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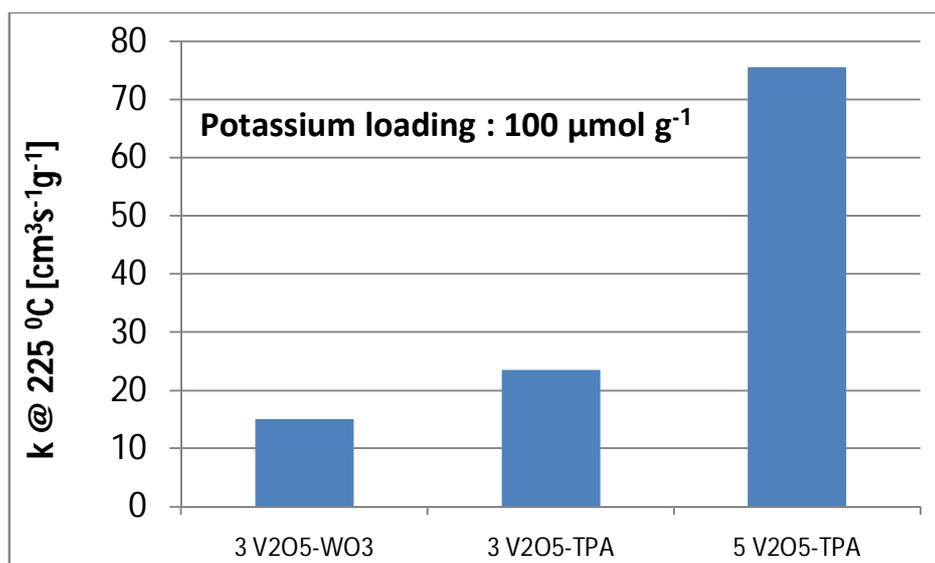
**Promoted V<sub>2</sub>O<sub>5</sub>/TiO<sub>2</sub> catalysts for selective catalytic reduction of NO  
with NH<sub>3</sub> at low temperatures**

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**Graphical abstract**



## Highlights

- Increased low temperature deNO<sub>x</sub> activity by increasing vanadia loading (3 to 6 wt.%)
- Increased K tolerance by increasing vanadia loading from 3 to 6 wt.%.
- Increased K tolerance by using heteropoly acids instead of WO<sub>3</sub>.

## Abstract

The influence of varying the V<sub>2</sub>O<sub>5</sub> content (3-6 wt.%) was studied for the selective catalytic reduction (SCR) of nitrogen oxides by ammonia on heteropoly acid (HPA)- and tungsten oxide (WO<sub>3</sub>)-promoted V<sub>2</sub>O<sub>5</sub>/TiO<sub>2</sub> catalysts. The SCR activity and alkali deactivation resistance of HPA-promoted V<sub>2</sub>O<sub>5</sub>/TiO<sub>2</sub> catalysts was found to be much higher than for WO<sub>3</sub>- promoted catalysts. By increasing the vanadium content from 3 to 5 wt.% the catalysts displayed a two fold increase in activity at 225 °C and retained their initial activity after alkali doping at a molar K/V ratio of 0.181. Furthermore, the catalysts were characterized by N<sub>2</sub> physisorption, XRPD, NH<sub>3</sub>-TPD, H<sub>2</sub>-TPR, Raman, FTIR and EPR spectroscopy to investigate the properties of the catalysts. XRPD, Raman and FTIR showed that promotion with 15 wt.% HPA does not cause V<sub>2</sub>O<sub>5</sub> to be present in crystalline form, also at a loading of 5 wt.% V<sub>2</sub>O<sub>5</sub>. Hence, use of HPAs does not cause increased N<sub>2</sub>O formation or unselective oxidation of NH<sub>3</sub>. NH<sub>3</sub>-TPD showed that promotion by HPA instead of WO<sub>3</sub> causes the catalysts to possess a higher number of acid sites, both in fresh and alkali poisoned form, which might explain their higher potassium tolerance. *Ex-situ* EPR spectroscopy revealed that HPA-promoted catalysts have a higher V<sup>4+</sup>/V<sub>total</sub> ratios than their WO<sub>3</sub>-promoted counterparts. H<sub>2</sub>-TPR suggests that HPAs do not have a beneficial effect on the V<sup>5+</sup>-V<sup>3+</sup> redox system, relative to WO<sub>3</sub>.

*Keywords:* SCR of NO with NH<sub>3</sub>; V<sub>2</sub>O<sub>5</sub>; Potassium poisoning

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## 1. Introduction

The selective catalytic reduction (SCR) of NO with NH<sub>3</sub> is widely employed for reduction of NO<sub>x</sub> emissions from stationary sources like gas, oil and coal-fired power plants. The most well-known and commercially applied catalyst is vanadium well-dispersed on a titania support and promoted by WO<sub>3</sub>- (V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub>/TiO<sub>2</sub>) [1-3]. The commercial catalyst has high activity and N<sub>2</sub> selectivity in NH<sub>3</sub>-SCR at 300-400 °C. To achieve this temperature the commercial catalysts are usually placed in the high-dust position, since the low dust-position in the flue gas stream requires reheating of the flue gas [4].

Applying NH<sub>3</sub>-SCR for flue gas cleaning from biomass and waste incineration plants demands a highly active catalyst, which is able to withstand the high content of ash (impurities include K, Na and Ca) and SO<sub>2</sub> in the flue gas. The rate of deactivation is especially high for biomass and waste incineration plants [5, 6], and therefore the tail-end configuration downstream of the flue gas desulphurization unit is recommended.

At the tail-end position the lower levels of SO<sub>2</sub> in the flue gas allow the use of catalyst formulations with higher V<sub>2</sub>O<sub>5</sub> contents and the low levels of dust allow the use of monoliths with a high geometric surface area. Further, the lifetime of the catalyst

is increased due to less deposition of dust and ammonium sulfates [7]. However, for tail-end configuration it is necessary to install a more active catalyst capable of providing sufficient conversion at lower temperatures (approximately 200-250 °C). Thereby a minimum reheating of the flue gas should be applied. It is known that the selectivity towards  $N_2$  during SCR conditions is a function of operating temperature and content of vanadium [1]. Thus at low operating temperatures catalysts with more reactive formulations (higher content of vanadium, promoters etc.) might be operated without compromising the selectivity towards  $N_2$ .

Over the last decade there has been a great interest in the development of low-temperature SCR catalysts containing transition metal oxides such as Mn-Fe/TiO<sub>2</sub> [7, 8] and V<sub>2</sub>O<sub>5</sub>/TiO<sub>2</sub> [9-11]. Active formulations containing metals other than vanadium have not been widely commercialized because of issues with selectivity and sensitivity to SO<sub>2</sub>. Also there has been much attention towards developing a highly active vanadium formulation using sol-gel [9], deposition precipitation [10] and sequential impregnation methods via high surface area titania hydrate carriers [11]. The sol-gel method affords catalysts with up to 20 wt.% vanadia which have shown excellent potassium tolerance. However, the synthesis is relatively elaborate which might make its industrial implementation difficult. Recently, it has been reported that increasing the vanadia loading of catalysts prepared by impregnation can result in increased potassium tolerance [12-13]. Another approach is to use HPAs promoters instead of the commonly used WO<sub>3</sub>. The majority of catalytic applications use the most stable and easily available Keggin type HPAs e.g. H<sub>3</sub>PW<sub>12</sub>O<sub>40</sub>, H<sub>4</sub>SiW<sub>12</sub>O<sub>40</sub> and H<sub>3</sub>PMO<sub>12</sub>O<sub>40</sub>. In our previous publications we reported the promotional effect of HPAs, for NH<sub>3</sub>-SCR of NO<sub>x</sub> [14-15]. Combining

the use of HPAs [14-15] with increased vanadia loadings [12-13] could be a promising and relatively easily implementable approach. However, there are some open questions such as: (i) Will an increase in the vanadia content change the HPAs structure and reduce its acidity? (ii) Will the presence of HPAs allow high vanadia loadings to be present in non-crystalline form? (iii) Will HPAs adversely affect the  $V^{5+}$ - $V^{3+}$  redox system? (iv) Will  $N_2O$  be formed at increased rates? All these issues can have a large effect on the activity and potassium tolerance and therefore merit further experimental investigation.

