditions. Severe deactivation occurs at high temperature, especially with higher water content, where the dispersion of active metals could decrease, as well as the surface area and pore volume. For the cases where zeolites are used as supports, dealumination of the framework could occur.²⁸ Most studies have investigated the effect of water on H₂-SCR catalysts at concentrations up to 5%.²⁹ However, the application of H₂-ICES highlights the need to develop efficient H₂-SCR catalysts under conditions with elevated water content.

This study addresses two major challenges: enhancing catalytic activity and water resistance. In addition, we propose a novel strategy with *in situ* generation of NH₃ during lean H₂-SCR and utilizing the formed NH₃ in a second catalyst. Briefly, we examined Pd on different supports and found that the H₂-SCR performance was significantly enhanced when using Mn-doped TiO₂. The crucial hydrogen spillover process was facilitated, which was thoroughly investigated and experimentally validated. Moreover, this study evaluated the catalytic

performance of Pd catalysts under high humidity conditions (up to 12% water content) in the H₂-SCR process – a scenario rarely focused on in previous studies. To effectively utilize the by-product NH₃ generated from the H₂-SCR, an innovative hybrid post-treatment strategy that integrates a secondary NH₃-SCR catalyst was proposed. This approach led to an increase in NO conversion up to 78% and an improvement in N₂ selectivity to around 76%.

Experimental

Catalyst preparation

H-SSZ-13 zeolite preparation. Na-SSZ-13 (Si/Al = 9.5) was lab-synthesized with a hydrothermal method.³⁰ The details of the synthesis of Na-SSZ-13 are given in the SI. The product was obtained after the hydrothermal reaction at 160 °C for 6 days in a Teflon-lined stainless-steel autoclave and washed with Milli-Q water. It was dried at 80 °C for 12 h and calcined at 600 °C for 8 h to remove the organic template. The Na-SSZ-13 powder was collected and ion-exchanged with 0.5 M NH₄NO₃ solution (Thermo Scientific) at 80 °C for 2 h, during which 400 mL of solution containing 4 g of zeolite powder was thoroughly stirred. It was then washed with Milli-Q water, and the solids were separated from the liquid using a centrifuge. The ion-exchange and washing process was repeated twice. Afterward, the H-form SSZ-13 sample was obtained after drying in an oven at 80 °C for 12 h, followed by calcining at 550 °C for 6 h.

Preparation of Pd-based catalysts (Pd/SSZ-13, Pd/TiO₂, and Pd/ZrO₂). 1 wt% of Pd was loaded onto various supports (H-SSZ-13, TiO₂ and ZrO₂) using an incipient wetness impregnation technique. A Pd solution was prepared by mixing the Pd(NO₃)₂ precursor (Alfa Aesar 10% Pd) with Milli-Q water. Titanium oxide (400 mesh powder ground from pellets) and zirconia oxide (UEP-100) were commercially purchased from Zeolyst and Daiichi Kiegnso Kagaku Kogyo, respectively. The wet volume of each support was determined using N₂ physisorption. The Pd solution was dropped into the carrier in batches, accompanied by grinding with a pestle to achieve a homogeneous distribution.³¹ The impregnated sample was dried in an oven at 80 °C for 12 h and then calcined at 550 °C for 8 h. The prepared catalysts were systematically labelled, with the active metal (Pd) indicated before the slash and the corresponding support specified after the slash (Pd/SSZ-13, Pd/TiO₂, and Pd/ZrO₂).

Mn modified catalyst (Pd/MnTiO₂) preparation. Mn was introduced as a metal promoter to modify the Pd/TiO₂ catalyst. The Pd/MnTiO₂ catalyst was prepared using a two-step incipient wetness impregnation method.¹² First, 1 wt% Mn was loaded onto TiO₂ powder using manganese(II) nitrate hydrate (Mn(NO₃)₂·6H₂O, Sigma-Aldrich) as the Mn precursor. Specifically, 4 g of TiO₂ support was impregnated with 0.21 g of Mn(NO₃)₂·6H₂O to obtain a Mn loading of 1 wt%. After drying at 120 °C for 12 h, the resulting powder was used as the support for Pd. Subsequently, 1 wt% Pd was introduced using the same impregnation approach. In this step, 0.4 g of Pd(NO₃)₂ solution (10% Pd) was impregnated onto 4 g of MnTiO₂ to obtain a Pd loading of 1 wt%. Since the Pd loading was identical to that of the other Pd-based catalysts, the catalyst was labelled Pd/



MnTiO₂, where Pd denotes the active metal and MnTiO₂ represents the Mn-modified TiO₂ support. Finally, the catalyst was subjected to the same drying and calcination procedures as those of the other samples. 2 wt% Cu/SSZ-13 was synthesized using an ion-exchange method^{32,33} and was placed downstream from 1 wt% Pd/MnTiO₂ to utilize the ammonia produced from the Pd/MnTiO₂ catalysts during H₂-SCR for further NO_x reduction.

Washcoating process. The powder catalyst was then dispersed in a mixture of 50 wt% ethanol and 50 wt% Milli-Q water, along with a 5 wt% boehmite binder (Disperal P2, Sasol) to make a slurry. This slurry was stirred at room temperature for 12 h. The slurry was then coated onto a honeycomb monolith substrate (cordierite, $D \times L = 1.5 \text{ cm} \times 2.0 \text{ cm}$, 400 cpsi) until reaching the target loading of 300 mg. The monolith was dried in an oven at 80 °C for 12 h and calcined at 500 °C for 2 h after coating.³⁴ The wash-coated monolith was stored and ready for activity measurements.

