Removal of NO\textsubscript{x} by Adsorption/Decomposition on H\textsubscript{3}PW\textsubscript{12}O\textsubscript{40}·6H\textsubscript{2}O Supported on Ceria

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ABSTRACT

We synthesized catalysts composed of CeO\textsubscript{2} and varying percentages of HPW and assessed their capacity to adsorb and decompose NO\textsubscript{x} using XRD, FTIR spectroscopy, and BET analysis. The denitrification performance of the catalysts was evaluated by investigating the dynamic NO\textsubscript{x} adsorption as well as other relevant factors. The IR spectra of the HPW revealed that the adsorbed NO\textsubscript{x} entered the bulk phase of the HPW and replaced the crystallization water, combining with its protons to form NOH\textsuperscript{+}. The HPW/CeO\textsubscript{2} composites displayed a maximum NO\textsubscript{x} adsorption rate (85.6 mg·NO\textsubscript{x}·g·HPW\textsuperscript{−1}) that far exceeded that of HPW alone (50.5 mg·NO\textsubscript{x}·g·HPW\textsuperscript{−1}). GC-MS confirmed that temperature programming reduced the adsorbed NO\textsubscript{x} to N\textsubscript{2}.

Keywords: Polyoxometalates; NO\textsubscript{x}; Adsorption and decomposition; H\textsubscript{3}PW\textsubscript{12}O\textsubscript{40}·6H\textsubscript{2}O/CeO\textsubscript{2}.

INTRODUCTION

Nitrous oxides NO\textsubscript{x} (NO + NO\textsubscript{2}) abatement from stationary power sources and mobile sources has attracted great attention in recent years due to the caused environmental problems (acid rain, photochemical smog, and ozone layer depletion) and harm for human health (Huang et al., 2019; Wang et al., 2019; Shan et al., 2020). To solve this serious environmental problem, many well-developed technologies have been employed for NO\textsubscript{x} removal. Among these technologies, although selective catalytic reduction of NO\textsubscript{x} with ammonia (NH\textsubscript{3}-SCR) has been considered to be one of the most efficient techniques to resolve the NO\textsubscript{x} issue (Imanaka and Masui, 2012), it has the disadvantages of high cost of NH\textsubscript{3} and secondary pollution caused by NH\textsubscript{3} leakage. The direct decomposition of NO\textsubscript{x} is regarded as the most ideal and environmentally friendly technology for the removal of NO\textsubscript{x}, in which NO\textsubscript{x} can be direct decomposed into harmless N\textsubscript{2} and O\textsubscript{2} without reductant (Konsolakis et al., 2015; Sun et al., 2018). In general, the level of NO\textsubscript{x} adsorption performance determines the alternative strategy for eliminating NO\textsubscript{x}. Many different types of catalytic decomposition materials have been employed for NO\textsubscript{x} removal (Sun et al., 2018).

