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# Adverse effects of potassium on NO<sub>x</sub> reduction over Di-Air catalyst (Rh/La-Ce-Zr)

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## ABSTRACT

The influence of potassium in Rh on a lanthium promoted zirconia stabilised ceria (CZ) catalysts was studied toward NO<sub>x</sub> reduction reactivity and selectivity. The results are compared with a Rh/CZ catalyst. The samples were characterised by N<sub>2</sub> adsorption, XRD, SEM, ICP, and H<sub>2</sub>-TPR. The study highlighted the importance of stored NO<sub>x</sub> regeneration over potassium in determining the overall performance of the Rh/K/CZ catalyst. The NO<sub>x</sub> stored over Rh/K/CZ in the previous NO gas stream cannot be regenerated sufficiently during the C<sub>3</sub>H<sub>6</sub> gas stream, and stored NO<sub>x</sub> gradually decreased from one cycle to the next, resulting in deteriorating performance of Rh/K/CZ. Besides, problem of NO<sub>x</sub> slip, the formation of both NH<sub>3</sub> and N<sub>2</sub>O (selectivities up to 30% for each side product) were observed by the addition of potassium into the Rh/CZ catalyst system, depending on the reaction conditions applied and the severity of the catalyst deactivation.

## 1. Introduction

Recently, the car manufactures and catalyst company are struggling to lower the NO<sub>x</sub> emission. Unfortunately, the on-road real NO<sub>x</sub> emissions are much higher than those are allowed under the Europe 6 emission regulation driving legislation [1–3]. Ammonia/ Urea-SCR is a mature technology to reduce NO<sub>x</sub> emission from stationary sources and heavy-duty vehicles [4–6]. Although NH<sub>3</sub> (or urea) is an efficient reducing agent, the requirement for an injection system and NH<sub>3</sub> slip problem affect the economics and practicability of this application to passenger car, especially under the dynamic driving conditions. NO<sub>x</sub> Storage and Reduction (NSR) system [7–9], developed by Toyota researchers, is regarded as the leading technology to control NO<sub>x</sub> emission under lean-burn conditions. The engine is operating in the order of 60 s under the excess of oxygen (lean) condition. Subsequently, small hydrocarbon pulses are (in the order of 3 to 5 s) injected into the engine to create short periods with a reducing (rich) condition. Many challenges have still to be resolved. Firstly, the NO<sub>x</sub> conversion decreases at high gas-flow conditions and at high temperatures. Secondly, during the lean and rich cycle switching step, the NO<sub>x</sub> slip problem (up to 30% slip of the stored NO<sub>x</sub>) is highly unwanted. Thirdly, the formation of side products N<sub>2</sub>O (very strong greenhouse gas) and NH<sub>3</sub> (toxicity) are of a major environmental concern. Most importantly, in the studies on the NSR catalyst using even most active reductant (H<sub>2</sub>), the results showed that although at a relatively low temperature, the NO<sub>x</sub> storage

capacity was sufficient, but that the rates of NO<sub>x</sub> release and reduction (NO<sub>x</sub> conversion into nitrogen) were slow and insufficient, respectively [10,11]. These drawbacks of the NSR technology will limit its application in the real driving, especially as of September 2017 in Europe. The European Commission had proclaimed that the real driving emission (RDE) test protocol will partially replace the current certification laboratory test [12].

The application of the RDE requires that the catalyst has to work in wide temperature window and with a high space velocity (short contact time). Alternatives to the NO<sub>x</sub> Storage Reduction and Ammonia (urea)-SCR systems, Di-Air system, Diesel NO<sub>x</sub> after treatment by Adsorbed Intermediate Reductants, is under development, which is promising technology to efficiently abate NO<sub>x</sub> especially at high temperatures and high flows all of the time in a lean burn exhaust gas stream. In this Di-Air system, continuously short fuel injections with a high frequency are applied downstream of the engine in the exhaust system upstream of a NSR catalyst (Pt/Rh/Ba/K/Ce/Al<sub>2</sub>O<sub>3</sub>) [13]. Limited information and experience are reported in both the open literature and patents archives on this newly developed technology. Mechanistic studies, especially on the individual role of each catalyst component in the Di-Air system, are required to develop to reduce more deeply NO<sub>x</sub> emissions from lean-burn gasoline and diesel vehicles and can come in compliance with the current and future more stringent NO<sub>x</sub> emission standards.

In our previous work, the catalyst containing noble metal, especially Rh, and ceria are the promising starting materials for the Di-Air system.

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Ceria was found to be an critical catalyst ingredient in the Di-Air system. During the fuel injection, the oxygen from the ceria lattice can react with the fuel, resulting in several layers of ceria support reduction and a carbon deposition on the ceria surface [14]. The oxygen defects of ceria were found to be the key sites for the NO reduction into N<sub>2</sub> [15]. The deposited carbon formed during the fuel injection, acted as a buffer reductant. The oxidation of the deposited carbon will occur *via* the oxygen from the ceria lattice, which created additional oxygen vacancies for additional NO reduction. The loading of noble metals over the ceria, e.g. Rh and Pt, can efficiently lower the ceria support reduction temperature by the fuel [16]. Additionally, the presence of noble metal will accelerate the N<sub>2</sub> formation rate. More importantly, the reduction of NO over a reduced Rh or Pt loaded ceria showed that NO was still selectively reduced into N<sub>2</sub> in an excess of oxygen (a factor of 100 in respect to NO, which is a typical value for a diesel engine exhaust stream) [17].

In the Di-Air system by Toyota, potassium (K) is one of the ingredients of the catalyst composition. Potassium (and/or barium) is a common ingredient in NSR catalyst, acting as the NO<sub>x</sub> storage component during the fuel lean stage of the engine operation. The stored NO<sub>x</sub> will be released and react with reductants from and during the fuel rich stage [18]. However, the reduction of the stored NO<sub>x</sub> over potassium or barium is somewhat restricted or a kind of bottleneck for the entire NO<sub>x</sub> storage and reduction process. NO<sub>x</sub> storage sites are not completely regenerated during the fuel rich stage if the temperature was below 400 °C [19,20]. Furthermore, the amount of NO<sub>x</sub> released relatively to the amount stored decreased with decreasing temperatures, which can be determined by the relative rate of reductant production (from the fuel injection), nitrate decomposition, OSC (oxygen storage capacity) consumption, and actual NO<sub>x</sub> reduction over the noble metal site of the NSR catalyst [20].