Activity measurements

Activity test cycles were performed with a laboratory-scale flow reactor (synthetic gas bench, SGB). The monolith sample was inserted into a horizontal reactor tube with heating insulation. The inlet gas mixture was regulated using Bronkhorst mass flow controllers (MFCs), and water vapor was controlled using an evaporation and mixing system (CEM, Bronkhorst). The outlet gas composition was measured and monitored using FTIR (MKSTM Multigas 2030) and mass spectroscopy (Hiden HPR-20 QIC). It should be noted that the N₂ concentrations reported in ppm in the results and SI sections are based on calculations from FTIR data of NO, N₂O, NO₂ and NH₃, assuming 100% mass balance. The detailed test procedure and the reaction conditions are shown in Table 1. A pretreatment of the catalyst was the first step to stabilize the catalyst's state. The temperature was thereafter lowered to 80 °C and maintained for 90 min before starting the feed of the reaction gas mixture. The total flow was kept at 1200 NmL min⁻¹ in an Ar balance. The cycle test consisted of a continuous warming and cooling process from 80 °C to 500 °C with a reaction gas composition of 500 ppm NO, 5000 ppm H₂, 10% O₂, and 5–12% H₂O. Each test

cycle was repeated four times. The test results discussed in the paper were selected from the fourth cycle.

Characterization methodology

The element analysis was performed with inductively coupled plasma sector field mass spectrometry (ICP-SFMS) by ALS Scandinavia (Luleå, Sweden). The surface area and pore structure parameters were determined with the Brunauer–Emmett–Teller and *t*-plot methods by N₂ physisorption (Micromeritics Tristar II 3000 analyzer). The catalyst's crystalline structure was measured by powder X-ray diffraction (XRD) using a Bruker AXS D8 Advance. The metallic particle dispersion and mean size were determined by CO chemisorption and high-resolution transmission electron microscopy (HRTEM). HRTEM was performed on an FEI Titan 80–300 microscope equipped with a high-angle annular dark-field (HAADF) detector. Particle size analysis was conducted with the software DigitalMicrograph.

CO chemisorption measurements were performed using an ASAP2020 Plus instrument (Micromeritics). Approximately 0.1 g of powder catalyst was reduced in 1% hydrogen at 400 °C for 1 h. The adsorption isotherms of CO were measured at intervals of 25 mmHg from 100 to 600 mmHg at 35 °C.

The oxidation state of Pd was determined by X-ray photoelectron spectroscopy (XPS) analysis using a PHI5000 VersaProbe III Scanning XPS MicroprobeTM with an X-ray source of monochromatic Al K α radiation ($H\nu = 1486.6 \text{ eV}$). Data analysis was based on the calibration of the adventitious carbon peak (C 1s) at 284.8 eV using MultiPak software. A survey scan was first performed for all the samples to identify the elements in the material within the range of 0–1100 eV. Subsequently, a fine scan of Pd was performed 15 times in the range of 330–348 eV in high power mode to improve the accuracy of the spectrum due to the low loading. Since the Zr 2p and Pd 3d lines overlapped, the narrow scan range was expanded to 320–358 eV. The XPSPEAK41 software was employed for fitting the spectrum and data analysis.

The surface chemistry and molecular interactions on the catalyst powder under different gas atmospheres were studied using *in situ* diffuse reflectance infrared Fourier-transform spectroscopy (DRIFTS) spectra (Bruker Vertex 70 spectrometer). The outlet gases were measured using a mass

Table 1 The activity test cycle procedure and reaction conditions (GHSV = 20 000 h⁻¹ (STP))

Step	H ₂ -SCR experiment	Conditions
1	Pretreatment	(i) 10% O ₂ and 5% H ₂ O in Ar for 4 h at 550 °C
2	Cooling	(i) Cooling from 500 °C to 80 °C in Ar (rate: 5 °C min ⁻¹) and (ii) keeping at 80 °C for 90 min
3	Test cycle \times 4	(i) Continuous reaction from 80 °C to 500 °C (heating rate: 5 °C min ⁻¹) in a gas mixture of 500 ppm NO, 5000 ppm H ₂ , 10% O ₂ , and 5–12% H ₂ O in Ar, (ii) keeping at 500 °C with the same gas mixture for 30 min and (iii) continuous reaction from 500 °C to 80 °C (cooling rate: 5 °C min ⁻¹) in the same gas mixture and keeping at 80 °C for 90 min



spectrometer (Hiden HR20). In the first study of CO adsorption, 1000 ppm of H₂ in a total Ar balanced flow of 100 NmL min⁻¹ was passed through at 250 °C to reduce the sample. After that, the temperature was cooled to 35 °C, while exposing the sample to Ar only, to record a background spectrum. 1000 ppm CO/Ar was introduced over the sample for 60 min, and spectra were collected every 1 min. A pure Ar stream was then introduced for 1 h to observe the weaker desorption of CO species. The second study focused on the H₂-SCR without water on the Pd catalysts. In these experiments, the pretreatment was done under 10% O₂ at 300 °C for 30 min. Thereafter, the temperature was lowered to 80 °C, while flushing with Ar, to collect the background spectrum. Then, a 500 ppm NO/Ar purge was passed through for 60 min. 2000 ppm H₂ was then introduced for 60 min, which could react with the NO_x species adsorbed on the catalyst surface. Thereafter, a fresh sample was loaded and pretreated at 300 °C with 10% O₂/Ar. The system was cooled to 80 °C, while flushing with Ar, and the background spectrum was recorded. Following 500 ppm NO exposure for 1 h, 1% H₂O was added to the 500 ppm NO and kept flowing for another 1 h. Finally, the feed was switched to 2000 ppm H₂ with 1% H₂O for 60 min.

A differential scanning calorimeter (Sensys DSC calorimeter, Setaram) was used to detect the hydrogen spillover phenomenon. Yellow-colored WO_x was obtained by calcining ammonium metatungstate hydrate (Sigma-Aldrich) at 500 °C for 5 h. Approximately 20 mg of catalyst powder mixture (catalyst/WO_x = 1/8 mass ratio) was loaded inside a quartz tube and plugged with quartz wool. 1 vol% H₂/Ar at a total flow of 20 NmL min⁻¹ was introduced into the sample for 1 h after the temperature was elevated to 200 °C. The outlet gases were measured with a mass spectrometer. The samples after H₂ reduction were compared to observe the color change, since WO_x is yellow, while H_xWO₃ which is formed during reduction is blue.