In the present work, 3-6 wt.%  $V_2O_5$  was studied for  $NH_3$ -SCR of nitrogen oxides on Keggin type HPAs and  $WO_3$ -promoted  $V_2O_5/TiO_2$  catalysts. The deactivation effect of potassium additives on the SCR activity was studied on 3 and 5 wt.%  $V_2O_5$  catalysts, since even at tail-end position there may be a small amount of aerosols that could poison the catalyst. Optimum catalysts were characterized by various techniques to obtain a detailed understanding of the SCR performance.

## 2. Experimental

### 2.1 Catalyst preparation and characterization

HPA- and  $WO_3$ -promoted  $V_2O_5/TiO_2$  catalysts were prepared as described previously [14]. Briefly, anatase-supported HPAs  $H_3PW_{12}O_{40}$  (TPA),  $H_4SiW_{12}O_{40}$  (TSiA), and  $H_3PMo_{12}O_{40}$  (MPA) (Aldrich, 99.9%) were prepared by suspending a known amount of dried  $TiO_2$  anatase powder (Aldrich, 99.9%) in aqueous solutions of the corresponding HPA. The suspension mixture (optimum HPA loading, 15 wt.%) was dried at 120 °C for 12 h [14-15]. Similarly, 10 wt.%  $WO_3$ - $TiO_2$  was prepared by incipient wetness impregnation using ammonium metatungstate (Fluka, 99%) as a precursor on

anatase TiO<sub>2</sub>. The 10 wt.% WO<sub>3</sub>-TiO<sub>2</sub> was dried and calcined at 500 °C for 5 hours. This temperature was chosen because former studies on HPA-promoted catalysts have shown that calcination at higher temperatures reduces the catalytic activity [14].

3-6 wt.% V<sub>2</sub>O<sub>5</sub> modified catalysts were prepared by wet impregnation of the HPA-TiO<sub>2</sub> and 10 wt.% WO<sub>3</sub>-TiO<sub>2</sub> supports with 0.5-1.2 M vanadium oxalate solutions. The vanadium oxalate solutions were prepared from ammonium meta-vanadate and oxalic acid (Aldrich, 99.9%) in the molar ratio 1:2 at 70 °C. The obtained HPA-V<sub>2</sub>O<sub>5</sub>/TiO<sub>2</sub> catalysts were dried and calcined for 4 hours at 400 °C and the WO<sub>3</sub>-promoted V<sub>2</sub>O<sub>5</sub>/TiO<sub>2</sub> catalysts were calcined at 450 °C for 4 hours.

The potassium-doped catalysts were prepared by subsequent wet impregnation with a solution of KNO<sub>3</sub> (Sigma-Aldrich, 99.9%) to obtain a potassium loading of 100 μmol/g catalyst, corresponding to molar K/V ratios of 0.303 and 0.181 for 3 and 5 wt.% V<sub>2</sub>O<sub>5</sub>, respectively. The potassium-doped catalysts were oven-dried at 100 °C for about 2 hours and then calcined for 4 hours at 400 °C.

XRPD measurements were performed on a Huber G670 powder diffractometer using CuK<sub>α</sub> radiation within a 2θ range of 2-80° in steps of 0.02°. BET surface areas of the samples (100 mg catalyst) were determined from nitrogen physisorption measurements at liquid nitrogen temperature with a Micromeritics ASAP 2010 instrument.

FTIR spectra of the samples were recorded on a Perkin Elmer 1710 spectrometer at ambient conditions in KBr disks (1 mg in 100 mg). Raman spectra were measured by microscopic confocal Raman Spectrometer (Renishaw plc, UK) under

ambient conditions using a LEXEL 95-SHG-QS Argon-ion laser (from Cambridge Laser Laboratories Inc., California, USA) as a light source with a wavelength of 488 nm. The spectra were recorded with a resolution of  $1\text{ cm}^{-1}$  and a scan number of 20 from 200-1200  $\text{cm}^{-1}$ .

EPR: The catalyst samples were transferred directly into a dessicator after calcination and stored there until the measurement. *Ex-situ* EPR spectra were recorded on approximately 20 mg sample at room temperature in a 4mm suprasil quartz EPR tube using a continuous wave X-band Bruker EMX-EPR spectrometer with the ER 4102ST cavity and a gun diode microwave source. The microwave power was 6.5 mW, modulation frequency 100 kHz, modulation amplitude 8 G, microwave frequency 9.4-9.7 GHz. 2048 points were summed up over 4 scans in the interval 240-450 mT. Data treatment was performed with Matlab using EasySpin 4.5.3 [16]. Reference spectra for spin quantification were recorded with identical instrument settings on known solid solutions of  $\text{VO}_2$  in  $\text{K}_2\text{SO}_4$ .

$\text{NH}_3$ -TPD experiments were conducted on a Micromeritics Autochem-II instrument. In a typical TPD experiment, 100 mg of sample was placed in a quartz tube and pretreated in helium flow at 100 °C for 1 hour. The sample was treated with anhydrous  $\text{NH}_3$  gas (Air Liquide, 5%  $\text{NH}_3$  in He) at 100 °C. After  $\text{NH}_3$  adsorption, the sample was flushed with helium (50 mL/min) for 1 hour at 100 °C. Finally, the TPD operation was carried out by heating the sample from 100 to 600 °C (10 °C /min) under a flow of helium (50 mL/min).

H<sub>2</sub>-TPR studies were conducted on a Micromeritics Autochem-II instrument. In a typical experiment, 100 mg of sample was placed in one arm of a U-shaped quartz sample tube on a quartz wool plug. The TPR analysis was carried out in a reducing mixture (50 mL/min) consisting of 4% H<sub>2</sub> and balance Ar (Air Liquide) from 50 °C to 850 °C (10 °C/min). The hydrogen concentration in the effluent stream was monitored by a thermal conductivity detector (TCD) and the H<sub>2</sub> consumption was calculated from calibration experiments.

## 2.2 Catalytic activity measurements

The SCR activity measurements were carried out at atmospheric pressure in a fixed-bed reactor loaded with 50 mg of fractioned (180-300 μm) catalyst at a flow rate of 300 NmL/min (at room temperature). This corresponds to a space velocity of about 180,000 h<sup>-1</sup> assuming a density of 0.5 g mL<sup>-1</sup> of a monolith in an industrial application. This is about 20 to 40 times higher than the typical real life space velocities. We chose a higher space velocity in the screening experiments for the following reasons: (i) Industrial catalyst (in monolithic form) suffers from mass transport limitations; (ii) High NO<sub>x</sub> reductions (i.e. 90%) are required and (iii) Deactivation over a lifetime of 5-10 years needs to be allowed for. The inlet concentrations were: NO = 1000 ppm, NH<sub>3</sub> = 1000 ppm, O<sub>2</sub> = 4% and H<sub>2</sub>O = 2.3% with He as balance gas. During the experiments the temperature was increased stepwise from 125 to 300 °C while the NO and NH<sub>3</sub> concentrations were continuously monitored by a Thermo Electron Model 17C chemiluminescent NH<sub>3</sub>-NO<sub>x</sub> gas analyzer. At each set-temperature the N<sub>2</sub>O concentration was further measured by gas chromatography (Shimadzu-14 B GC, TCD detection,

poraplot column). The NO conversion (%) was measured after attaining steady state, approximately 45 min at each temperature.

### 3. Results and discussion

The results of N<sub>2</sub>-BET surface area are shown in Table 1. The surface area of the 3V<sub>2</sub>O<sub>5</sub>10WO<sub>3</sub>-TiO<sub>2</sub>, 3V<sub>2</sub>O<sub>5</sub>TPA-TiO<sub>2</sub>, 3V<sub>2</sub>O<sub>5</sub>TSiA-TiO<sub>2</sub>, and 3V<sub>2</sub>O<sub>5</sub>MPA-TiO<sub>2</sub> catalysts was found to be 103, 112, 114 and 96 m<sup>2</sup>/g, respectively. The surface area of the 5V<sub>2</sub>O<sub>5</sub>WO<sub>3</sub>-TiO<sub>2</sub>, 5V<sub>2</sub>O<sub>5</sub>TPA-TiO<sub>2</sub>, 5V<sub>2</sub>O<sub>5</sub>TSiA-TiO<sub>2</sub> and 5V<sub>2</sub>O<sub>5</sub>MPA-TiO<sub>2</sub> catalysts was found to be 99, 105, 106 and 90 m<sup>2</sup>/g, respectively. With an increase in metal loading from 3 to 5 wt.% V<sub>2</sub>O<sub>5</sub>, a slight decrease in surface area is noticed.