For a further optimisation the overall catalyst formulation and improving the performance of the Di-Air catalysts, it is meaningful to clarify whether potassium is required to add in the catalyst composition. Can the addition of potassium into Di-Air catalyst influence on the NO<sub>x</sub> reduction performance, especially in NO<sub>x</sub> slip, N<sub>2</sub>O and NH<sub>3</sub> formation, and the deactivation on catalyst performance, which were so far not observed in the simplified Di-Air system of only a Rh and ceria based catalyst composition. To answer these questions, the NO reduction experiments on a ceria and Rh ceria based catalyst with the addition of potassium with simulated exhaust gasses were performed. Controlled experiment without potassium loading was included into the experiment approach.

## 2. Experimental

### 2.1. Materials preparation

Rh/CZ was prepared *via* an incipient wetness impregnation method of a rhodium precursor on Zr-La doped ceria (denoted as CZ, a gift from Engelhard, now BASF). Rhodium (III) nitrate hydrate (Aldrich, ~36% rhodium (Rh) basis) was used as the precursor. Subsequently, the sample was dried at 110 °C overnight and calcined at 550 °C for 5 h. For Rh/K/CZ, potassium was loaded on Rh/CZ by using incipient wetness impregnation method with KHCO<sub>3</sub> (Aldrich) as precursor. Subsequently, the sample was dried at 110 °C overnight and calcined at 550 °C for 5 h in a static air furnace.

### 2.2. Characterisation

#### 2.2.1. Inductively coupled plasma optical emission spectroscopy (ICP-OES)

Approximately 50 mg of sample was destructed in 4.5 ml 30% HCl + 1.5 ml 65% HNO<sub>3</sub> using the microwave. The destruction time in the microwave was 120 min at max power of 900 W. After destruction, the samples were diluted to 50 ml with MQ water. The samples were analysed with ICP-OES (PerkinElmer Optima 5300).

#### 2.2.2. N<sub>2</sub> adsorption

Tristar II 3020 Micromeritics was used to determine the textural properties like specific BET surface area and pore volume. The catalyst samples were degassed at 200 °C for 16 h in a vacuum (0.05 mbar) before the nitrogen adsorption. The adsorption measurement was carried at -196 °C.

#### 2.2.3. Scanning Electron microscopy (SEM) and energy-dispersive X-ray (EDX) analysis

SEM images and EDX mapping of Rh/K/CZ was performed by using scanning electron microscope (JEOL JSM-6010 LA) equipped with an integrated EDX (Standard LA Version) with Silicon Drift Detector (SDD). The samples were analysed at accelerating voltage of 20 kV.

#### 2.2.4. X-ray diffraction (XRD)

The Powder X-Ray diffraction (XRD) was recorded on a Bruker-AXS D5005 with a Co K $\alpha$  source. The data were times collected by varying the 2 $\theta$  angle from 30° to 90° with a step size of 0.02.

#### 2.2.5. Temperature programming reaction (TPR)

TPR for all the samples were carried out in a fixed bed reactor system connected to a thermal conductivity detector (TCD) to monitor the consumption of hydrogen by the catalyst. 200 mg of samples were packed between SiC layers (300–425  $\mu$ m). The samples were then reduced in the H<sub>2</sub> (10%)/Ar flow at a flow rate of 30 ml<sub>STP</sub> min<sup>-1</sup>, with temperature from room temperature to 1000 °C with a heating rate of 5 °C/min. TCD was calibrated by using CuO as a reference. A perma-pure tubular drier was used to remove the water produced during the reduction upstream of the TCD detector.

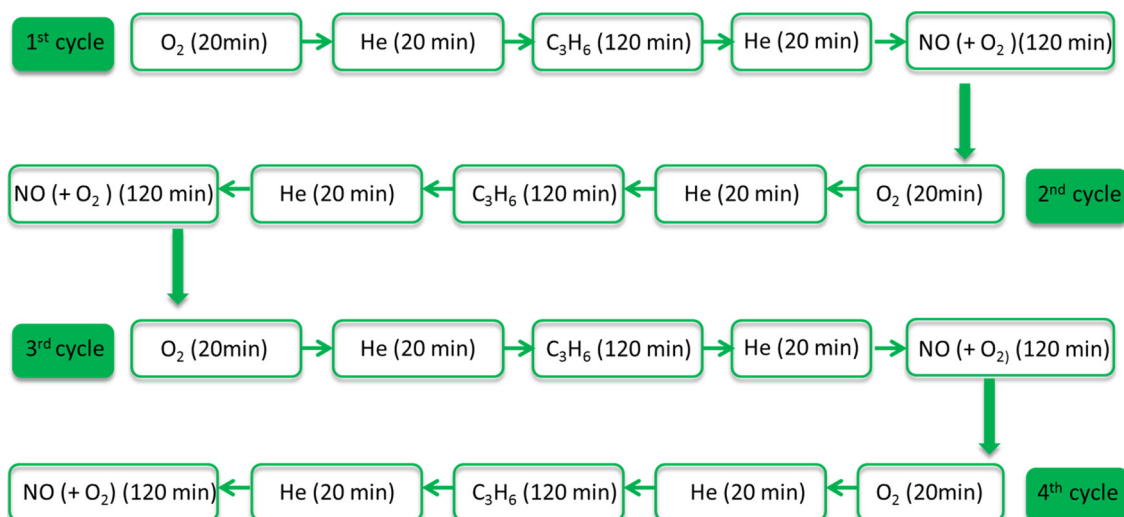
### 2.3. Catalytic testing

#### 2.3.1. Reactivity and selectivity study in flow reactor

A flow reactor was explored for the study of the NO reduction reactivity and selectivity with and without gas-phase oxygen. 200 mg catalyst was placed in a 6 mm inner-diameter quartz reactor tube. The reactor effluent was online analysed by a mass spectrometry (MS, Hiden Analytical, HPR-20 QIC) and infrared (IR) spectroscopy (Perkin-Elmer, Spectrum One). For the IR analysis a gas cell with KBr windows with a path length of ~5 cm was used. The spectra were measured in a continuous mode using the Perkin-Elmer 'Time-Base' software between 4000 - 700 cm<sup>-1</sup> wavenumbers with a spectral resolution of 8 cm<sup>-1</sup> and an acquisition of 8 scans per spectrum, resulting in a time interval of 23 s between each displayed spectrum. For the NO reduction in the presence of O<sub>2</sub>, a feed composition of 0.2% NO and 5% of O<sub>2</sub> (with He as balance) was used with a space velocity of 67.0000 L/L/h. Prior to the feeding in 0.2% NO and 5% O<sub>2</sub> in He, the catalyst was firstly pre-treated by 1.25% C<sub>3</sub>H<sub>6</sub> in He for 2 h. Scheme 1 described the experiment procedural.