Temperature-programmed desorption of ammonia (NH₃-TPD) was conducted using the same setup. Initially, the catalyst samples were pretreated with 20 NmL min⁻¹ Ar at 300 °C for 1 h. Following that, 2000 ppm of NH₃/Ar with a total flow of 20 NmL min⁻¹ at 100 °C was added for 2 h until NH₃ was saturated on the sample. Then, an Ar flow was used to purge the physisorbed NH₃, and the temperature was elevated to 700 °C at a ramping rate of 10 °C min⁻¹ in pure Ar for examining the ammonia desorption. The outlet gas was measured and monitored using a mass spectrometer (Hiden, HPR-20 QIC). The acidity analysis was performed using an area integration method compared with the calibration of NH₃.

Results and discussion

Catalyst characterization

After loading 1 wt% Pd on the support (SSZ-13, TiO₂, MnTiO₂, and ZrO₂), their original crystal structures were retained (Fig. S1). All the XRD patterns were compared and confirmed with the reference patterns (baddeleyite_ZrO₂ #37-1484, anatase_TiO₂ #21-1272, and chabazite_CHA #89-0735).³⁵ Fig. S1 also shows the XRD peak positions of PdO particles. Only the first characteristic peak of PdO at around 34° can be faintly observed in Pd/SSZ-13 and the two TiO₂ samples, indicating

Table 2 Physical properties of 1 wt% loaded Pd-based catalysts

	Pd (wt%)	Surface area (m ² g ⁻¹)	Pore volume (cm ³ g ⁻¹)	Mean particle size (nm)
Pd/SSZ-13	0.80	613.8	0.43	1.7 ^a
Pd/TiO ₂	0.88	30.9	0.13	16.0 ^b
Pd/MnTiO ₂	0.71	28.8	0.12	11.8 ^b
Pd/ZrO ₂	1.10	62.0	0.26	12.6 ^b

^a Particle size of Pd/SSZ-13 is measured from CO chemisorption.

^b Particle size was measured with TEM.

that Pd primarily exists in the form of oxides on the support surface. The physical properties of each sample are listed in Table 2. Unlike the three metal oxide supports, SSZ-13, as a small-pore zeolite, has the largest surface area of 613.8 m² g⁻¹ and the smallest pore size.³⁶ Due to its complex three-dimensional topological structure, it possesses a large pore volume³⁷ (0.43 cm³ g⁻¹).

The mean particle sizes of Pd were measured by TEM (Table 2), except for Pd/SSZ-13 where CO chemisorption was used. Clearly, Pd/SSZ-13 exhibited the smallest particle size compared to the others. For the oxide-supported catalysts, 50–100 randomly selected particles were measured to calculate Gaussian distributions and generate histograms, embedded in Fig. 1. As shown in Fig. 1d, HRTEM mode was used for Pd/ZrO₂ instead of HAADF-STEM due to the close atomic numbers of Pd and Zr, making it difficult to clearly distinguish them based on brightness contrast in the dark-field. Particle sizes calculated from TEM images were 16.6 nm for Pd/TiO₂, 11.8 nm for Pd/MnTiO₂, and 12.6 nm for Pd/ZrO₂.

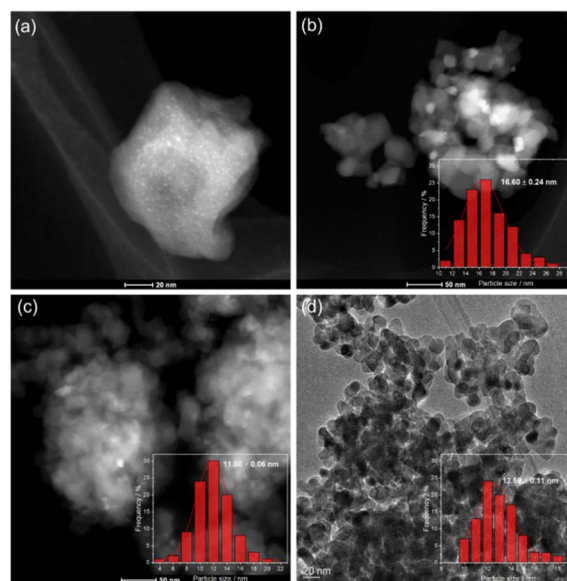


Fig. 1 HAADF-HRTEM images of (a) 1 wt% Pd/SSZ-13, (b) 1 wt% Pd/TiO₂, (c) 1 wt% Pd/MnTiO₂ and (d) 1 wt% Pd/ZrO₂ catalysts. Insets in panel b–d show Pd particle size distribution histograms of the Pd/metal oxide catalysts.



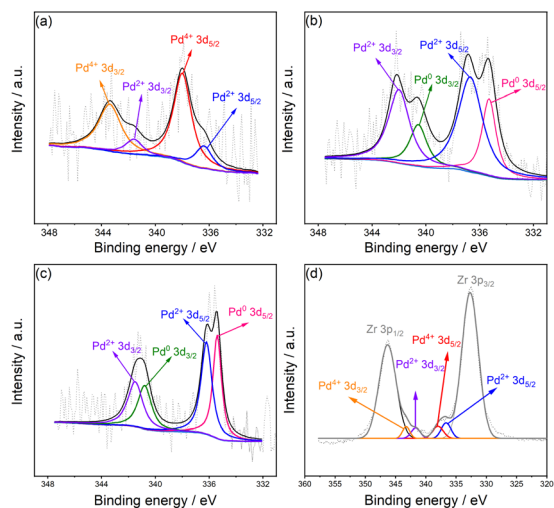


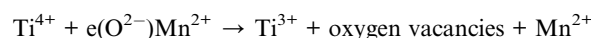
Fig. 2 Pd 3d X-ray photoelectron spectra of (a) 1 wt% Pd/SSZ-13, (b) 1 wt% Pd/TiO₂, (c) 1 wt% Pd/MnTiO₂, and (d) 1 wt% Pd/ZrO₂ catalysts.

Both the XRD and BET results show no significant differences between Pd/TiO₂ and Pd/MnTiO₂ catalysts. However, Fig. 1b and c demonstrate a decreased Pd particle size with the addition of Mn on the TiO₂ support. The introduction of MnO_x could structurally increase the surface heterogeneity by creating additional facets and anchoring sites, thereby effectively separating Pd species.³⁸ Numerous studies have confirmed a synergistic effect between Pd and manganese oxides.^{12,39} This synergy suggests that the interactions between Pd and Mn oxides, particularly through Pd–O–Mn interfacial structures,⁴⁰ play a key role in stabilizing Pd species and suppressing their surface migration and aggregation during synthesis and pretreatment. As a result, the Pd/MnTiO₂ catalyst exhibits smaller Pd particle sizes and improved dispersion compared with the unmodified Pd/TiO₂ catalyst.