Polyoxometalates (POMs) have been extensively studied due to their excellent properties (pseudo-liquid phase, strong Bronsted acidity, and remarkable redox properties) (Ren et al., 2017a, b). As a new type of green environmental protection material, POMs has been used in a variety of catalytic fields (Wang and Yang, 2015; Wei et al., 2018; Liu and Wang, 2019). Especially, the Keggin-type heteropolyacid (HPA) show attractive NO\textsubscript{x} adsorption behavior (Heylen et al., 2010). Yang and Chen reported that NO\textsubscript{x} adsorbed on phosphotungstic acid (H\textsubscript{3}PW\textsubscript{12}O\textsubscript{40}·6H\textsubscript{2}O; HPW) was stimulated in the form of protonated NO\textsubscript{x} (NOH\textsuperscript{+}), which weakened the N-O band. The break of N-O generated in the rapid heating process, thus resulting in the yield of N\textsubscript{2} (Chen and Yang, 1995; Yang and Chen, 2004). Moffat et al. (1995) have further claimed that the adsorbed quantities of NO\textsubscript{x} followed the order of H\textsubscript{3}PW\textsubscript{12}O\textsubscript{40} > H\textsubscript{2}SiW\textsubscript{12}O\textsubscript{40} > H\textsubscript{2}PMO\textsubscript{12}O\textsubscript{40}. However, pure HPA has a small specific surface area, low mechanical strength and is easily soluble in polar molecules. The high heating rate may easily cause the oven temperature to exceed the target temperature, leading to inactivation of HPA with inferior thermal stability, which makes it difficult to reuse in practical applications (Ma et al., 2012; Zhang et al., 2013). In order to increase the adsorption capacity, catalytic decomposition activity and catalyst stability, many heteropolyacid-based adsorbent materials have been developed. Zhang and Wang (2013) designed a new HPW-USY catalyst with a three-dimensional bottle-in-boat structure, which has high thermal stability and good NO\textsubscript{x} decomposition performance. HPW/CNTs catalysts were prepared and the results show that the yield of N\textsubscript{2} by microwave heating is higher than that of rapid heating by resistance furnace (Zhang et al., 2012). In representative lean-gas mixture conditions, the performance of NO\textsubscript{x} storage and reduction over H\textsubscript{3}PW\textsubscript{12}O\textsubscript{40}·6H\textsubscript{2}O loaded on Ti-Zr and Ce-Zr were studied, which possess high nitrogen selectivity.
Ceria (CeO$_2$) as a catalyst promoter and catalyst has attracted considerable attention in the three-way catalyst (TWC) system owing to its excellent oxygen storage capacity (OSC), redox properties and ability to serve as a good support (Katta et al., 2010; Zhu et al., 2017). HPW-supported CeO$_2$ composites have been reported as the SCR catalysts (Song et al., 2017; Weng et al., 2016; Geng et al., 2018), and the composites exhibit synergistic interaction due to their improved specific surface area and exposure of more acidic sites. As is well known, there are few reports on HPW-supported CeO$_2$ materials for adsorption and decomposition of NO$_x$. Detailed investigation of the key factors in the experimental process and reaction mechanisms are still need further research.

In this work, to improve the thermal stability and specific surface area of HPW, and to avoid inactivation of HPW due to exceeding the target temperature at high heating rate, a series of heteropolyacid-based adsorbent materials supported by CeO$_2$ were synthesized and used for vigorous removal of NO$_x$. The synthesized HPW/CeO$_2$ were characterized by powder X-ray diffraction (XRD), Fourier-transform infrared (FTIR) spectroscopy and Brunauer-Emmett-Teller (BET) analysis. The denitrification performance of HPW/CeO$_2$ was determined by the dynamic NO$_x$ adsorption study, along with various relevant factors.

### SYNTHESIS OF HPW-LOADED MATERIALS

#### The Transition Metal Doped Ceria-based Solid Solutions

CeO$_2$ support was prepared by precipitation method. NH$_3$·H$_2$O solution were added dropwise to the solution containing Ce(NO$_3$)$_3$·6H$_2$O with continuous stirring until pH = 10. The precipitate was then filtered and washed three times with sufficient deionized water and absolute ethanol. The CeO$_2$ support was obtained after drying at 100°C for 12 h and calcination at 750°C for 4 h.

The HPW-doped CeO$_2$ supports was prepared by impregnation method. A certain mass ratio of the supports was immersed in a quantitative HPW solution for 24 h, and then dried in a 60°C water bath for 1 h to obtain the samples. The samples are denoted as x%HPW/CeO$_2$ (x is the mass ratio of HPW/CeO$_2$).

#### Catalyst Characterization

FTIR spectroscopy was performed on a Nicolet Avatar 370 and the spectral was recorded in the range of 400–4000 cm$^{-1}$ with a 4 cm$^{-1}$ resolution. The XRD patterns were recorded with a Rigaku D/Max-RA powder X-ray diffractometer, using Cu Kα monochromatized radiation at a scan speed of 5° min$^{-1}$. BET surface areas of the catalysts were measured by N$_2$ adsorption using a Micromeritics ASAP 2010 apparatus.