#### 2.3.2. He-Temperature programmed desorption (TPD) after NO and O<sub>2</sub> co-adsorption

200 mg catalyst was placed inside a quartz tube. The reactor effluent was online analysed by infrared (IR) spectroscopy (Perkin-Elmer, Spectrum One). Prior to Temperature Programmed Desorption experiments, the sample was firstly oxidised at 600 °C with 5% O<sub>2</sub> in He in order to remove carbon residues, e.g. adsorbed CO<sub>2</sub>. Subsequently, the samples were exposed to the reactive gas ((2000 ppm NO + 5 % O<sub>2</sub>)/He balance) at 200 °C for 10 h. Afterward, the samples were outgassed in He in order to remove the weakly bound physical adsorbed NO<sub>x</sub>. After cooling down to 40 °C, the samples were heated up from 40 to 700 °C with a heating rate of 5 °C / min using He as the carrier gas (200 ml / min). Concentration profiles of NO, N<sub>2</sub>O, and NO<sub>2</sub> in parts per million (ppm) were obtained. The IR spectrometer was calibrated with 1% NO, 1% N<sub>2</sub>O, and (1% N<sub>2</sub> + 2% O<sub>2</sub>) in He, respectively.



Scheme 1. Experimental protocol in the fixed bed reactor.

### 2.3.3. In-situ drift

Infrared spectra were recorded in the  $4000 - 700 \text{ cm}^{-1}$  range (resolution =  $8 \text{ cm}^{-1}$ , 128 scans), performed by a Thermo Scientific Nicolet 8700 FT-IR spectrometer using MCT detector with a KBr beam splitter. The catalyst was placed in the cell and the gas was flown through the catalyst bed ( $30 \text{ ml}_{STP} \text{ min}^{-1}$ ), confined in a three-window chamber.

### 2.3.4. Temporal analysis of products (TAP) study

$\text{H}_2$  and  $\text{C}_3\text{H}_6$  titration experiments were performed in TAP over a pre-oxidised and pre-nitrated Rh/K/CZ to reduce oxidised and nitrated Rh/K/CZ, respectively. Pre-oxidised Rh/K/CZ was exposed to about 2000 pulse of 80 vol. %  $\text{O}_2$  in Ar, and pre-nitrated sample was exposed to about 2000 pulse of 80 vol. %  $^{15}\text{NO}$  in Kr. Rh/K/CZ reduction experiments were performed by using either 66.7 vol. %  $\text{H}_2$  in Ar or 80 vol. %  $\text{C}_3\text{H}_6$  in Ne both at  $450^\circ\text{C}$ .

The NO reduction was performed using 80 vol.%  $^{15}\text{NO}$  in Kr over Rh/CZ and Rh/K/CZ.  $\text{H}_2$  was used to pre-reduce the samples until  $\text{H}_2$  and  $\text{H}_2\text{O}$  MS signals were stable. Subsequently,  $^{15}\text{NO}$  was pulsed.

10 mg Rh/CZ and Rh/K/CZ were investigated in the TAP reactor. In all experiments starting pulse sizes of approximately  $2 \cdot 10^{15}$  molecules, including reactants (80 vol. %) and inert gas (20 vol. %), were used. The inert gas was used as internal standard. The pulse size gradually decreased during an experiment since as the reactant was pulsed from a closed and calibrated volume of the pulse-valve line. Details can be found elsewhere [15].

## 3. Results

### 3.1. Characterisation

Characterisation details of the Zr-La doped ceria support (hereafter denoted as CZ) were reported elsewhere [15,21]. In brief, a typical fluorite structure of CZ was detected by Raman and XRD. The crystal size of CZ determined by the Scherrer's equation and TEM image analyses was 5.0 nm for both techniques. The BET surface area was  $65 \text{ m}^2/\text{g}$ . The BET surface area of fresh and used Rh/CZ and Rh/K/CZ were similar to the bare CZ support ( $65 \pm 2 \text{ m}^2/\text{g}$ ). Measured by the ICP-OES, the loading of Rh was determined to be 0.5 wt % for the samples of Rh/CZ and Rh/K/CZ. The particle size of Rh was around 2 nm from TEM [17]. The loading of K was determined to be 5 wt % for the samples of K/CZ and Rh/K/CZ. Fig. 1 shows the SEM and EDX mapping images of Rh/K/CZ. The intensities in EDX signal were represented as the colour code on the left scale. As shown in Fig. 1, Zr, La, and Ce were

all homogeneously distributed. K was highly homogenous dispersed with a few numbers of small agglomerates. Rh could not be detected due to its low loading (0.5 wt %).

Fig. 2A shows the XRD patterns of oxidised CZ, Rh/CZ, and Rh/K/CZ. The patterns of metal loaded samples showed the fluorite cubic structure of the CZ. Diffraction lines to be assigned to Rh and K metals or any their oxides could not be observed. The reduction properties of Rh/K/CZ, Rh/CZ, and CZ were studied by TPR- $\text{H}_2$  technique, as presented in Fig. 2B. The pure ceria generally showed two-peak pattern due to surface and bulk reduction at the temperature of  $500$  and  $750^\circ\text{C}$ , respectively [22]. The bare CZ sample showed a main broad reduction feature with roughly two peaks at  $430$  and  $550^\circ\text{C}$ . The lower temperature reduction peak as compared to the pure ceria might be due to the promotion of the reduction in the bulk of the mixed oxide upon doping with  $\text{ZrO}_2$  [23]. Compared to bare CZ support, surface and bulk reduction of Rh/CZ shifted to lower temperatures. For the Rh/K/CZ with a potassium loading of 5% potassium, the feature of low-temperature  $\text{H}_2$  reduction disappeared while the higher-temperature  $\text{H}_2$  reduction peak slightly shifted to a lower temperature in comparison to the Rh/CZ sample, but at the same time the consumption of hydrogen almost doubled. The amount of  $\text{H}_2$  consumption is reported in Table 1.