The oxidation states of Pd in the four catalysts were determined by X-ray photoelectron spectroscopy. The peak deconvolution and fitting are shown in Fig. 2, and the corresponding results are listed in Table 3. The binding energies near 336.5 eV and 341.75 eV (with a fixed separation of 5.26 eV) correspond to the Pd 3d_{5/2} and Pd 3d_{3/2} peaks of Pd²⁺ species, with a fixed peak area ratio of 3 : 2.⁴¹ Another pair of peaks at 338.0 eV and 343.3 eV is attributed to Pd⁴⁺ species. Therefore, Pd exists as both Pd²⁺ and Pd⁴⁺ in the Pd/ZrO₂ and Pd/SSZ-13 catalysts following the oxidative pretreatment. It is noteworthy that there is significant overlap between the Zr 3p and Pd 3d peaks within the same binding energy range, which may affect spectral

interpretation. For the Pd/SSZ-13 sample, about 80.5% was assigned to PdO₂ oxides; however, it should be noted that the noise level is high (grey dotted line in Fig. 2), which could be due to the low palladium loading in combination with ion-exchanged Pd.

The XPS results provide strong support for the strong metal–support interaction (SMSI) effect on the TiO₂-support catalysts. TiO₂'s reducibility promotes electron transfer between the support and the dispersed metal, which is considered a key origin of SMSI effect and may also manifest as partial encapsulation of metal particles by Ti oxides overlayers.^{42–44} Instead of the Pd⁴⁺ peaks, a pair of peaks appeared at much lower binding energies of 335.3 eV/340.6 eV and 335.4 eV/340.8 eV, which were assigned to Pd⁰ species.^{43,45,46} These findings indicate that even after an oxidative pretreatment, 31.8% of Pd remained in the metallic state (Pd⁰) in the Pd/TiO₂ catalyst, likely as a result of the SMSI effect which limits oxygen adsorption on the Pd surface. Upon doping with Mn, the proportion of metallic Pd even further increased to 46.7%. In addition to changes in Pd oxidation states, a shift in the valence state of Ti was also observed in Fig. S2. As shown in Table S1, Pd/TiO₂ contained approximately 78.1% of Ti⁴⁺ and 21.9% of Ti³⁺, whereas after Mn doping, the composition shifted to 42.7% of Ti³⁺ and 57.3% of Ti²⁺.⁴⁷ This observation is consistent with previous studies reporting that Mn partially substitutes Ti in the TiO₂ lattice.^{48–50} The substitution of Ti⁴⁺ by Mn²⁺ introduces a charge imbalance, which is compensated for by the formation of oxygen vacancies. As a result, Ti that was originally coordinated with lattice oxygen is reduced to lower oxidation states. This mechanism was summarized by Nguyen *et al.* as follows:⁵⁰



To further support this interpretation, additional O 1s XPS spectra were analyzed (Fig. S3). Two main peaks are observed at 529.4–529.6 eV and 531.1–531.3 eV, which are attributed to lattice O²⁻ in TiO₂ and oxygen vacancies or absorbed oxygen species, respectively.^{51–53} It should be noted that an alternative interpretation assigns the O 1s signal in the 531–532 eV range to surface hydroxyl groups formed from ambient water.⁵⁴ In the present study, the enhanced intensity of the peak at 531.3 eV is primarily attributed to an increased concentration of oxygen vacancies induced by Mn substitution and the associated charge-compensation effects. Meanwhile, the decreased intensity of the lower binding energy peak suggests a reduction in lattice oxygen. Moreover, both oxygen peaks exhibit a shift of

Table 3 X-ray photoelectron spectroscopy results of Pd 3d in the catalysts

Sample	Pd ⁰		Pd ²⁺		Pd ⁴⁺	
	BE/eV (3d _{5/2} /3d _{3/2})	Fraction/%	BE/eV (3d _{5/2} /3d _{3/2})	Fraction/%	BE/eV (3d _{5/2} /3d _{3/2})	Fraction/%
Pd/TiO ₂	335.3/340.6	31.8	336.7/342.0	68.2		
Pd/MnTiO ₂	335.4/340.8	46.7	336.2/341.5	53.3		
Pd/ZrO ₂			336.7/341.7	53.8	338.0/343.3	46.2
Pd/SSZ-13			336.4/341.6	19.5	338.0/343.4	80.5



approximately 0.2 eV toward higher binding energies, confirming that Mn incorporation alters the local electronic environment, leading to a partial reduction of both Pd and Ti species.^{55,56}

The acid properties of the catalysts were determined using NH₃-TPD (Fig. S4). It is evident that the SSZ-13 support exhibits by far the highest acid site density and the strongest acidity, as indicated by NH₃ desorption occurring with two desorption peaks at 205 °C and 425 °C, respectively. Desorption of NH₃ over 400 °C suggests strong adsorption binding of NH₃, typically associated with Brønsted acid sites.⁵⁷ Therefore, it can be inferred that SSZ-13, due to its stronger acidity, is capable of storing ammonia, that possibly generates during the H₂-SCR process. In addition, the desorption peaks observed between 100 and 300 °C are attributed to weakly bound ammonia, which generally originates from Lewis acid sites. Among the metal oxide-supported catalysts, ZrO₂ exhibits a slightly higher concentration of Lewis acid sites compared to the TiO₂-supported catalysts. This also implies that catalysts supported by oxides with weaker acidity tend to store less ammonia, which will be further discussed in relation to catalytic performance.