The X-ray powder diffraction (XRPD) patterns of 3 and 5 wt.% V<sub>2</sub>O<sub>5</sub> catalysts are shown in Fig. 1. No peaks attributable to crystalline V<sub>2</sub>O<sub>5</sub>, WO<sub>3</sub>, or HPA phases were observed, only support TiO<sub>2</sub> phases were observed indicating that the vanadium and promoters are highly dispersed on the support. The detection limit of the XRPD apparatus is around 5 nm, and any crystalline particles would be undetected below this size. Dominant anatase ( $2\theta = 25.3^\circ, 37.9^\circ, 47.8^\circ$  and  $54.3^\circ$ ) and a very small amount of the rutile ( $2\theta = 27.4^\circ, 36.1^\circ$  and  $54.2^\circ$ ) phases are present in the catalysts. The decrease in surface area with increasing V<sub>2</sub>O<sub>5</sub> loading from 3 to 5 wt.% suggests that crystalline TiO<sub>2</sub> is covered with an amorphous V<sub>2</sub>O<sub>5</sub> surface leading to some pore blocking.

It is well known that the SCR reaction requires NH<sub>3</sub> to adsorb on the catalyst. The adsorption capacity and desorption patterns as a function of temperature are greatly influenced by the surface acidity of the SCR catalysts. Promoters such as WO<sub>3</sub> or MoO<sub>3</sub> on the TiO<sub>2</sub> support increase the acidity and mechanical strength. In the present

investigation, the acidity of the catalysts was measured using the  $\text{NH}_3$ -TPD method. Even though this method is not able to discriminate between Brønsted- and Lewis-acid, it still gives valuable information regarding the total number and strength of the acid sites. The  $\text{NH}_3$ -TPD profiles of  $\text{V}_2\text{O}_5\text{TPA-TiO}_2$ ,  $\text{V}_2\text{O}_5\text{TSiA-TiO}_2$ ,  $\text{V}_2\text{O}_5\text{MPA-TiO}_2$  and  $\text{V}_2\text{O}_5\text{WO}_3\text{-TiO}_2$  catalysts are shown in Fig. 2 a) and Fig. 2 b). Figure 2 c) shows the total number of acid sites as a function of promoter. All the fresh catalysts show broad  $\text{NH}_3$ -desorption patterns from 150 to 650 °C. The total amount of adsorbed ammonia, which is determined from the area under the TPD curve, corresponds to weakly adsorbed ammonia (desorption temperature below 200 °C) and strongly adsorbed ammonia (desorption temperature above 300 °C). These sites originate from the  $\text{TiO}_2$  support, promoters ( $\text{WO}_3$  or heteropoly ions) and vanadium present in the catalyst. It is observed that the desorption peaks for the HPA-promoted catalysts (100- 550 °C) are broader compared to the  $\text{WO}_3$ -promoted catalysts (100- 400 °C). Pure and  $\text{TiO}_2$ -supported HPAs were previously reported to be super acidic [14]. The super acidic nature of HPAs is due to their discrete and mobile ionic structure, which is tunable through the chemical composition. The  $\text{NH}_3$ -TPD results are summarized in Table 1.

The fresh, HPA-promoted samples possess significantly more acid sites than the  $\text{WO}_3$ -promoted ones, regardless of the vanadia loading. Increasing the vanadia loading from 3 to 5 wt.% causes the total number of acid sites of  $\text{V}_2\text{O}_5\text{WO}_3\text{-TiO}_2$  and  $\text{V}_2\text{O}_5\text{TPA-TiO}_2$  to increase by 40 and 144  $\mu\text{mol g}^{-1}$ , respectively. The total number of acid sites of  $\text{V}_2\text{O}_5\text{TSiA-TiO}_2$  and  $\text{V}_2\text{O}_5\text{MPA-TiO}_2$  decrease by 20 and 121  $\mu\text{mol g}^{-1}$ , respectively.

Figure 2 also shows the  $\text{NH}_3$ -TPD profiles of potassium-doped catalysts (100  $\mu\text{mol/g}$  of potassium) as dotted lines. A significant decrease in total peak area and intensity of strongly adsorbed ammonia peaks are observed. All the potassium-doped catalysts showed above stoichiometric (moles of adsorbed  $\text{NH}_3$ /moles of K) loss of surface acid sites. The  $3\text{V}_2\text{O}_5\text{TPA-TiO}_2$ ,  $3\text{V}_2\text{O}_5\text{TSiA-TiO}_2$  and  $3\text{V}_2\text{O}_5\text{MPA-TiO}_2$  catalysts lost 339 -412  $\mu\text{mol/g}$  of acid sites, whereas the  $3\text{V}_2\text{O}_5\text{WO}_3\text{-TiO}_2$  catalyst lost only 126  $\mu\text{mol/g}$  of acid sites.  $5\text{V}_2\text{O}_5\text{TPA-TiO}_2$  and  $5\text{V}_2\text{O}_5\text{TSiA-TiO}_2$  lost 432 and 404  $\mu\text{mol/g}$  of acid sites, respectively, which is close to the losses of the corresponding 3 wt.% vanadia samples.  $5\text{V}_2\text{O}_5\text{TPA-TiO}_2$  lost only 141  $\mu\text{mol/g}$ . This makes it a promising candidate. The result was confirmed by reproducing the potassium impregnation step. The  $5\text{V}_2\text{O}_5\text{WO}_3\text{-TiO}_2$  catalyst lost 161  $\mu\text{mol/g}$  of acid sites which is close to the value of  $3\text{V}_2\text{O}_5\text{WO}_3\text{-TiO}_2$ . Above stoichiometric loss of acid sites can be explained by a recently reported deactivation mechanism. Here, one potassium metal atom can deactivate up to four vanadium atoms [17] and if we also consider impact of potassium on vanadia and titania the atomic ratio of K:V:Ti is 1:2:4 [18]. It is expected that promoters are decreasing the impact of potassium on the active V-OH sites, which are responsible for initiating the SCR reaction through ammonia adsorption. The HPAs probably provide sacrificial acid sites as was reported earlier [14].

In order to study the redox properties of catalysts,  $\text{H}_2$ -TPR measurements were performed. The TPR profiles of 3 wt.%  $\text{V}_2\text{O}_5$  and 5 wt.%  $\text{V}_2\text{O}_5$  catalysts are shown in Fig. 3 a) and Fig. 3 b), respectively. The catalysts show three reduction peaks between

450-480 °C (assigned to the reduction of  $V^{5+}$  to  $V^{3+}$ ), 600-630 °C (assigned to the  $W^{6+}$  reduction to  $W^{4+}$  from  $WO_3$ , TPA and TSiA or  $Mo^{6+}$  reduction to  $Mo^{4+}$  from MPA) and 740-790 °C (assigned to the further reduction of  $W^{4+}$  or  $Mo^{4+}$  to  $W^0$  or  $Mo^0$ ), respectively [11, 19]. The difference in reduction temperatures for the catalysts is due to the combined effect of the vanadium content, promotor formulations and constituent elements associated in HPAs. By increasing the  $V_2O_5$  content from 3 to 5 wt.% an increase in the intensity of the vanadium reduction peak can be observed around 450 °C. Figure 3 c) shows the ( $V^{5+}$  to  $V^{3+}$ ) peak temperatures of both fresh and poisoned catalysts and Figure 3 d) gives the peak shifts due to K. Fresh catalysts loaded with 5 wt.%  $V_2O_5$  reduce at slightly higher temperatures than the corresponding 3 wt.% samples. This is probably due to the formation of slightly bigger vanadia particles at higher loadings. Potassium doping causes pronounced peak shifts. In the case of  $WO_3$ -, TPA- and TSiA-promoted catalysts the shifts are little affected by the vanadia loading. The MPA-promoted catalyst, however, shows a significantly lower shift at the higher vanadia loading. This, together with the high retention of acid sites, is expected to result in lower reduction of the SCR activity. The poisoned,  $WO_3$ -promoted samples show  $V^{5+}$  to  $V^{3+}$  reduction temperatures close to the ones of the HPA-promoted counterparts. The peaks assigned to the reduction of  $W^{4+}$  or  $Mo^{4+}$  to  $W^0$  or  $Mo^0$  shift very little due to K doping.