### 3.2. Catalytic testing

#### 3.2.1. NO reduction in the absence of $\text{O}_2$ in fixed bed reactor

Fig. 3 shows the results of exposure 0.2% NO/He over the  $\text{C}_3\text{H}_6$  reduced Rh/CZ at  $450^\circ\text{C}$  with a GHSV of  $67,000 \text{ L/L/h}$ . Fig. 3A shows the MS response of gasses from the exit of the reactor.  $m/e = 28$  was observed, attributed to the formation of  $\text{N}_2$  and CO. NO was not observed during the first 460 s. A low intensity of  $m/e = 44$  was observed, attributed to the formation of  $\text{CO}_2$ . Fig. 3B shows the FT-IR spectra of the gasses from the exit of the reactor. Peaks at  $2174$  and  $2116 \text{ cm}^{-1}$ , attributed to CO, were observed instantly when switching to the NO gas stream. The CO peak intensity increased to the maximum at the time of 250 s and then declining. Hardly any CO formation was observed after 1500s. A low intensity of peak at  $2350 \text{ cm}^{-1}$ , assigned to  $\text{CO}_2$ , was also observed during the first 500 s.  $1908$  and  $1850 \text{ cm}^{-1}$  were observed from 460 s onwards, assigned to NO. The rise of two bands at  $1601$  and  $1628 \text{ cm}^{-1}$  from 1500s onwards was attributed to the formation of  $\text{NO}_2$ . Small peaks at  $2235$  and  $2208 \text{ cm}^{-1}$ , assigned to  $\text{N}_2\text{O}$ , were only observed after 460 s, which was from the impurity in the NO gas bottle at the level of 1 ppm. The NO reduction experiments were recycled 4 times over the same Rh/CZ sample, as described in Scheme 1. The results could be repeated. The NO conversion showed the same reactivity

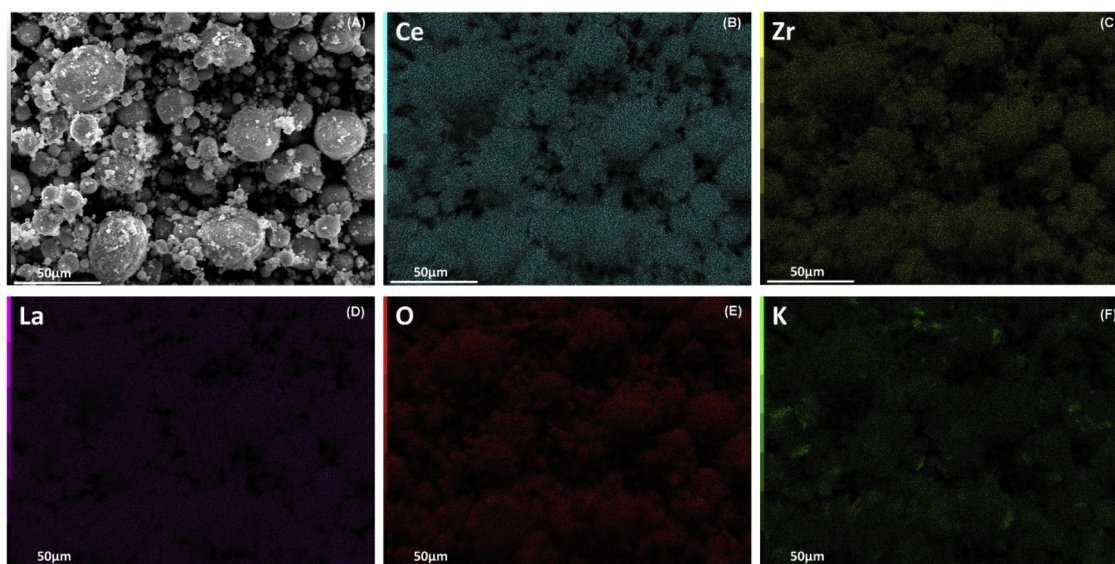


Fig. 1. SEM-EDX analysis of fresh Rh/K/CZ.

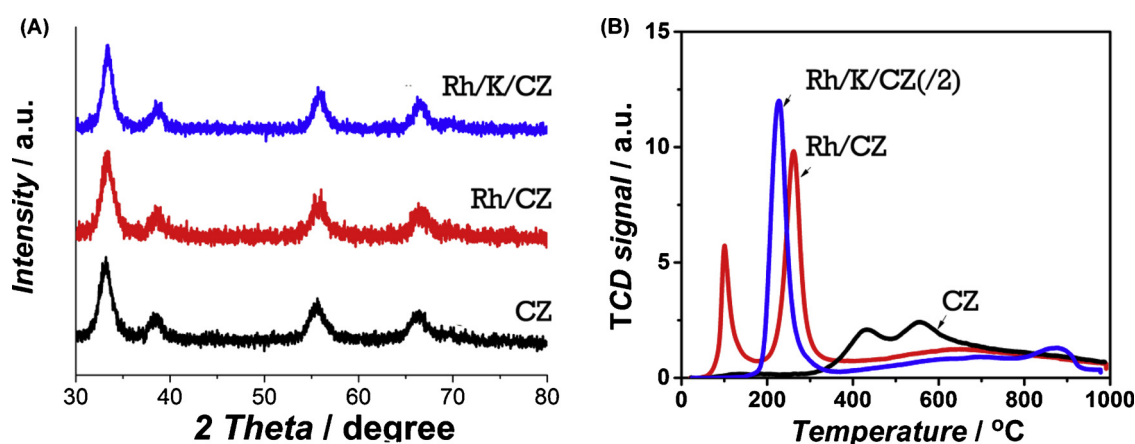
Fig. 2. (A) XRD patterns and (B) H<sub>2</sub>-TPR of oxidised CZ, Rh/CZ, and Rh/K/CZ.

Table 1

H<sub>2</sub> consumption in TPR experiments for Rh/K/CZ, Rh/CZ, and CZ.

Sample	H <sub>2</sub> consumption (mmol/g <sub>cat</sub> )
CZ	1.2
Rh/CZ	1.7
Rh/K/CZ	2.7

regardless to the number of NO cycles experiment.

The same experiments were performed over the sample containing potassium. Fig. 4 shows the results of the exposure of 0.2% NO/He over the fresh Rh/K/CZ pre-treated by C<sub>3</sub>H<sub>6</sub> at 450 °C with GHSV of 67,000 L/L/h. Fig. 4A shows the MS response of the gasses from the exit of the reactor. Similar to the result over Rh/CZ, m/e = 28 was observed, attributed to the formation of N<sub>2</sub> and CO. The CO formation was confirmed by FT-IR peaks at 2174 and 2116 cm<sup>-1</sup> (Fig. 4B). From Fig. 4C, the highest CO concentration was less than 500 ppm. Small amount of CO<sub>2</sub> formation was observed from the FT-IR spectra. No NO was observed during the first 750 s, followed by NO signal intensity gradually increased. The N<sub>2</sub>O band, centred at 2235 and 2208 cm<sup>-1</sup>, started to appear from the time of 500 s, arriving at a maximum level of 25 ppm (Fig. 4C).