Hydrogen spillover effect

The hydrogen spillover effect on the catalysts was determined using the same equipment as that for NH₃-TPD. This phenomenon was investigated by reducing a mixture of yellow-colored WO₃ with the catalyst sample. The hydrogen spillover leads to the formation of blue H_xWO₃ after the reduction treatment, applying the method developed by Yu *et al.*⁵⁸ Among the four catalysts, Pd/TiO₂ and Pd/SSZ-13 exhibited the lightest colors (Fig. S5a), indicating the weakest H spillover effect. However, the addition of Mn to Pd/TiO₂ enhanced the spillover, as evident by a darker blue color. The redox activity of Mn (Mn²⁺, Mn³⁺, and Mn⁴⁺) modulates the surface structure and electronic properties of TiO₂. From an electronic perspective, Mn incorporation promotes the formation of a higher fraction of metallic Pd species, as supported by the XPS results. From a structural perspective, the introduction of Mn creates a more heterogeneous surface and, due to the sequential impregnation method in which Mn is loaded onto TiO₂ prior to Pd, can spatially separate Pd species from the TiO₂ surface. This partial separation may weaken the SMSI effect between Pd and TiO₂, thereby reducing the encapsulation or coverage of Pd by TiO₂ overlayers. Therefore, the increased fraction of metallic Pd promotes H₂ dissociation, while the modified surface structure facilitates the migration of hydrogen atoms. Additionally, Zhou *et al.* revealed that H spillover is more pronounced on smaller Ru particles.⁵⁹ As Fig. 1 demonstrates, Mn addition improved Pd dispersion and reduced particle size on TiO₂, which likely contributed to the enhanced spillover. The Pd/ZrO₂ sample showed an intermediate color, suggesting a moderate spillover effect. The mechanism of H spillover differs between non-reducible zeolites and reducible metal oxides such as TiO₂ and ZrO₂.¹⁵ On zeolites, the process is primarily governed by the conjugated interaction between Brønsted (BAS) and Lewis (LAS) acid sites. In contrast, hydrogen migration over oxide supports

proceeds through the transfer of H/H pairs between LASs. In addition, due to the unique microporous structure of zeolites, hydrogen spillover is inherently restricted and localized.^{60,61} Due to the relatively small color differences among the samples as shown in Fig. S5a, the RGB color components were extracted, and the average proportion of the blue channel was quantitatively calculated (Fig. S5b). The resulting blue fractions for the four catalysts are 58% for Pd/SSZ-13, 72% for Pd/ZrO₂, 68% for Pd/TiO₂, and 74% for Pd/MnTiO₂.

CO adsorption was examined on the surfaces of the three oxide-supported catalysts, with spectra collected after 60 min of CO exposure as shown in Fig. 3. For the Pd/ZrO₂ catalyst, peaks were observed at 2085 cm⁻¹, 1980 cm⁻¹, 1930 cm⁻¹, 1630 cm⁻¹, 1568 cm⁻¹, 1425 cm⁻¹, 1340 cm⁻¹, and 1220 cm⁻¹. The IR peaks can be grouped into two regions: 2085–1930 cm⁻¹, corresponding to CO adsorbed on Pd species, and 1630–1220 cm⁻¹, corresponding to CO adsorbed on the oxide supports in various forms. The band at 2085 cm⁻¹ is attributed to terminal carbonyls adsorbed on the Pd⁰ defects.^{62,63} The peak at 1930 cm⁻¹ corresponds to bridge-bonded CO on Pd (111) planes, while the 1980 cm⁻¹ peak likely arises from CO adsorbed on Pd facets or bridge-bonded CO at edge sites.^{63,64} Three sharp peaks at 1630 cm⁻¹, 1425 cm⁻¹, and 1220 cm⁻¹ are assigned to surface bicarbonate species on the bulk oxides, while weaker peaks at 1568 cm⁻¹ and 1340 cm⁻¹ are attributed to formate species.⁶⁵ In contrast, the Pd/TiO₂ catalyst exhibits minimal molecular adsorption, consistent with the SMSI effect discussed previously. The CO adsorption behavior on Pd/TiO₂ is influenced by the TiO₂ crystal phase (anatase or rutile) and pretreatment conditions. According to Zhou *et al.*, Ru/anatase-TiO₂ catalysts subjected to air annealing at 400 °C and H₂ reduction at 300 °C showed no distinct CO peaks in DRIFTS spectra, whereas rutile-TiO₂ or differently treated anatase-TiO₂ catalysts showed varied performance.⁶⁶ In our case, the catalyst is based on anatase-TiO₂ (confirmed by the XRD results), and the air calcination and pre-treatment in an oxygen-rich environment resemble the conditions used in Zhou's study, explaining the absence of distinct CO peaks. However, Mn

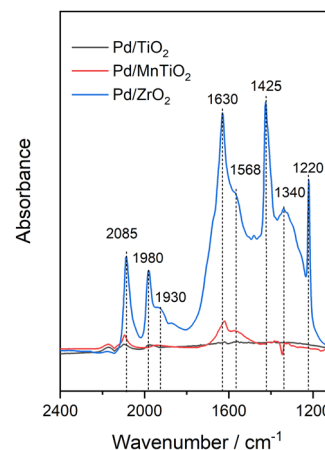


Fig. 3 CO DRIFTS spectra recorded on pre-treated 1 wt% Pd/TiO₂, 1 wt% Pd/MnTiO₂, and 1 wt% Pd/ZrO₂ catalysts.



incorporation significantly altered the surface adsorption properties of Pd/TiO₂, leading to the emergence of IR peaks at 2085 cm⁻¹, 1630 cm⁻¹, and 1568 cm⁻¹. The 2085 cm⁻¹ peak corresponds to linear CO adsorption on Pd⁰, consistent with the Pd3d XPS results showing increased Pd⁰ content upon Mn doping. A small peak at 2170 cm⁻¹ is attributed to CO adsorption on Pd ions.^{67,68} Notably, a negative peak at around 1340 cm⁻¹ is observed, indicating desorption of CO₂ originally adsorbed from air on the fresh catalyst. Based on the CO-DRIFTS results, CO is predominantly adsorbed on both Pd and the support surface in the case of Pd/ZrO₂, whereas TiO₂-supported catalysts shows limited CO adsorption on Pd. ZrO₂ is known to act as an oxygen supplier due to its high oxygen mobility, which significantly enhances CO adsorption also on the ZrO₂ support.^{69,70} In contrast, the TiO₂ surface has a higher oxygen density and forms stronger metal-support interactions, which suppress CO adsorption on Pd sites.⁴⁴ The addition of Mn modifies the oxygen structure and electronic structure, which has been confirmed by the XPS results and discussed in previous sections, thereby enhancing surface adsorption properties.