FTIR spectra of the  $V_2O_5$ TPA-TiO<sub>2</sub>,  $V_2O_5$ TSiA-TiO<sub>2</sub>,  $V_2O_5$ MPA-TiO<sub>2</sub> and  $V_2O_5$ WO<sub>3</sub>-TiO<sub>2</sub> catalysts along with support patterns are shown in Fig. 4. Pure  $V_2O_5$

spectra show stretching mode of V=O (vanadyl) at  $1020\text{ cm}^{-1}$  and the V-O-V stretching mode at  $830\text{ cm}^{-1}$  [10]. Except for the pure  $\text{V}_2\text{O}_5$  all catalysts display a broad band in the region between  $3200\text{-}3600\text{ cm}^{-1}$  and a sharp peak at  $1620\text{ cm}^{-1}$ , which are due to the stretching and bending vibrations of O-H groups, respectively. The peak at  $1400\text{ cm}^{-1}$  and the bands below  $800\text{ cm}^{-1}$  are due to the Ti-O-Ti stretching vibrations.

Metal-oxygen stretching modes of the Keggin units are mainly present in the  $650\text{-}1150\text{ cm}^{-1}$  range. In the literature the most common assignments reported for pure TPA, TSiA and MPA are given as: TPA shows bands at  $1081$  (P-O),  $982$  (W=O),  $888$  and  $804\text{ cm}^{-1}$  (W-O-W) [20], TSiA shows bands at  $1021$  (Si-O-Si),  $984$  (W=O),  $928$  (Si-O),  $885$ , and  $791\text{ cm}^{-1}$  (W-O-W) [21] and MPA shows bands at  $1065$  (P-O),  $963$  (Mo=O),  $869$  and  $793\text{ cm}^{-1}$  (Mo-O-Mo) [22]. The  $\text{V}_2\text{O}_5\text{TPA-TiO}_2$ ,  $\text{V}_2\text{O}_5\text{TSiA-TiO}_2$  and  $\text{V}_2\text{O}_5\text{MPA-TiO}_2$  catalysts display similar bands in the  $1082\text{-}962\text{ cm}^{-1}$  region indicating that the Keggin structure is maintained after impregnation. The lower wave number bands (lower than  $900\text{ cm}^{-1}$ ) are covered with intense broad vibration peaks originating from Ti-O-Ti bonds [20]. The  $\text{V}_2\text{O}_5\text{WO}_3\text{-TiO}_2$  catalyst shows a band at  $977\text{ cm}^{-1}$  which is associated with the W=O stretching of the tungstyl species [23]. The vanadyl species are not detected because of their low concentrations compared to the promoters and the support.

Raman spectroscopy was applied in order to understand the molecular structure of the HPAs, tungstyl and vanadyl species. HPAs typically show symmetric ( $\nu_s$ ) and asymmetric ( $\nu_{as}$ ) vibrations of: terminal oxygen ( $\nu(\text{M}=\text{O}_t)$ ), corner shared bridged oxygen ( $\nu(\text{M}-\text{O}_b-\text{M})$ ), edge shared bridged oxygen ( $\nu(\text{M}-\text{O}_c-\text{M})$ ) and oxygen in the central tetrahedron ( $\nu(\text{M}-\text{O}_a)$ ) with M being W, Mo, P or Si. Characteristic Raman peaks of the bulk  $\text{H}_3\text{PW}_{12}\text{O}_{40}$  (TPA) were reported at  $1007$ ,  $991$ ,  $982$  and  $902\text{ cm}^{-1}$ , which were

attributed to  $\nu_s(\text{W}=\text{O}_t)$ ,  $\nu_{as}(\text{W}=\text{O}_t)$ ,  $\nu(\text{P}-\text{O}_a)$  and  $\nu(\text{W}-\text{O}_b-\text{W})$ , respectively [24-25]. Similarly, bulk  $\text{H}_4\text{SiW}_{12}\text{O}_{40}(\text{TSiA})$  exhibited bands at 1002, 980, 922 and 881  $\text{cm}^{-1}$  due to  $\nu_s(\text{W}=\text{O}_t)$ ,  $\nu_{as}(\text{W}=\text{O}_t)$ ,  $\nu(\text{Si}-\text{O}_a)$  and  $\nu(\text{W}-\text{O}_b-\text{W})$ , respectively [25-26]. Raman spectra of pure  $\text{H}_3\text{PMo}_{12}\text{O}_{40}$  (MPA) was reported with bands at 996, 983, 882, 606 and 246  $\text{cm}^{-1}$  which were assigned to  $\nu_s(\text{Mo}=\text{O}_t)$ ,  $\nu_{as}(\text{Mo}=\text{O}_t)$ ,  $\nu_s(\text{Mo}-\text{O}_b-\text{Mo})$ ,  $\nu_s(\text{Mo}-\text{O}_c-\text{Mo})$  and  $\nu_s(\text{Mo}-\text{O}_a)$  [27]. Raman spectra of bulk  $\text{WO}_3$  are expected to show bands at 808, 714 and 276  $\text{cm}^{-1}$  and were assigned to the  $\text{W}=\text{O}$  stretching mode, the  $\text{W}=\text{O}$  bending mode, and the  $\text{W}-\text{O}-\text{W}$  deformation mode respectively [28]. Raman spectra of bulk  $\text{V}_2\text{O}_5$  bands are reported at 993, 703, 405 and 285  $\text{cm}^{-1}$  [29]. Crystalline  $\text{V}_2\text{O}_5$  was reported to give a sharp band at 994  $\text{cm}^{-1}$  [30]. This is very close to some of the bands of  $\text{H}_3\text{PW}_{12}\text{O}_{40}$  (TPA) (980  $\text{cm}^{-1}$ ),  $\text{H}_4\text{SiW}_{12}\text{O}_{40}(\text{TSiA})$  and  $\text{H}_3\text{PMo}_{12}\text{O}_{40}$  (MPA) (996 and 983  $\text{cm}^{-1}$ ).

The molecular structure of the supported species depends on the loading and the sample pre-treatment during measurement. The Raman bands at 1007, 992 and 1008  $\text{cm}^{-1}$  correspond to the TPA, MPA and TSiA, respectively, see Fig. 5. Since the bands are not sharp it is unlikely that they represent crystalline  $\text{V}_2\text{O}_5$ . The presence of the same Raman bands in the spectra for the  $\text{V}_2\text{O}_5$ -HPA- $\text{TiO}_2$  catalysts and for the bulk HPAs indicate that the Keggin structure of the HPA remain stable upon impregnation on  $\text{TiO}_2$ . The stable structure of the HPAs is further supported by the absence of bands of the individual oxides, i.e.,  $\text{WO}_3$  or  $\text{MoO}_3$ , which would appear upon decomposition of the Keggin structure at 808 and 818  $\text{cm}^{-1}$ , respectively [28, 31]. This observation as well as the  $\text{NH}_3$ -TPD results given above indicates that increasing the vanadium content from 3 to 5 wt.% does not compromise the structure of poly acids.

The signal at  $1026\text{ cm}^{-1}$  observed for all the catalysts can be assigned to isolated surface vanadium oxide species [11, 30]. The position of the Raman bands are the same after increasing the  $\text{V}_2\text{O}_5$  content from 3 to 5 wt.%. Furthermore, increasing the vanadia loading does not increase the intensity of the band at around  $990\text{-}1010\text{ cm}^{-1}$  relative to the band at around  $1026\text{ cm}^{-1}$ , which would be the case if significant amounts of crystalline  $\text{V}_2\text{O}_5$  were formed. In corroboration with the XRD results this shows that the nature of the vanadia species has not changed significantly. Therefore, unselective oxidation of ammonia and increased  $\text{N}_2\text{O}$  formation are not expected under the SCR conditions used in this study.

Recently [32] a direct correlation between high surface  $\text{V}^{4+}/\text{V}^{5+}$  ratio (derived from *ex-situ* XPS measurements) and SCR activity has been reported. In order to investigate the prevalence of reduced vanadium in the catalysts we proceeded to use EPR spectroscopy to probe the  $\text{V}^{4+}$  state. EPR spectroscopy is a powerful technique for detecting the paramagnetic  $\text{V}^{4+}$  species in vanadium catalysts. Fig. S2 and S3 show the EPR spectra of fresh and poisoned 3 and 5 wt.%  $\text{V}_2\text{O}_5$  catalysts recorded at room temperature. The total amount of  $\text{V}^{4+}$  was determined by comparison of the double integral of the EPR signal of the sample to the signal of a series of  $\text{V}^{4+}$  standard samples. The results are shown in Fig. 6. The  $\text{V}^{4+}$  content of fresh samples varies a lot and is lowest in the  $\text{WO}_3$  containing catalyst, irrespective of the vanadia loading, and higher in especially the MPA- and TPA-doped catalysts. The higher content of  $\text{V}^{4+}$  in HPAs-doped catalysts could be another reason for their higher activities. Potassium causes the difference between the  $3\text{V}_2\text{O}_5\text{-TiO}_2$  promoted with  $\text{WO}_3$  and HPAs to become almost

negligible. The poisoned  $5\text{V}_2\text{O}_5\text{-TiO}_2$  catalysts reveal larger differences. The  $\text{WO}_3$ -promoted one contains only 2.2%  $\text{V}^{4+}$  compared to the total vanadium content while the MPA-promoted one contains 8.0%. Whether these differences also exist under *in-situ* conditions (elevated temperatures, presence of ammonia and NO) might be investigated in the future.