The NO reduction experiments were additionally performed over

the used Rh/K/CZ, in which the Rh/K/CZ was firstly pre-adsorbed NO during the 1st NO reduction experiment and then pre-treated by C<sub>3</sub>H<sub>6</sub> during the 2nd cycle experiment, as described in Scheme 1. During the 2nd run of the NO experiment, NO started to form from t = 500 s. The NO signal increasing rate during the 2nd run of NO experiment was much steeper than that during the 1<sup>st</sup> run (Figs. 4C and 5 B). N<sub>2</sub>O formation was observed instantly when switching over to the NO gas stream. The highest CO concentration was around 50 ppm, which was less than that during the 1st run, as shown in Fig. 4C. During the 4th NO reduction experiment, NO started to be observed from the time of 475 s onwards. The NO signal increasing rate during the 4th run of NO experiment is similar to that during the 2<sup>nd</sup> run (Figs. 4C and 5 B). N<sub>2</sub>O was observed instantly upon NO exposure.

### 3.2.2. NO reduction in the presence of O<sub>2</sub> in fixed bed reactor

Fig. 6A shows the MS response during (0.2% NO + 5% O<sub>2</sub>)/He over the C<sub>3</sub>H<sub>6</sub> reduced Rh/CZ at 400 °C. Full NO conversion was observed during the first 69 s, followed by a gradual decreasing in the NO conversion. Both m/e = 28 and m/e = 44 were observed from the t = 0 s and their intensities dropped down from t = 23 s. The observation of m/e = 28 was attributed to the formation of N<sub>2</sub> and CO. Both CO<sub>2</sub> and N<sub>2</sub>O could contribute to the MS response at m/e = 44. O<sub>2</sub> started to breakthrough after 5 s and became stable after 10 s.

From the FT-IR (Fig. 6B), CO and CO<sub>2</sub> were formed from the start of the NO flow and reached maximum production at the time of 23 s,

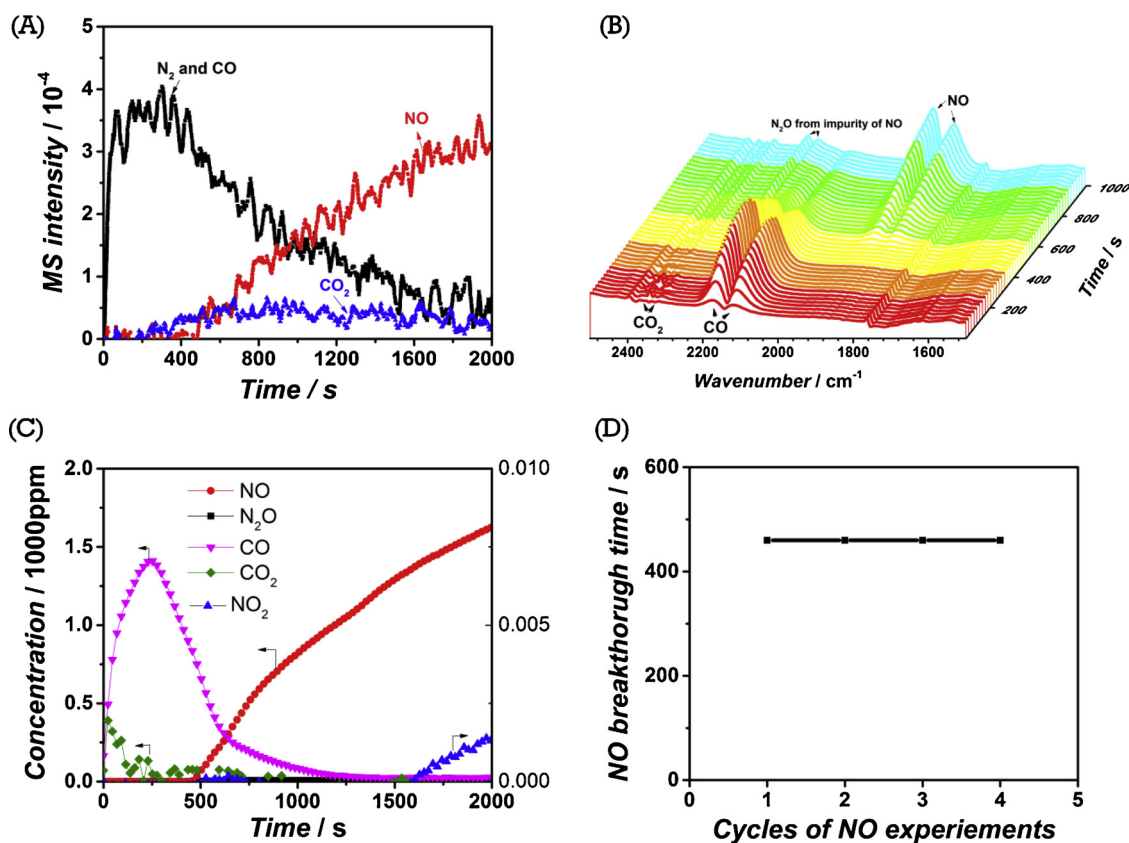


Fig. 3. Gasses evolution from the exit of the reactor: (A) MS signal; (B) FT-IR spectra; (C) the quantitative data from (B); and (D) complete NO conversion time interval versus the number of NO experiment cycles. All the experiments were performed at the condition of 0.2% NO/He gas stream over  $C_3H_6$  reduced Rh/CZ at 450 °C, GHSV of 67,000 L/L/h.

afterwards the  $CO$  formation dropped down.  $N_2O$  was not observed during the first 69 s. 1 ppm  $N_2O$  was observed after 69 s, which came from the impurity of the NO gas bottle. Therefore, the MS response of  $m/e = 44$  was assigned to the formation of  $CO_2$ . The concentrations of NO,  $NO_2$ ,  $N_2O$ , CO, and  $CO_2$  during the (0.2% NO + 5%  $O_2$ )/He gas stream were plotted and shown in Fig. 6C. NO and  $NO_2$  started to breakthrough almost at the same time ( $t = 69$  s) and they became stable after 250 s, and hardly any  $CO_2$  was observed.