#### Activity Tests

##### Standard Test Procedure: Adsorption Stage

The tests were conducted in a fixed-bed quartz tube reactor of 8 mm internal diameter. The amount of catalyst used is 0.2 g. The sample was first placed in the middle of the reactor between two quartz wool plugs and pretreated in a highly purified N$_2$ stream at 150°C for 1 h. During NO adsorption, the feed gas containing NO, O$_2$, H$_2$O and balance N$_2$ was passed through the bench blending reactor and partially converted to NO$_2$ (2NO + O$_2$ = 2NO$_2$), obtaining a mixture of NO and NO$_2$. TH-990S NO and NO$_2$ analyzers were used to continually record the concentration of NO and NO$_2$ in the outlet.

The NO$_x$ adsorption amount is calculated by integrating the curve below the baseline (1000 ppm) and expressed in mg NO$_x$ g$^{-1}$ HPW$^{-1}$. The calculation formula is shown below:

$$M = \frac{\int_0^t Q \, C \, dt}{m}$$

where $m$: mass of adsorbent (g), $Q$: total gas flow (m$^3$ min$^{-1}$), $C$: NO$_x$ removal concentration (mg m$^{-3}$), $t$: adsorption time (min).

##### Decomposition Stage

After NO$_x$ adsorption, saturation, the reactor containing catalyst was purged with He flow (5 mL min$^{-1}$) for 1 h. Then reactor placed in an oven was rapid heated from 30°C to 450°C at a heating rate of 150°C min$^{-1}$. The decomposition product was detected by GC-MS analyzer.

NO conversion was then calculated by: $N_2$ yield = $N_2$ formation/NO adsorbed, where $N_2$ adsorbed represents the NO$_x$ adsorbed amount of HPW and $N_2$ formation represents the generated $N_2$ amount during NO$_x$ decomposition.

## RESULTS AND DISCUSSION

### Characterizations

Figs. 1 and 2 are XRD and FTIR spectra of HPW and HPW/CeO$_2$ with different loadings, respectively. It could be seen that XRD patterns of CeO$_2$ correspond to that of a mixture of cubic fluorite structure (PDF: 43-1022). The crystalline-phase HPW diffraction peak appears when the HPW loading is 40%. With the increase of the HPW loading, the diffraction peaks attributed to the HPW crystal phase and its peaks intensity gradually increases. It can be seen from Fig. 2, pure CeO$_2$ has only a strong peak assigned to symmetrical stretching mode of Ce-O at about 450 cm$^{-1}$. For HPW, several distinct characteristic peaks can be observed. According to the previous studies (Yang et al., 2005; Cheng and Wang, 2013), the peaks at 1083 and 988 cm$^{-1}$ can be ascribed to the stretching vibration of P=O-O and W=Ox, and the stretching of W=O=x-W between edge-sharing octahedra and vibration of W=O=W between vertex-sharing W=O$_{13}$ octahedra appeared approximately at about 802 and 891 cm$^{-1}$, respectively, which is an accepted way to identify Keggin structure of HPA. In addition, the band at 1640 cm$^{-1}$ are characteristic peak of lattice water in HPA. When the HPW loading is 70%, the characteristic peaks of the Keggin structure appear at 700–1100 cm$^{-1}$, indicating that the basic Keggin structure does not change after the HPW loaded on CeO$_2$. The results of BET analysis showed that the specific surface area of HPW is only 3.2 m$^2$ g$^{-1}$. When HPW was supported on CeO$_2$, its specific surface area is as high as...
13.8 m² g⁻¹ (70%HPW/CeO₂), which also indicates that HPW was effectively loaded on the CeO₂ support.