Building on the CO-DRIFTS results, a similar trend can be suggested for the hydrogen spillover behavior. According to the mechanism of hydrogen spillover, hydrogen molecules dissociate on active metal sites and subsequently migrate onto the support surface. The SMSI of Pd/TiO₂ limits the surface adsorption and migration of hydrogen species. However, combining the XPS results reveals that TiO₂-supported catalysts contains metallic Pd species. Mn doping further increases the proportion of metallic Pd and optimizes the electronic structure and surface oxygen structure of the catalyst, thereby enhancing the storage and migration of hydrogen atoms on the surface. In Pd/ZrO₂, hydrogen spillover is facilitated by the oxygen-rich nature of the support, which allows for greater accommodation of hydrogen atoms.

In situ DRIFT study of NO-H₂

In situ DRIFTS studies of NO reduction by H₂ over the Pd/ZrO₂ catalyst were performed to investigate the surface-adsorbed species and intermediates involved in the reaction. From the CO DRIFTS data, there were fewer adsorbed species observed on

TiO₂-supported catalysts; therefore, Pd/ZrO₂ was selected for this study. The detailed experimental procedure is described in the Characterization methodology. Fig. 4a illustrates the DRIFTS spectrum following H₂ introduction after NO adsorption under dry conditions, covering a 60-minute reaction period. At the initial stage, prominent bands appear at 1628 cm⁻¹ and 1219 cm⁻¹, corresponding to bridged nitrates and weakly adsorbed NO₂⁻ species, respectively.⁷¹⁻⁷⁵ After approximately 30 min of H₂ exposure, a new band emerges at 1800 cm⁻¹, which gradually diminishes over time. This band is attributed to nitrosyl species (NO-metal), previously identified as key reactive intermediates in the H₂-SCR pathway.⁷⁶ The transient nature of this band indicates that nitrosyl species are formed on Pd sites and subsequently consume during the reaction. Notably, this feature is absent under wet conditions, as shown in Fig. S6b, indicating that water inhibits the formation of nitrosyl species. This inhibition can be attributed to the competitive adsorption of water molecules on Pd active sites, which suppresses NO adsorption and thus hinders the formation of NO-metal nitrosyl intermediates. As H₂ exposure continues for 60 min, additional peaks appear at 1610 cm⁻¹, 1585 cm⁻¹, 1518 cm⁻¹, 1288 cm⁻¹, and 1254 cm⁻¹, suggesting the formation and transformation of various surface nitrate species. The peaks at 1585 cm⁻¹, 1518 cm⁻¹, 1288 cm⁻¹, and 1254 cm⁻¹ are assigned to monodentate and bidentate nitrates, which could accumulate stably on the surface.^{71,73,75,77} Additionally, the band at 1610 cm⁻¹ is attributed to adsorbed H₂O.^{5,78} Fig. S6a shows NO adsorption under wet conditions. Upon water addition, the surface nitrate species are altered, with bridged nitrates converting into bidentate nitrates. Thus, the presence of water promotes the transformation of NO_x species into more stable nitrate species rather than reactive nitrosyl intermediates. The peak at 1292 cm⁻¹ becomes significantly more intense compared to that under dry conditions (Fig. S6b and 4a) and shifts from 1288 cm⁻¹, indicating a more uniform adsorption configuration and stronger bond, stabilized by the presence of water.

In the high wavenumber region of 2000–4000 cm⁻¹ (Fig. 4b and c), broad O–H stretching vibrations from water are found and show a more significant increase with dry conditions with time (blue) compared to the wet conditions (green). Apart from this, two sharp bands appear at 3336 cm⁻¹ and 3268 cm⁻¹, which are characteristic of NH₃ adsorption on Lewis acid sites.^{74,77,79} It is important to note that H₂-SCR inherently generates water and under conditions of additional water co-feeding, these NH₃-related peaks become significantly broader and less distinct (Fig. 4c). This implies that NH₃ formation is inhibited under wet conditions, likely due to competitive adsorption effects. Such inhibition may also contribute to the observed suppression in overall H₂-SCR activity in the presence of water.

Activity performance

The NO conversion and N₂ selectivity of the catalysts with different supports were evaluated by flow reactor cycle tests. The water content was gradually increased (5%/7.5%/10%/12%),

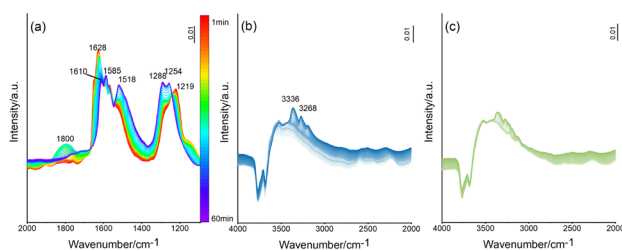


Fig. 4 *In situ* DRIFTS spectra for the Pd/ZrO₂ catalyst exposed to 2000 ppm H₂ for 1 h after flowing 500 ppm NO for 1 h in the regions (a) 1100–2000 cm⁻¹ and (b) 2000–4000 cm⁻¹; (c) 2000 ppm H₂ exposure for 1 h after flowing 500 ppm NO + 1% H₂O within the region of 2000–4000 cm⁻¹.