The results of NO reduction experiments over  $C_3H_6$  reduced Rh/CZ were repeated during at least 4 cycles of NO experiment. The complete NO conversion time interval remained the same during the 4 cycles of NO reduction experiment, as shown in Fig. 6D.

The NO reductions in the presence of  $O_2$  were additionally performed over the fresh propene pre-reduced Rh/K/CZ and used propene reduced and followed by a NO/ $O_2$  pre-treated Rh/K/CZ. Fig. 7 shows the MS response during (0.2% NO + 5%  $O_2$ )/He as stream over the  $C_3H_6$  reduced Rh/K/CZ at 400 °C for the 1st run of NO experiment over fresh Rh/K/CZ. As illustrated in Fig. 7A,  $O_2$  was broken through instantly ( $t = 0$  s) and it became stable from time of 15 s. NO showed a period of full conversion (around 340 s). From 340 s onwards, a progressive increasing of NO was observed.  $m/e = 28$  was observed with high intensity up to 20 s, followed by a low intensity till  $t = 70$  s. The observed  $m/e = 28$  was assigned to CO and  $N_2$ . Similarly, a high intensity of  $m/e = 44$  was observed up to 20 s. A constant intensity of  $m/e = 44$  was observed between  $t = 20$ –340 s, followed by gradual decline till the end of the experiment. The observed  $m/e = 44$  was assigned to  $CO_2$  and  $N_2O$ .

Fig. 7B shows the results of the 4th cycle of NO experiment. Low intensities of  $m/e = 28$  and  $m/e = 44$  were observed. NO showed a shorter time interval for full conversion (around 70 s) as compared to the 1st cycle of NO experiment (340 s). From 70 s onwards, a

breakthrough of NO signal was observed in MS.  $O_2$  broke through instantly (time of 0 s) and became stable at 5 s.

Fig. 8 shows the FT-IR spectra during (0.2% NO + 5%  $O_2$ )/He gas stream. For the 1st cycle of NO reduction experiment (Fig. 8A), Peak at 2350  $cm^{-1}$ , assigned to  $CO_2$ , was observed from the beginning of (0.2% NO + 5%  $O_2$ )/He gas stream. Similarly, peaks at 2174 and 2116  $cm^{-1}$ , attributed to CO, were observed instantly during the (0.2% NO + 5%  $O_2$ )/He gas stream. Both CO and  $CO_2$  intensity declined from the time of  $t = 23$  s onwards. Peaks at 1908 and 1850  $cm^{-1}$  were observed from 340 s onwards and was assigned to NO. The rise of two bands at 1601 and 1628  $cm^{-1}$  from 600 s was attributed to the formation of  $NO_2$ .  $N_2O$ , centring at 2235 and 2208  $cm^{-1}$ , was observed during whole (0.2% NO + 5%  $O_2$ )/He gas stream exposure. Fig. 8B shows the FT-IR results of the 4th cycle of NO reduction experiment. As compared to Fig. 8A, less  $CO_2$  and CO were formed during the (0.2% NO + 5%  $O_2$ )/He gas stream. In addition, NO and  $NO_2$  started to rise from the time of 77 s and 200 s, respectively, in the 4th cycles.

Fig. 9 shows the NO (Fig. 9A) and  $NO_2$  (Fig. 9B) breakthrough time during (0.2% NO + 5%  $O_2$ )/He gas stream. The full NO conversion time interval dropped from 340 s at 1st NO run to 45 s at 6th NO experiment cycle. The formation of  $NO_2$  started from 600 s at 1st NO run experiment, and started from 140 s at 6th NO experiment. The formation of  $NO_2$  appeared earlier when increasing the cycles.

### 3.2.3. $NO_x$ -TPD and in-situ DRIFTS

The  $NO_x$ -TPD experiments were carried out over the Rh/CZ and Rh/K/CZ. Fig. 10A shows the result of  $NO_x$ -TPD in He. For Rh/CZ, two  $NO_x$  desorption regions were observed, centred at 250 and 400 °C, respectively. No  $NO_x$  desorption were observed after 450 °C. For Rh/K/CZ, a wide  $NO_x$  desorption temperature range was observed, especially, significant amount of  $NO_x$  desorption was observed above 600 °C.