The spin Hamiltonian parameters were determined by simulations in EasySpin and are listed in Table 2 (detailed information and figures in S1, S2 and S3). From this it is seen that approximately 88% of the EPR signal on all catalysts is found in a broad isotropic line with  $g = 1.97$  and a peak-to-peak width of 250 G. This species is similar to that observed for pure crystalline  $\text{V}_2\text{O}_5$ , and is assigned to tetragonal 5- or 6-coordinated vanadyl  $\text{VO}^{2+}$  species [33] The line broadening is due to the amorphous nature of the sites as well as spin-spin interactions with neighboring  $\text{V}^{4+}$  sites.

Species **A** with well-defined sharp lines in the EPR spectrum has spin Hamiltonian parameters of  $g_{\perp} = 1.97$ ,  $g_{\parallel} = 1.90$ ,  $A_{\perp} = 208$  MHz and  $A_{\parallel} = 560$  MHz. This species can be assigned to a well-defined and magnetically isolated 6-coordinate vanadyl species [34, 35]. Another species, **B** also with sharp lines has parameters that are very similar to species **A**. Although the local coordination around vanadium is different enough to give a distinct set of peaks it is still assigned as a tetragonal vanadyl species.

Figure 7 shows the NO conversion (%) profiles of 3-6 wt.%  $\text{V}_2\text{O}_5\text{TPA-TiO}_2$ ,  $\text{V}_2\text{O}_5\text{TSiA-TiO}_2$ ,  $\text{V}_2\text{O}_5\text{MPA-TiO}_2$  and  $\text{V}_2\text{O}_5\text{WO}_3\text{-TiO}_2$  catalysts as a function of the

reaction temperature. At temperatures below 175 °C, the catalysts exhibit low NO conversion, higher conversion is observed above 200 °C and almost full conversion is seen at 300 °C. Fig. 7(a, b and c) shows that a gradual increase in V<sub>2</sub>O<sub>5</sub> loading enhances the NO conversion which reaches a maximum at 5 wt.% V<sub>2</sub>O<sub>5</sub> and a further increase of the V<sub>2</sub>O<sub>5</sub> loading leads to a gradual decrease of NO conversion. Figure 7(d) also shows that a gradual increase in V<sub>2</sub>O<sub>5</sub> loading enhances the NO conversion and almost similar conversion profiles were observed for 5 and 6 wt.% V<sub>2</sub>O<sub>5</sub>. For a fair comparison with other catalysts we considered the 5 wt.% V<sub>2</sub>O<sub>5</sub> as the optimum V<sub>2</sub>O<sub>5</sub>WO<sub>3</sub>-TiO<sub>2</sub> catalyst.

It is interesting to see the NO conversion (%) of the catalysts loaded with 3 and 5 wt.% V<sub>2</sub>O<sub>5</sub>. The difference in NO conversion between these samples is apparent at the intermediate temperature 225 °C, where the catalysts are just active enough to initiate the reaction. 3V<sub>2</sub>O<sub>5</sub>TPA-TiO<sub>2</sub>, 3V<sub>2</sub>O<sub>5</sub>TSiA-TiO<sub>2</sub>, 3V<sub>2</sub>O<sub>5</sub>MPA-TiO<sub>2</sub> and 3V<sub>2</sub>O<sub>5</sub>WO<sub>3</sub>-TiO<sub>2</sub> exhibited NO conversions of 28.9, 28.8, 30.6 and 27.1%, respectively. By comparison with the samples with 5 wt.%: 5V<sub>2</sub>O<sub>5</sub>TPA-TiO<sub>2</sub>, 5V<sub>2</sub>O<sub>5</sub>TSiA-TiO<sub>2</sub>, 5V<sub>2</sub>O<sub>5</sub>MPA-TiO<sub>2</sub> and 5V<sub>2</sub>O<sub>5</sub>WO<sub>3</sub>-TiO<sub>2</sub> exhibited a NO conversion of 53.8, 51.6, 43.9 and 42.1%, respectively. Overall, an almost two fold increase in activity is observed by increasing the V<sub>2</sub>O<sub>5</sub> content from 3 to 5 wt.%. Similar observations were reported for WO<sub>3</sub>-promoted high surface area titania hydrate on 1.5, 3 and 5 wt.% V<sub>2</sub>O<sub>5</sub> catalysts [11].

SCR catalysts are expected to be sufficiently selective so that minimal or no N<sub>2</sub>O formation occurs. It is known that at sufficiently high temperatures, N<sub>2</sub>O formation occurs from the partial oxidation of ammonia in the presence of an SCR catalysts. Especially at relatively high reaction temperatures (i.e. > 400 °C) this is an issue even for low content V<sub>2</sub>O<sub>5</sub> catalysts (1-3 wt.%) [36]. Under the current experimental conditions

(i.e with 2.3 vol.% water), it should be mentioned that even for the 6 wt.%  $V_2O_5$  catalysts no traces of  $N_2O$  were detected throughout the investigated temperatures.

Doping the catalysts with potassium (100  $\mu\text{mol/g}$ ) resulted in a decrease in the SCR activity (Fig. 8). At 225 °C, K-3 $V_2O_5$ TPA-TiO<sub>2</sub>, K-3 $V_2O_5$ TSiA-TiO<sub>2</sub>, K-3 $V_2O_5$ MPA-TiO<sub>2</sub> and K-3 $V_2O_5$ WO<sub>3</sub>-TiO<sub>2</sub> catalysts displayed NO conversion of 23.4, 23.3, 28.4 and 15.1%, respectively. Increasing the  $V_2O_5$  loading to 5 wt.% the K-5 $V_2O_5$ TPA-TiO<sub>2</sub>, K-5 $V_2O_5$ TSiA-TiO<sub>2</sub>, K-5 $V_2O_5$ MPA-TiO<sub>2</sub> and K-5 $V_2O_5$ WO<sub>3</sub>-TiO<sub>2</sub> catalysts displayed NO conversions of 54.6, 48.9, 45.2 and 38.8%, respectively.

The K-3 $V_2O_5$ TPA-TiO<sub>2</sub>, K-3 $V_2O_5$ TSiA-TiO<sub>2</sub>, K-3 $V_2O_5$ MPA-TiO<sub>2</sub> and K-3 $V_2O_5$ WO<sub>3</sub>-TiO<sub>2</sub> catalysts retained 81, 80, 92 and 55% of the initial activity, respectively. The 5 wt.%  $V_2O_5$  loaded K-5 $V_2O_5$ TPA-TiO<sub>2</sub>, K-5 $V_2O_5$ TSiA-TiO<sub>2</sub>, K-5 $V_2O_5$ MPA-TiO<sub>2</sub> and K-5 $V_2O_5$ WO<sub>3</sub>-TiO<sub>2</sub> catalysts performed with 100, 95, 100 and 92% of their initial activity, respectively. Replacing WO<sub>3</sub> with HPAs is obviously a fruitful approach also at a relatively high vanadia loading of 5 wt.%.

#### 4. Conclusions

Promoting  $V_2O_5$ /TiO<sub>2</sub> with 15 wt.% HPA instead of 10 wt.% WO<sub>3</sub> increases the potassium tolerance at 225 °C at both 3 and 5 wt.% vanadia. This is most probably due to a higher number of surface acid sites left after potassium poisoning as shown with NH<sub>3</sub>-TPD. Redox properties, on the other hand, seem not to be generally enhanced by HPAs as shown by H<sub>2</sub>-TPR. The combination of high vanadia loadings (5 wt.%) with HPAs does not induce the formation of crystalline  $V_2O_5$  as confirmed by XRD, FTIR and Raman spectroscopy. Therefore, unselective oxidation of ammonia and  $N_2O$  formation are not higher than in the WO<sub>3</sub>-promoted case. *Ex-situ* EPR studies have shown that the  $V^{4+}/V_{\text{total}}$

ratio is higher in HPA-promoted catalysts than in the  $\text{WO}_3$ -promoted counterparts. The differences are more pronounced for the fresh catalysts and might give an additional explanation for the promotional effect of HPAs. Future studies could comprise optimization of both HPAs and vanadia loadings as well as the effect of higher potassium loadings. Furthermore, investigation of the thermal stability of HPAs- and  $\text{WO}_3$ -promoted catalysts at temperatures above 300 °C could be of interest in order to assess the viability of the former under high-dust conditions.