**Effect of HPW Loading on NOₓ Adsorption**

The effect of HPW loading on NOₓ adsorption was investigated over CeO₂ as support. As can be seen from Fig. 3, the adsorption rate of NOₓ of the mixture was higher than pure oxide. After the loading of HPW is increased to 50%, the adsorption rate of the system rapidly increases to 74.6%, and the best removal rate, i.e., 75.3%, is obtained over 70%HPW/CeO₂. Combined with the XRD and IR characterization results of the HPW/CeO₂ system, it can be seen that when the HPW loading is 70%, the crystal phase of HPW on the support surface is almost identical to the pure HPW. Although HPW is the active component of the system, the adsorption rate of NOₓ of the mixture increased by nearly 10% compared to HPW (66.3%). This indicates that CeO₂ is an excellent carrier, and there is a synergistic effect between CeO₂ and HPW. Considering this fact, 70%HPW/CeO₂ is used as the representative material to further explore the effect of different experimental factors on NOₓ adsorption performance in the following section.

**Effect of Oxygen Content on NOₓ Adsorption**

The oxygen content is an important factor for affecting the NOₓ adsorption performance. NOₓ adsorption experiments were carried out at different oxygen content over 70%HPW/CeO₂ and the results were shown in Fig. 4. It can be seen that under oxygen-free conditions, the adsorption rate is low at only about 20%. As the oxygen content increases, the adsorption rate of the system gradually increases. When the oxygen content reaches 8%, the maximum adsorption rate is obtained, and the adsorption rate remains stable even with further increase of oxygen content. Therefore, the suitable oxygen content for NOₓ adsorption by HPW/CeO₂ system is 8%.

**Effect of Water Vapor Content on NOₓ Adsorption**

Fig. 5 shows the adsorption performance of 70%HPW/CeO₂ at different water vapor content. It can be clearly seen that the adsorption rate shows a volcanic curve with the increasing water vapor content. When the water vapor content is less than 4.2%, the adsorption rate increases with the water vapor content. However, when the water vapor content is higher than 4.2%, the adsorption rate is gradually decreasing. The suitable water vapor content for NOₓ adsorption in HPW/CeO₂ system is about 4.2%.

**Effect of Reaction Temperature on NOₓ Adsorption**

Temperature is a key factor for chemical reactions, especially for adsorption experiments. Fig. 6 shows the effect of temperature on the NOₓ adsorption performance of HPW/CeO₂ system. In the temperature range of 125–250°C, NOₓ adsorption rate is maintained above 60%. When the reaction temperature is 170°C, the adsorption rate can reach to 76.3%. After the temperature rises to 300°C, the adsorption rate drops sharply to less than 50%. The experimental results
show that HPW has better thermal stability when supported on CeO$_2$, and the suitable temperature for HPW/CeO$_2$ is 170°C.

**Fig. 4.** The effect of oxygen content on the NO$_x$ adsorption over 70%HPW/CeO$_2$. Reaction conditions: 800 ppm NO, 8% O$_2$, 4.2% H$_2$O, SV = 5298 h$^{-1}$.

**Fig. 5.** The effect of water vapor content on the NO$_x$ adsorption performance. Reaction conditions: 800 ppm NO, 8% O$_2$, T = 150°C. SV = 5298 h$^{-1}$.

**Fig. 6.** NO$_x$ adsorption curves of 70%HPW/CeO$_2$ at different temperatures. Reaction conditions: 800 ppm NO, 8% O$_2$, 4.2% H$_2$O, SV = 5298 h$^{-1}$.

**Fig. 7.** NO$_x$ adsorption performance under different space velocity. Reaction conditions: 800 ppm 8% O$_2$, 4.2% H$_2$O, T = 150°C.

**Fig. 8.** The effect of initial NO concentration on the NO$_x$ adsorption performance. Reaction conditions: 8% O$_2$, 4.2% H$_2$O, T = 150°C, SV = 5298 h$^{-1}$.

**The Effect of Space Velocity on NO$_x$ Adsorption**

The space velocity (SV) of reaction gas could be also a factor for its removal in the process due to the residence time of the gas in the reactor can be actually affected by the change of space velocity. Therefore, the effect of space velocity of NO$_x$ on NO$_x$ adsorption performance of HPW/CeO$_2$ at 150°C was studied (Fig. 7). It should be noted that the adsorption rate of the system decreases as the space velocity increases, indicating that free diffusion of gas has little effect on the adsorption surface reaction. The experimental results are mainly due to the reduction of the residence time of gas in the reactor by the changing space velocity. Considering the space velocity is in the range of 2649–5298 h$^{-1}$, the adsorption rate of NO$_x$ is relatively stable, and its decrease sharply due to the increasing space velocity. Therefore, the suitable space velocity for the adsorption of NO$_x$ by the HPW/CeO$_2$ system is 2649–5298 h$^{-1}$.