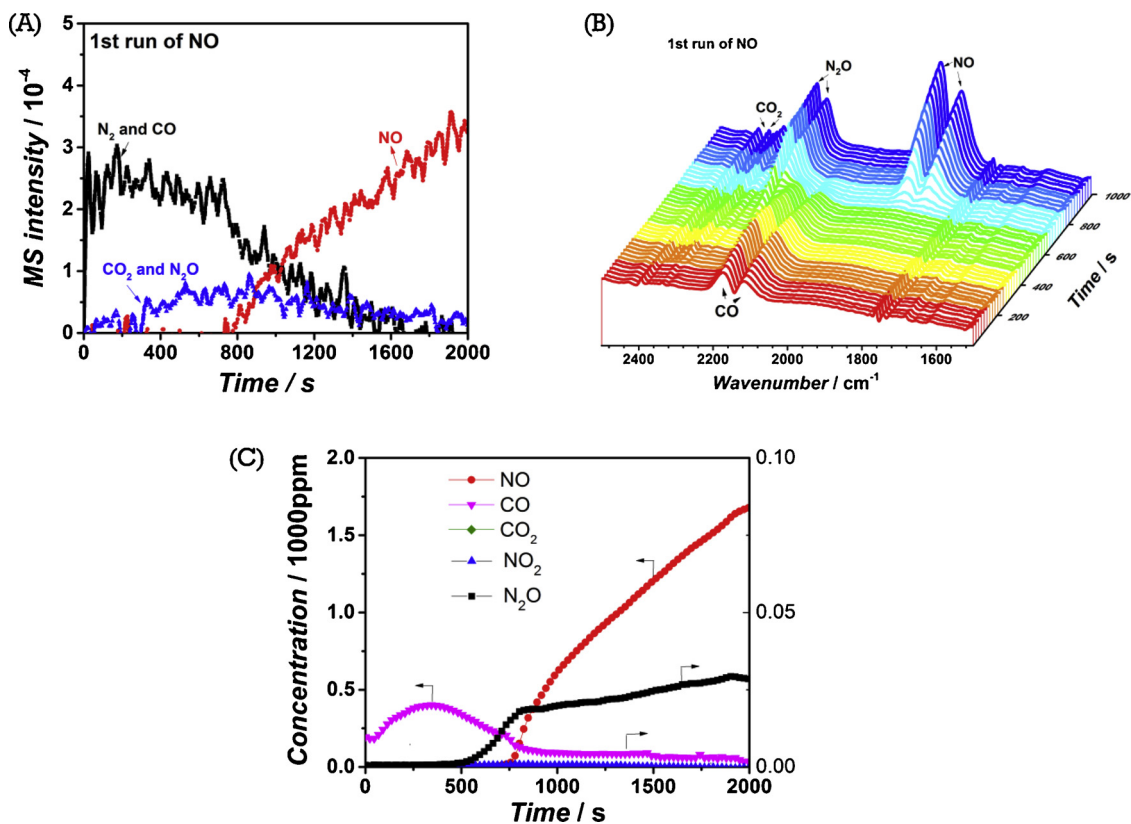


Fig. 4. Gases evolution from the exit of the reactor: (A) MS signal; (B) FT-IR spectra; (C) the quantitative data from (B). The experiments were performed at the condition of 0.2% NO/He gas stream over fresh Rh/K/CZ pre-treated by  $C_3H_6$  at 450 °C, GHSV of 67.000 L/L/h.

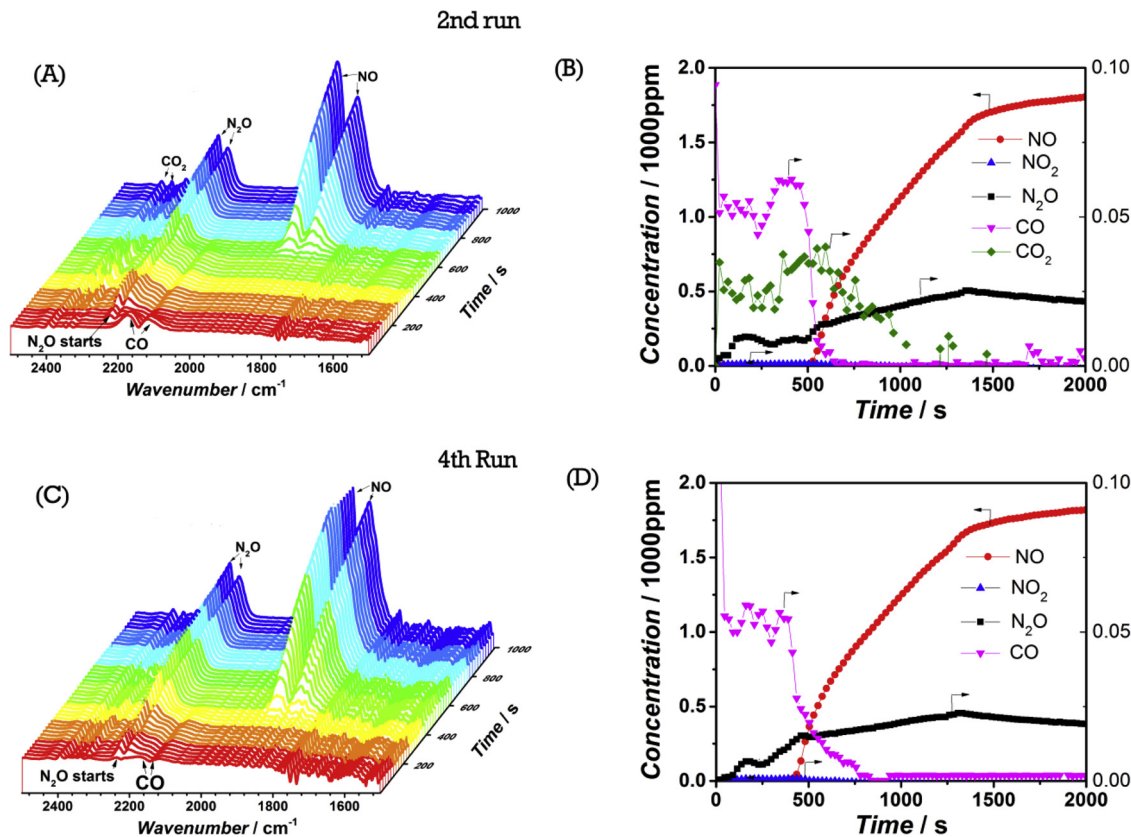


Fig. 5. Gases evolution from the exit of the reactor: (A) and (C) FT-IR spectra; (B) and (D) are the quantitative data from (A) and (C), respectively. (A) and (C) were obtained during the 2nd and 4th NO experiment, respectively. Both experiments were performed at the conditions of 0.2% NO/He gas stream over an used Rh/K/CZ pre-treated by  $C_3H_6$  at 450 °C, GHSV of 67.000 L/L/h.