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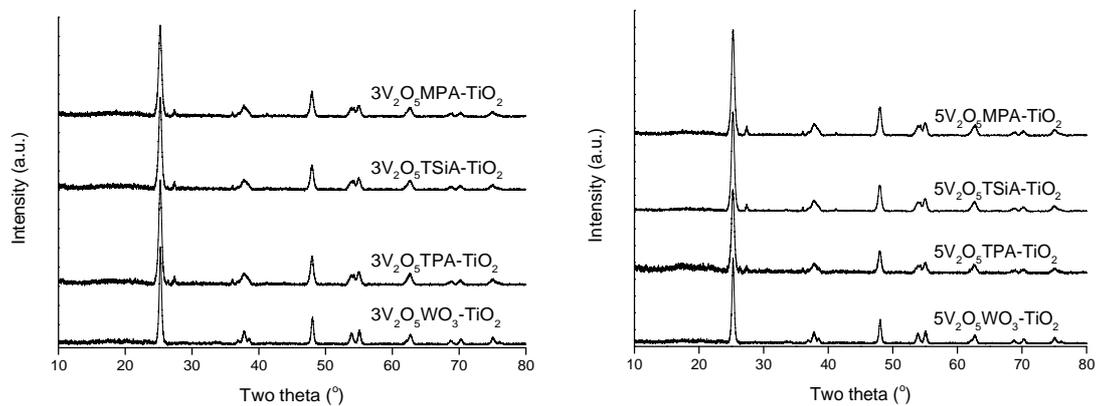
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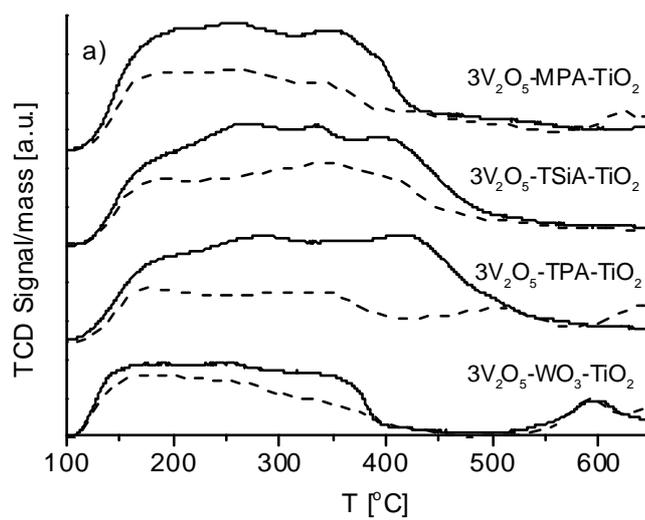
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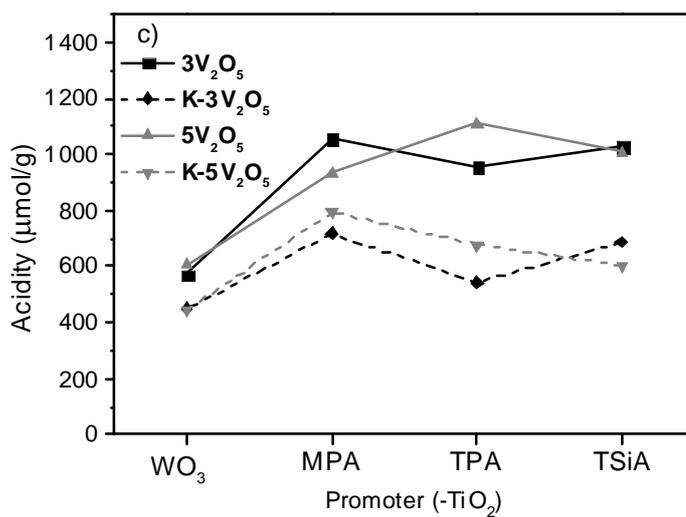
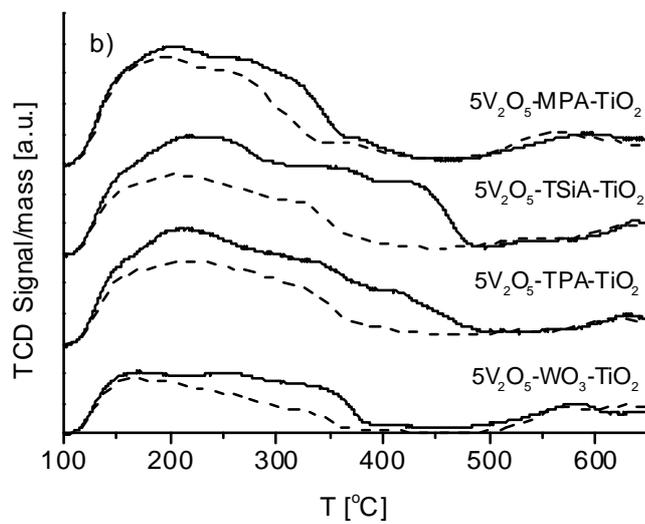
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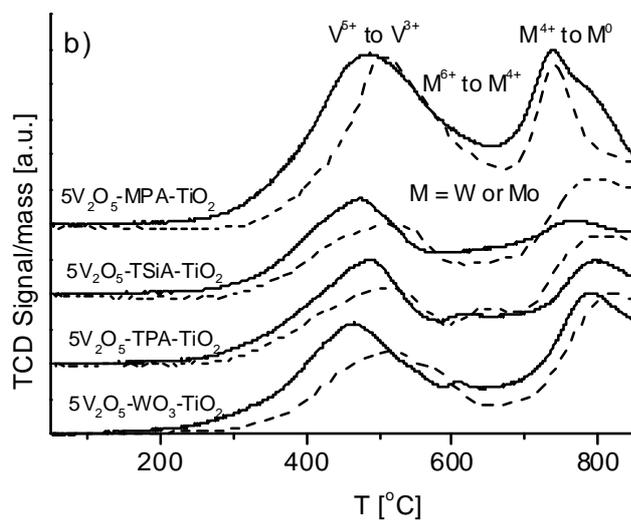
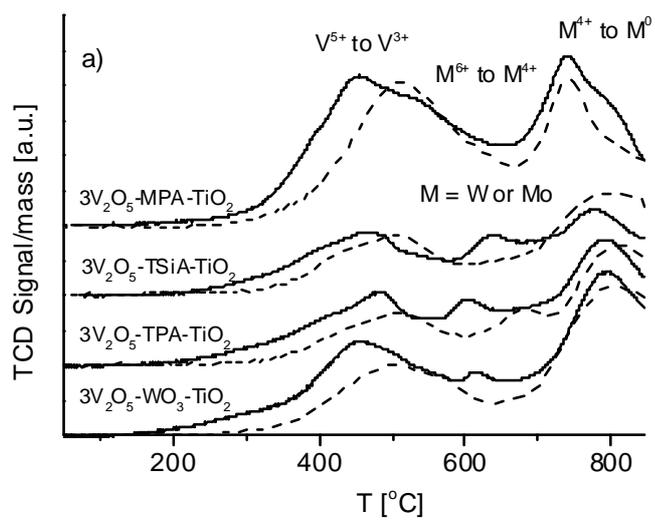