**Effect of Initial NO Concentration**

Fig. 8 shows the effect of initial NO concentration on the NO$_x$ adsorption performance of the system. With the
increase of the NO concentration of intake gas, the adsorption rate of the system gradually decreases. It should be noted that a linear relationship is exhibited between the NO adsorption rate and the initial NO concentration. When the initial concentration of NO is 387 ppm, the adsorption rate of the system is up to 79.3%.

**Adsorption Mechanism**

Under optimized experimental conditions (800 ppm NO, 8% O₂, 4.2% H₂O, T = 150°C, SV = 5298 h⁻¹), the saturated adsorption capacity was calculated. The saturation adsorption capacity of the system is significantly increased after the HPW was supported on CeO₂, and the saturation adsorption time became shorter. Based on experimental data, the saturated adsorption of NO₂ by HPW catalyst is 50.5 mg-NO₂ g⁻¹-HPW⁻¹. In addition, as shown in Table 1, the saturated adsorption of NO₂ by 70%HPW/CeO₂ catalyst is up to 85.6 mg-NO₂ g⁻¹-HPW⁻¹, which is higher than that of Ti-Zr (28 mg-NO₂ g⁻¹-HPW⁻¹) and TiO₂ (46 mg-NO₂ g⁻¹-HPW⁻¹) as support reported in previous literature (Hodjati et al., 2001b; Gómez-García et al., 2005a). Combined with the results of BET analysis, when HPW is loaded on CeO₂, support (70%HPW/CeO₂), its specific surface area is as high as 13.8 m² g⁻¹, which is much higher than the specific surface area of HPW (3.2 m² g⁻¹). That indicates that HPW could be highly dispersed on the CeO₂, leading to more available adsorption sites were used for NO adsorption.

The IR spectra of HPW before and after adsorption saturation are shown in Fig. 9. In the range of 700–1100 cm⁻¹, four characteristic peaks of Keggin structure for 70%HPW/CeO₂ after adsorption saturation still exist, indicating that the Keggin structure of HPW has not changed. In addition, a new characteristic peak appears at 2266 cm⁻¹ and the characteristic peak of H₂O (in secondary structure of HPW) at 1617 cm⁻¹ become weaker.

According to previous reports, there are two different viewpoints on the characteristic peak at 2266 cm⁻¹. Bélanger and Moffat (1995) reported that the characteristic peak at 2266 cm⁻¹ is caused by HNO₂ vibration. The interaction of NO₂ and HPW is not only appeared on the surface. NO₂ can also enter the secondary structure of HPW and combine with protons in the secondary structure to form HNO₂⁺ (Chen and Yang (1995) and Yang and Chen (2004) carried out NO₃ adsorption tests over HPW, and considered that the characteristic peak at 2266 cm⁻¹ was caused by NOH⁺ vibration. In the presence of oxygen, NO can pass through the surface of HPW into its bulk to replace H₂O⁺ in the secondary structure, and finally NOH⁺ is formed. Thermogravimetric analysis (TGA) and calculation of mass conservation principle of nitrogen proved that the bond with HPW is NO instead of NO₂. Hodjati et al. (1998) used KPW as an adsorbent to perform NO₃ adsorption experiments, and the DRIFTS results showed that the ion of NO₃ is only adsorbed on the surface of KPW (KPW does not contain crystal water). Besides the other characteristic peaks of NO⁺, NO₂⁺ and NO₃⁻ are detected on the surface of KPW after adsorption saturation. This result supported the view of Yang and Chen (2004), and the mechanism of NOH⁺ formation was proposed.