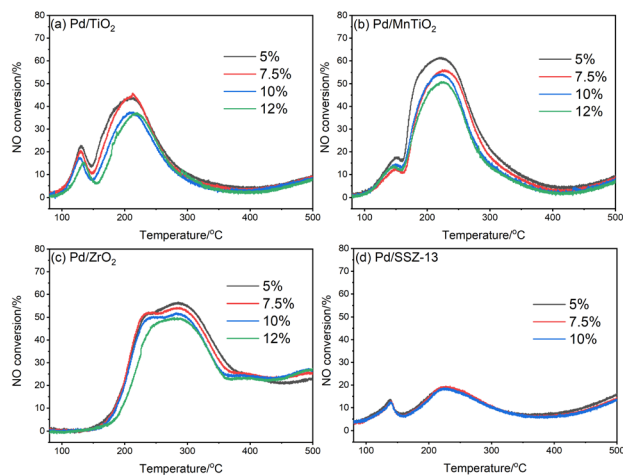


Fig. 5 NO conversion profiles with varying water content for (a) 1 wt% Pd/TiO₂, (b) 1 wt% Pd/MnTiO₂, (c) 1 wt% Pd/ZrO₂ and (d) 1 wt% Pd/SSZ-13 catalysts (GHSV = 20 000 h⁻¹ (STP); gas inlet: 500 ppm NO, 5000 ppm H₂, 10% O₂, and 5/7.5/10/12% H₂O balanced in Ar; 80–500 °C with a heating rate of 5 °C min⁻¹).

except for Pd/SSZ-13, which was examined for 5%/7.5%/10% H₂O. Each cycle was repeated four times. All data presented in Fig. 5 were extracted from the fourth cycle. Among all the samples, the SSZ-13-supported Pd catalyst showed minimal inhibition by water at concentrations between 5% and 10% (Fig. 5d). Fig. S7 compares the performance of Pd/SSZ-13 for H₂-SCR under anhydrous and 5% water conditions. N₂ was measured by mass spectrometry, while other gases were analyzed by IR spectroscopy. The overall trends were similar in both environments. However, the NO consumption peak at around 240 °C was suppressed in the presence of water, accompanied by a small reduction in N₂ production. The results show that while water inhibits reactivity on Pd/SSZ-13, further increases in water content do not significantly affect performance (Fig. 5d). It is well-known that water can readily adsorb on zeolites, as commonly observed in passive NO_x adsorbers (PNA) studies.⁸⁰ Moreover, NO adsorption is reduced in the presence of water for Pd/SSZ-13.⁸⁰ These results are in line with our results where a decline in SCR activity is observed when adding water. However, when increasing the water concentration, no further water inhibition is observed. It is likely that 5% H₂O is sufficient to saturate the zeolite pores, which may explain the absence of any further decrease in activity at higher water contents.

Compared to the zeolite-supported catalyst, the Pd on metal oxides exhibited much higher activity for H₂-SCR (Fig. 5a–c). Under 5% water conditions, the maximum NO conversion reached 56% for Pd/ZrO₂, 44% for Pd/TiO₂, and 61% for Pd/MnTiO₂. From a water resistance perspective, increasing the water content from 5% to 12% led to a clear decline in reactivity. For Pd/TiO₂, the maximum NO conversion dropped from 44% to 36%, with a corresponding temperature shift of approximately 5 °C. Although Pd/ZrO₂ showed a smaller decrease from 56% to 50%, a shift toward higher temperatures was also observed, showing reduced catalytic activity. Pd/MnTiO₂

exhibited a decrease in maximum NO conversion from 61% to 50%. Fig. S8 shows the data from all cyclic reaction tests (four cycles per condition) for the three oxide-supported catalysts. For Pd/TiO₂, NO conversion progressively declined with each cycle and increasing water content, indicating its instability under humid conditions. However, after the addition of Mn, the catalyst exhibited quite stable performance once the water content reached 10%, with only a slight drop. In the case of Pd/ZrO₂, the reaction performance remained quite similar across all four cycles under each water content condition, demonstrating good cycling stability. Nevertheless, a clear inhibitory effect of water was observed as increased humidity reduced overall catalytic activity. This inhibition arises from the competitive adsorption of water molecules on Pd active sites, which hinders the adsorption and activation of NO and H₂.⁸¹ Possibly, this also weakens the H spillover effect by reducing H₂ activation.

Interestingly, all catalysts except Pd/ZrO₂ have two characteristic NO conversion peaks: a small one at lower temperatures and a larger one at higher temperatures and a relatively low activity temperature range of about 80–150 °C, which was described as volcano-type behavior (the first peak). Peng and his colleagues introduced aluminum as a promoter into a Pd/CeZrO₄ support, resulting in enhanced activity, explained by increased hydrogen spillover.¹⁹ Based on previous characterization, Pd/ZrO₂ and Pd/MnTiO₂ exhibited greater hydrogen spillover compared to Pd/TiO₂. The higher dispersion and smaller particle size of Pd in Pd/ZrO₂ and Pd/MnTiO₂ relative to Pd/TiO₂ may also contribute to their superior catalytic activities. Pd/MnTiO₂ exhibits an attenuated SMSI effect, which results in a higher proportion of metallic Pd species, more active for H₂ activation. Additionally, the presence of multivalent Mn creates a highly tunable electronic environment that modifies surface properties, further enhancing the H migration.^{82,83}

Although the enhancement of hydrogen spillover and the improved dispersion of Pd particles both contribute to higher overall catalytic activity, we propose that the two distinct NO conversion peaks observed over Pd/TiO₂ at different temperatures are related to the presence of different Pd species. In contrast, Pd/ZrO₂ does not exhibit a low-temperature peak. The presence of metallic Pd in TiO₂-based Pd catalysts is considered to play a key role in low-temperature activity. Moreover, Pd/MnTiO₂ also contains metallic Pd species, as evidenced by the XPS results. Combined with the enhanced hydrogen spillover and improved Pd dispersion, this leads to increased activity. The double-peak behavior observed over Pd/SSZ-13 is also attributed to different reaction sites, since Pd/SSZ-13 includes both Pd particles and ion-exchanged Pd. We propose that the low-temperature peak originates from ion-exchanged Pd species in the zeolite, which significantly promote NO adsorption.⁸⁴

Fig. S9 and S10 show the effluent gas concentrations from the catalysts measured during H₂-SCR in the presence of 5% and 10% water. Although the zeolite-supported catalysts exhibited higher N₂ selectivity, the oxide-supported catalysts demonstrated greater overall activity and N₂ yield, indicating stronger potential for further development. As a result, cycle tests for the zeolite catalysts were conducted only up to a water



content of 10%. At temperatures over 400 °C, oxidation reactions occurred across all catalysts, with NO₂ becoming the main product. By examining the NO concentrations (black curves) in both figures, it is evident that the addition of Mn significantly enhances NO conversion. A comparison between Pd/MnTiO₂ and Pd/ZrO₂ reveals that Pd/MnTiO₂ produces N₂, NH₃, and N₂O within the active temperature range. Notably, Pd/ZrO₂ not only generates a small amount of NO₂ within the H₂-SCR temperature range but also produces significantly more NO₂ at higher temperatures compared to the other catalysts, indicating its stronger oxidation capability.