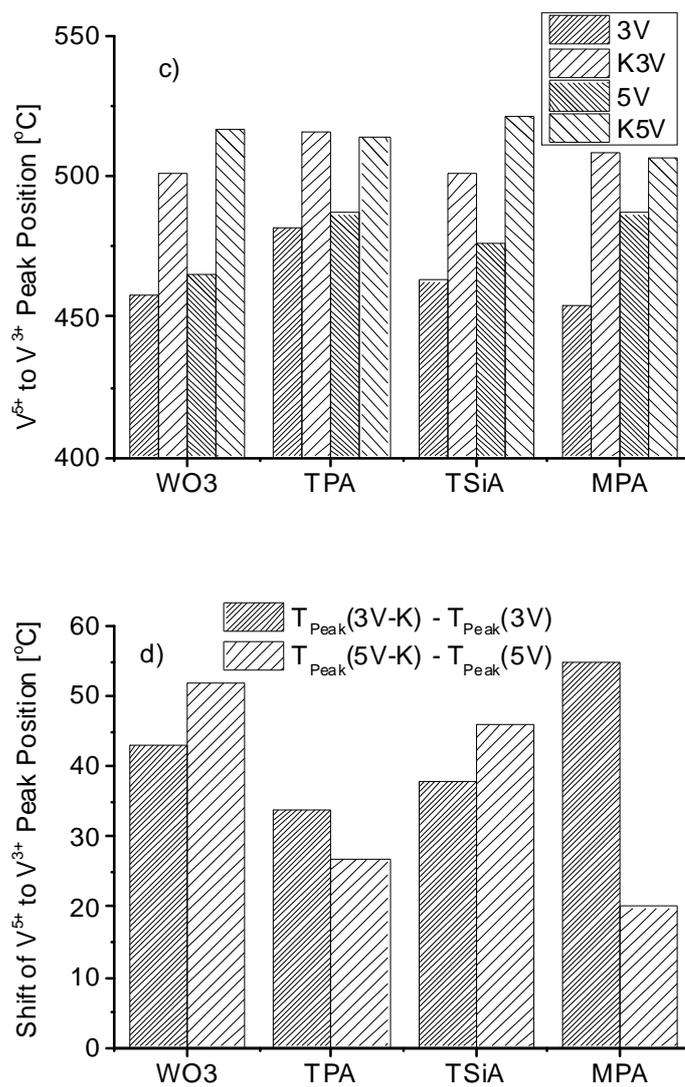
**Fig. 1** XRPD patterns of 3 and 5 wt.%  $V_2O_5$  catalysts.



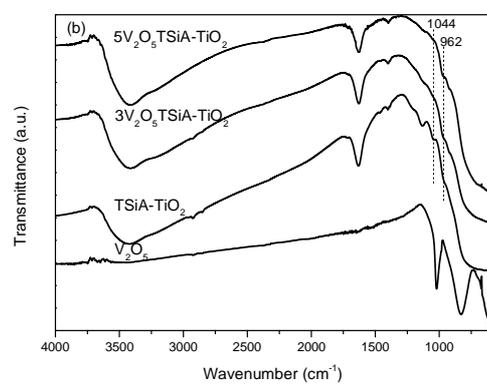
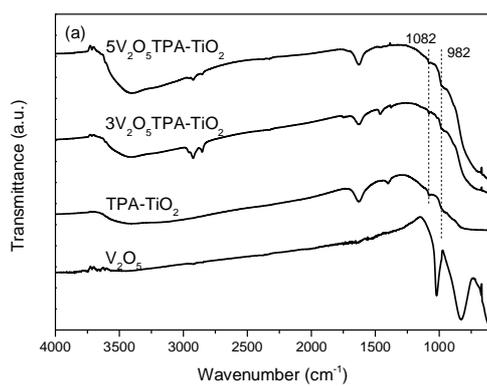


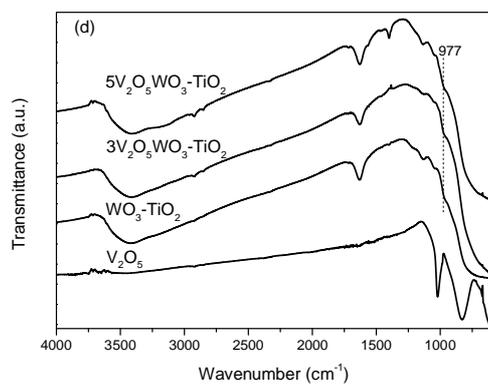
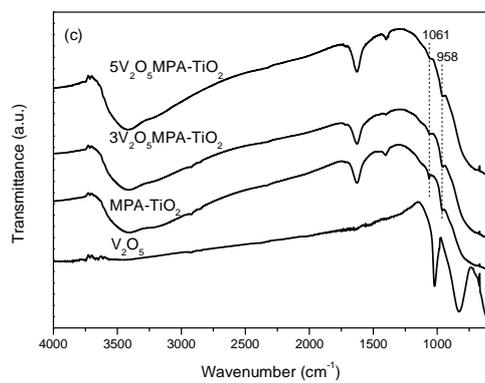
**Fig. 2** NH<sub>3</sub>-TPD profiles of fresh (straight lines) and potassium-doped (dotted lines); a) 3 wt.% V<sub>2</sub>O<sub>5</sub> catalysts, b) 5 wt.% V<sub>2</sub>O<sub>5</sub> catalysts, c) total number of acid sites.



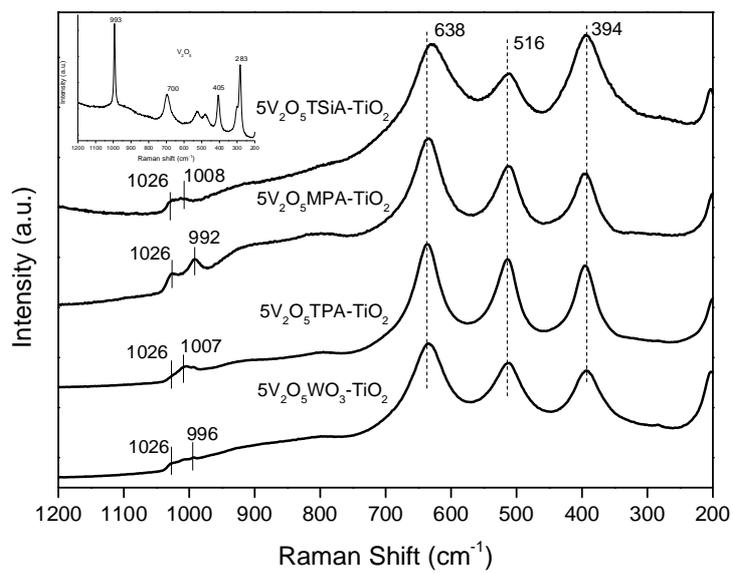
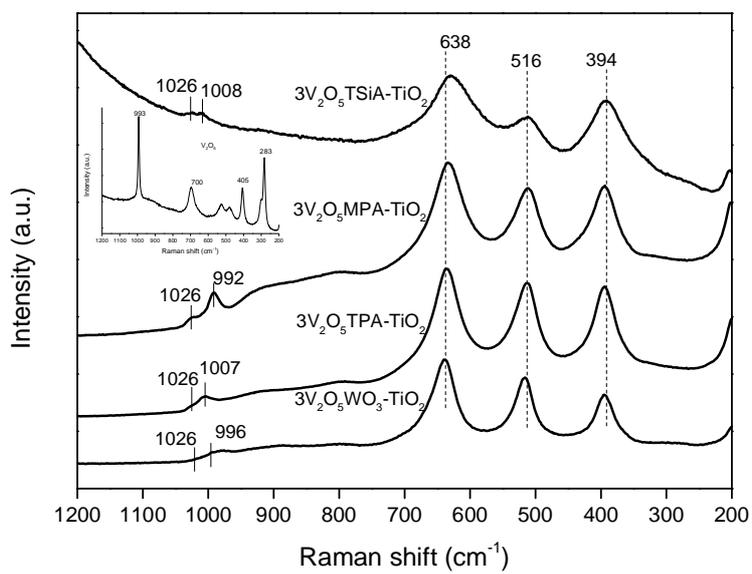


**Fig. 3**  $H_2$ -TPR profiles of fresh (straight lines) and potassium-doped (dotted lines); a) 3 wt.%  $V_2O_5$  catalysts, b) 5 wt.%  $V_2O_5$  catalysts, c) peak positions of  $V^{5+}$  to  $V^{3+}$  reduction, d) shift of peak positions of  $V^{5+}$  to  $V^{3+}$  reduction upon K poisoning.