Based on the above analysis, we believe that the characteristic peak at 2266 cm⁻¹ is caused by the NOH⁺ vibration entering the HPW secondary structure for 70%HPW/CeO₂. There is an antisymmetric stretching vibration peak near 2300 cm⁻¹ for NO⁺, which is only 34 cm⁻¹ different from the vibration peak at 2266 cm⁻¹ detected by this experiment. The stretching vibration peak of NO₂⁺ mainly exist in 2350–2375 cm⁻¹. The minimum difference between stretching vibration peak of NO₂⁺ and the peak at 2266 cm⁻¹ detected by the experiment is 84 cm⁻¹. On the other hand, the characteristic peaks of bending vibration of NO₂⁺ and the characteristic peaks of N₂O₃ on the surface of 70%HPW/CeO₂ were not detected. Furthermore, the weakening characteristic peak of H₂O at 1617 cm⁻¹ is mainly caused by the partial crystal water in the HPW secondary structure being replaced by NOH⁺. This experimental result is consistent with the conclusion of Herring et al. (1998). The heteropolyacid used in this work is H₃PW₁₂O₄0·6H₂O. At most, six crystal water molecules can be replaced in one HPW molecule and there is competitive adsorption between H₂O and NO. Therefore, a conclusion can be draw for HPW/CeO₂ system, namely, NO₂ is adsorbed on the surface of HPW in the form of NOH⁺, and NOH⁺ enters its bulk phase by replacing part of the crystal water in the secondary structure of HPW.

**Catalytic Decomposition of Adsorbed NO**

GC-MS was used to detect the decomposition products, and N₂ was found in the products. The results are shown in Fig. 10. The decomposition characteristics of adsorbed NO₂ on HPW and HPW/CeO₂ catalytic systems are similar. The detected N₂ reaches a peak at about 10 min, and the decomposition is basically completed at about 20 min. The results of this experiment show that NO in an oxygen-enriched atmosphere, HPW/CeO₂ catalytic systems can achieve a better decomposition and conversion effect due to the interaction between two components. Therefore, a new heteropoly compound catalysis system has been design for NO₂ elimination by adsorption/decomposition and the catalytic conversion of NO₂ to N₂ can be achieved without

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**Table 1. NO₂ adsorption capacity of different catalyst systems.**

| Catalyst   | NO₂ adsorption capacity (mg-NO₂ g⁻¹-HPW⁻¹) | Ref.                  |
|------------|------------------------------------------|-----------------------|
| HPW        | 38                                       | Hodjati et al. (2001a) |
| HPW/Ti-Zr  | 28                                       | Gómez-García et al. (2005a) |
| HPW/TiO₂   | 46                                       | Hodjati et al. (2001b)  |
| HPW/SiO₂   | 17                                       | Zhang and Wang (2013)  |
| HPW/NaY    | 2.38                                     | This work             |
| HPW/CeO₂   | 85.6                                     |                       |
in tungstophosphoric acid.

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ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Nos. 20576064 and 20776080) and the Key Research and Development Program of Shandong Province, China (2017GSF217006; 2008GG10006005).

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CONCLUSIONS

In this study, we synthesized catalysts composed of CeO2 and varying percentages of HPW and assessed their capacity to adsorb and decompose NOx. The adsorption performance of the most efficient catalyst, 70%HPW/\text{CeO}_2, was approximately linearly proportional to the initial NO concentration. The optimal conditions for adsorption were an environment containing 8% O2 and 4.2% H2O, a reaction temperature of 170°C, and a space velocity of 2649–5298 h–1. The IR spectra of the HPW revealed similar adsorption mechanisms for reducing agents. The used catalyst can be placed in humid air (5% water vapor), and HPW can replenish the lattice water replaced by NOx by adsorbing water molecules, thereby regenerating the catalyst. Detailed decomposition mechanism and process of the conversion of the adsorbed intermediate product (NOH) into N2 by the temperature programming process need to be further investigated.
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Received for review, March 22, 2020
Revised, April 23, 2020
Accepted, May 1, 2020

Zhu et al., Aerosol and Air Quality Research, 20: 2273–2279, 2020