Another observation can be made from a careful examination of the product formation profiles. Over Pd/MnTiO₂, the N₂ formation curves at water concentrations of 5% and 10% show only a small difference as the temperature increases, while the NH₃ formation is slightly suppressed. In contrast, over Pd/ZrO₂, increasing the water concentration from 5% to 10% leads to an increase in NH₃ formation in the temperature range of 200–300 °C, accompanied by a concurrent decrease in N₂ formation. These results indicate that, during the H₂-SCR reaction over Pd/MnTiO₂, the N₂ concentration remains more stable at high water concentrations. This behaviour suggests that the higher fraction of metallic Pd enhances H₂ dissociation, generating a larger number of active hydrogen atoms that can counteract the inhibitory effects of competitive water adsorption.

NH₃ was a prominent byproduct at around 230–250 °C from the Pd/MnTiO₂ catalyst at both 5% and 12% water feed (Fig. S9b and S10b). As is well known, ammonia can serve as an effective reducing agent for NO_x reduction.^{83,85} Therefore, the Pd/MnTiO₂ monolith was combined in series with a conventional NH₃-SCR monolith catalyst, containing Cu/SSZ-13, positioned downstream. Experiments were conducted under identical space velocity and reaction conditions. Since the total monolith volume was doubled, the total feed flow rate was also doubled to maintain the same space velocity. As shown in Fig. 6, the NO conversion was successfully enhanced, reaching a maximum of 78% at 230 °C with 5% water. This resulted in the formation of 148 ppm N₂ and 48 ppm N₂O, corresponding to an N₂ selectivity of 76%. These results indicate that the NH₃ generated by the upstream Pd/MnTiO₂ was completely consumed for NO_x reduction, leading to an approximately 20% improvement in NO conversion *via* NH₃-SCR over the Cu-based catalyst. However, when the water content was increased to 12%,

catalytic activity was suppressed. The maximum NO conversion dropped from 78% to 62%, mainly due to the competitive adsorption of water on the active surface sites. This inhibited the H₂-SCR performance of the Pd/MnTiO₂ catalyst, reducing NH₃ generation and consequently lowering the NH₃-SCR efficiency of the downstream Cu catalyst.

Further optimization of this dual catalyst system could focus on improving the water tolerance and hydrogen spillover efficiency of the upstream Pd/MnTiO₂ catalyst and enhancing spatial integration between the two components to maximize NH₃ utilization. This could further mitigate water inhibition and strengthen overall synergistic performance under high water vapor conditions.

Conclusions

This study compared the H₂-SCR performance of four catalysts: Pd supported on TiO₂, ZrO₂, SSZ-13, and Mn-doped TiO₂. Among these, the oxide-supported catalysts exhibited significantly higher catalytic activity than the zeolite-supported catalyst, with maximum NO conversions reaching 61% for Pd/MnTiO₂ and 56% for Pd/ZrO₂. However, in terms of water resistance, the zeolite-based catalyst outperformed the oxide-supported catalysts, which can be attributed to differences in the distribution of Pd species and the particle sizes on the supports. The inhibitory effect of water was confirmed by *in situ* DRIFTS analysis, showing that the formation of active nitrosyl species and NH₃ was suppressed, while stable surface bidentate nitrate species were promoted in the presence of water. When the water content increased from 5% to 12%, the maximum NO conversion of Pd/MnTiO₂ decreased from 61 to 50%, yet the active temperature window remained almost unchanged. XPS measurements revealed a higher proportion of metallic Pd with Mn addition, along with an increased presence of low-valence Ti species, and a reduction in lattice oxygen content. These changes can lead to the formation of active oxygen vacancies or surface-adsorbed oxygen species. Therefore, through the combined modulation of the electronic and surface structures, both H₂ dissociation and migration are enhanced, thereby promoting hydrogen spillover. Additionally, we suggest that the high activity of Pd/ZrO₂ stemmed from good hydrogen storage and transfer capabilities is related to its oxygen-rich properties.

Analysis of the reaction products revealed that NH₃ was one of the main byproducts formed during the H₂-SCR process over Pd/MnTiO₂. To effectively utilize this byproduct, a downstream Cu/SSZ-13 monolith catalyst was introduced to establish a combined H₂-SCR and NH₃-SCR reaction system. This integrated configuration resulted in an enhanced maximum NO conversion of 78% under 5% water vapor conditions. Moreover, NH₃ was completely consumed, with N₂ and N₂O being the only detected products.

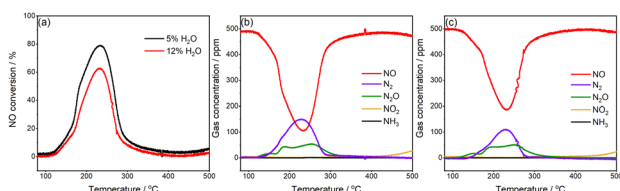


Fig. 6 Pd/MnTiO₂ and Cu/SSZ-13 monolith catalysts in series; (a) NO conversion profiles of 1 wt% Pd/MnTiO₂ + 2 wt% Cu/SSZ-13 with 5% water and 12% water contents and the effluent gas concentration profiles with (b) 5% water and (c) 12% water (GHSV = 20 000 h⁻¹ (STP); gas inlet: 500 ppm NO, 5000 ppm H₂, 10% O₂, and 5/12% H₂O balanced in Ar; T: 80–500 °C heating rate: 5 °C min⁻¹).

Conflicts of interest

There are no conflicts to declare.



Data availability

The data herein includes the data collected and analyzed to support this study, including the data underlying the main text and the supplementary information (SI). All data have been packaged as a single dataset and deposited in the Zenodo repository. The dataset is publicly available at the following DOI: <https://doi.org/10.5281/zenodo.18432637>. Supplementary information: the experimental preparation procedures of the zeolite, as well as characterization data and figures from XRD, XPS, NH₃-TPD, and DRIFTS measurements, together with additional catalytic activity results obtained from the flow reactor experiments. See DOI: <https://doi.org/10.1039/d6ta00954a>.

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