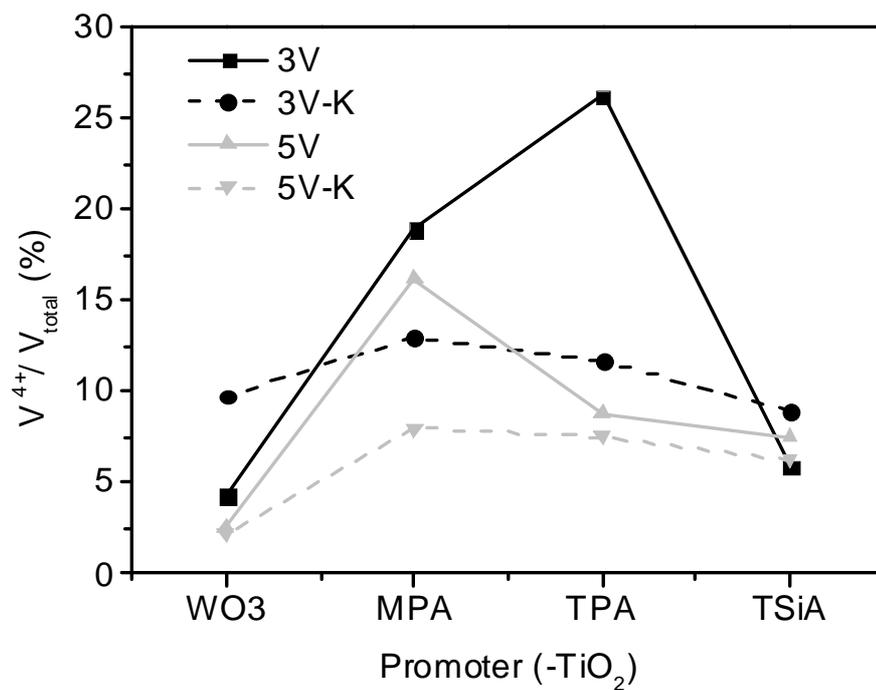




**Fig. 4** FTIR spectra of TPA-, TSiA-, MPA- and WO<sub>3</sub>-promoted V<sub>2</sub>O<sub>5</sub>/TiO<sub>2</sub> catalysts.



**Fig. 5** Raman spectra of 3 and 5 wt.%  $V_2O_5$  catalysts.



**Fig. 6**  $V^{4+}$  content as determined by EPR.

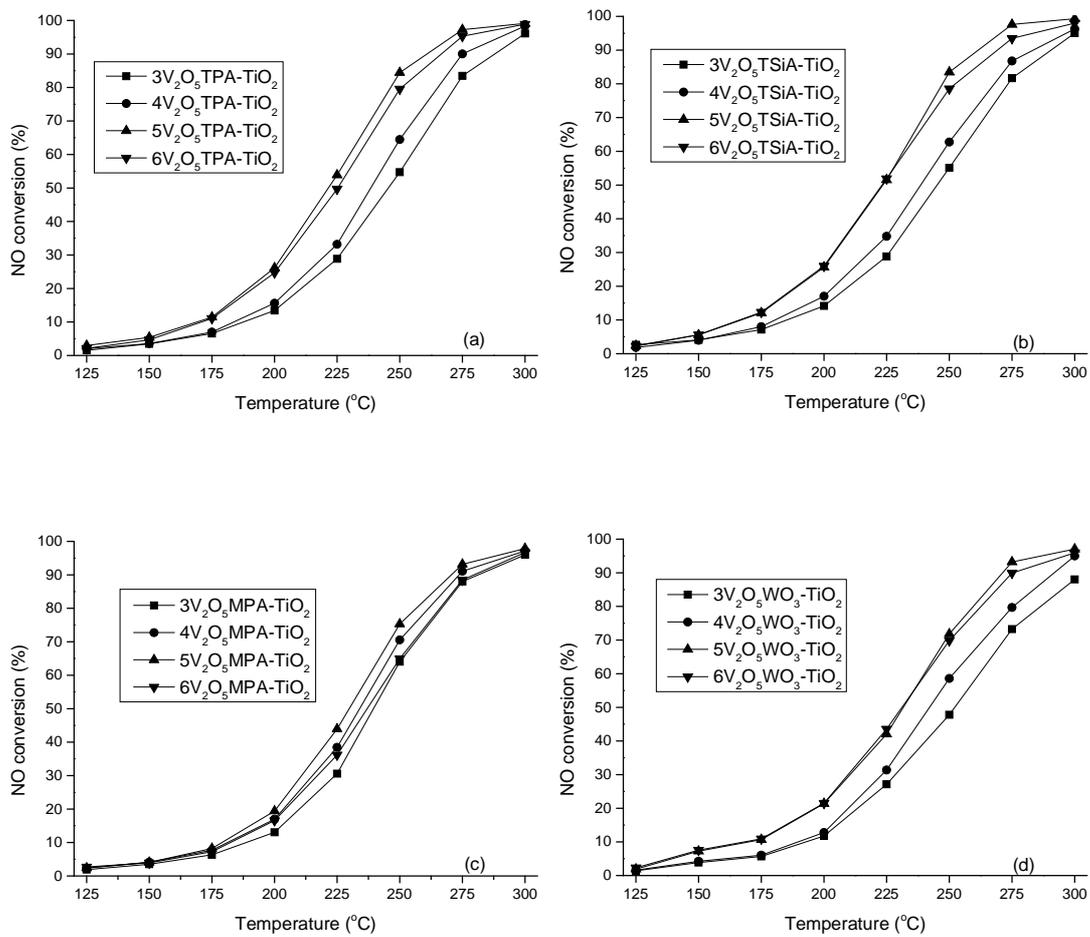
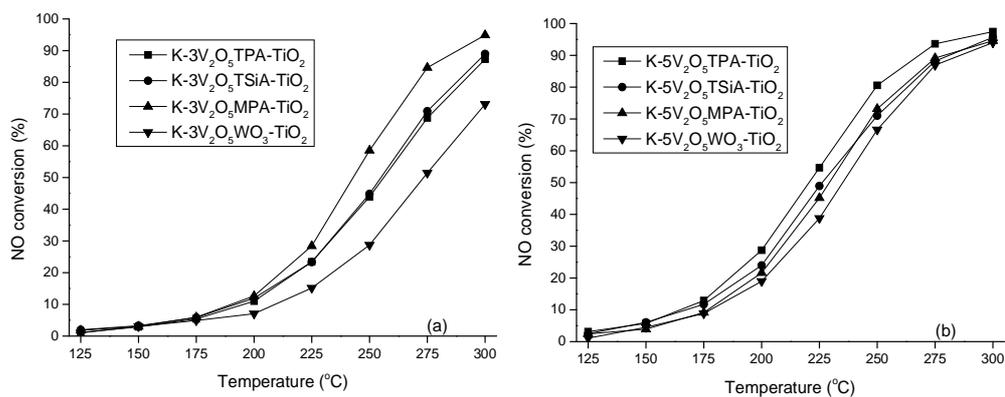


Fig. 7 SCR activity of 3-6 wt.%  $V_2O_5$  catalysts.



**Fig. 8** SCR activity of potassium-doped 3 and 5 wt.%  $V_2O_5$  catalysts.

**Table 1** Physico-chemical properties of the catalysts.

Catalyst	Surface area	Acidity [ $\mu\text{mol/g}$ ]		Acidity loss [ $\mu\text{mol/g}$ ]	Stoichiometry of acidity loss [mol $\text{NH}_3$ /mol K]
	Fresh	Fresh	K-doped		
$3V_2O_5WO_3-TiO_2$	103	574	448	126	1.26
$3V_2O_5TPA-TiO_2$	112	955	543	412	4.12
$3V_2O_5TSiA-TiO_2$	114	1028	687	341	3.41
$3V_2O_5MPA-TiO_2$	96	1056	717	339	3.39
$5V_2O_5WO_3-TiO_2$	99	608	447	161	1.61
$5V_2O_5TPA-TiO_2$	105	1111	679	432	4.32
$5V_2O_5TSiA-TiO_2$	106	1008	604	404	4.04
$5V_2O_5MPA-TiO_2$	90	935	794	141	1.41

**Table 2** Simulated spin hamiltonian parameters and their distribution. Individual parameters are found in S1 and simulation plots in S2.

Sample	$V^{4+}$ Site Distribution (%)		
	A	B	C
	$g_{\perp} = 1.97 \pm 0.01$ $A_{\perp} = 206 \pm 5$ $g_{\parallel} = 1.90 \pm 0.01$ $A_{\parallel} = 570 \pm 20$	$g_{\perp} = 1.97 \pm 0.01$ $A_{\perp} = 182 \pm 9$ $g_{\parallel} = 1.92 \pm 0.01$ $A_{\parallel} = 534 \pm 26$	$g = 1.97 \pm 0.01$ unresolved A
$3V_2O_5WO_3-TiO_2$	9.2	6.0	84.8
$5V_2O_5WO_3-TiO_2$	9.5	13.8	76.8
$3V_2O_5TPA-TiO_2$	7.1	4.1	88.8
$5V_2O_5TPA-TiO_2$	6.5	4.8	88.7
$3V_2O_5TSiA-TiO_2$	8.0	7.0	85.0
$5V_2O_5TSiA-TiO_2$	5.9	4.4	89.7
$3V_2O_5MPA-TiO_2$	6.7	4.4	88.9
$5V_2O_5MPA-TiO_2$	7.9	2.9	89.2