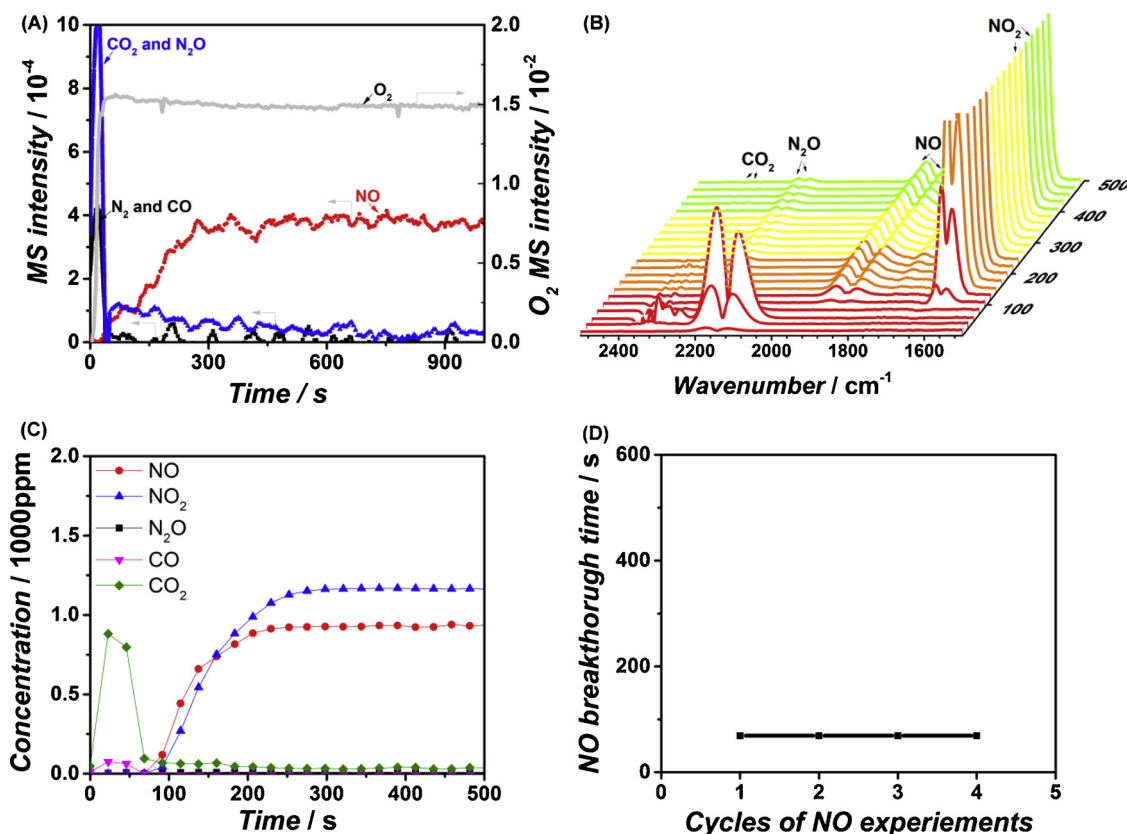


Fig. 6. (A) MS signal, (B) FT-IR spectra; and (C) the concentration of gasses during 0.2% NO + 5% O<sub>2</sub> in He flow over C<sub>3</sub>H<sub>6</sub> reduced Rh/CZ at 400 °C; (D) total NO conversion time interval versus the number of NO cycles experiment.

The chemical structure and stability of adsorbed NO<sub>x</sub> species were studied by *in-situ* DRIFTS. A DRIFT spectrum was firstly recorded in Ar after 30 min of reaction in the <sup>15</sup>NO/Ar gas mixture. The reaction feed stream was then switched to a C<sub>3</sub>H<sub>6</sub>/Ar gas mixture and DRIFT spectra were continuously recorded. Fig. 10B shows the recorded spectra. The pre-nitrated Rh/K/CZ sample showed peaks at 1341, 1212, and 1542 cm<sup>-1</sup>. The IR bands centred at 1542 cm<sup>-1</sup> corresponded to the ν NO<sub>2</sub>(as), ν NO<sub>2</sub>(sym), and ν N–O vibrational modes of bidentate nitrate formed on the Rh/K/CZ. The band at 1212 cm<sup>-1</sup> could be assigned to asymmetric (ν<sub>as</sub>) and symmetric (ν<sub>sym</sub>) NO stretching mode of the chelating nitrite (NO<sub>2</sub><sup>-</sup>). The band at 1434 cm<sup>-1</sup> was assigned to adsorbed nitrosyl (NO<sub>2</sub><sup>+</sup>). The assignments of the various adsorbed NO<sub>x</sub> species were based on well-documented literature data [24]. When switching to the C<sub>3</sub>H<sub>6</sub>/Ar gas stream, the band at 1212 cm<sup>-1</sup> vanished after 9 min, accomplishing with three new peaks at the position of

2143, 1971 cm<sup>-1</sup>, and 1420. The peak at 1420 cm<sup>-1</sup> was assigned to the carbonate [25]. The peak at 1542 cm<sup>-1</sup> remained constant while the peak at 1341 cm<sup>-1</sup> slightly decreased. The peaks at 2143 and 1971 cm<sup>-1</sup> did not show up over the Rh/CZ sample, as shown in Fig. 10D. In order to identify the species of the peaks at 2143 and 1971 cm<sup>-1</sup>, an isotope switching experiment were performed. The experimental protocol was shown in the Fig. 10C. Over the fresh Rh/K/CZ sample in air, only carbonate species were observed in the region of 1420 cm<sup>-1</sup>. When switching to <sup>14</sup>NO/Ar gas, peaks at the position of 1542, 1341, and 1222 cm<sup>-1</sup> were observed, which were assigned to bidentate nitrate, nitrosyl, and chelating nitrite. The peaks at 2160 and 2036 cm<sup>-1</sup> were observed during C<sub>3</sub>H<sub>6</sub>/Ar gas stream while they disappeared when switching to <sup>15</sup>NO/Ar gas stream. Chelating nitrite (<sup>15</sup>NO<sub>2</sub><sup>-</sup>), peak at 1212 cm<sup>-1</sup>, was observed during <sup>15</sup>NO/Ar gas stream, which disappeared when switching to C<sub>3</sub>H<sub>6</sub>/Ar. Peaks at 2143 and

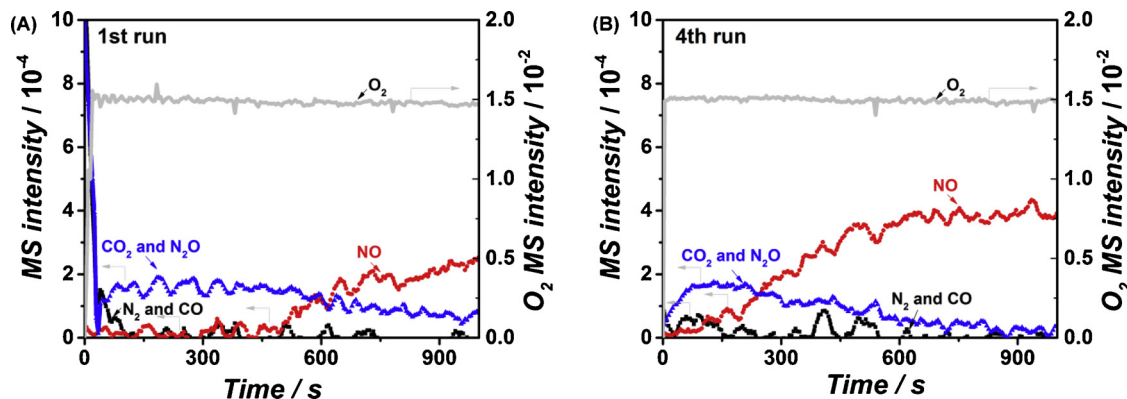


Fig. 7. Gasses evolution during exposure of Rh/K/CZ C<sub>3</sub>H<sub>6</sub> reduced at 400 °C to a 0.2% NO + 5% O<sub>2</sub> containing He flow at a GHSV of 67,000 l/l/h at 400 °C. (A) 1st cycle of NO and (B) 4th cycle of NO experiments.



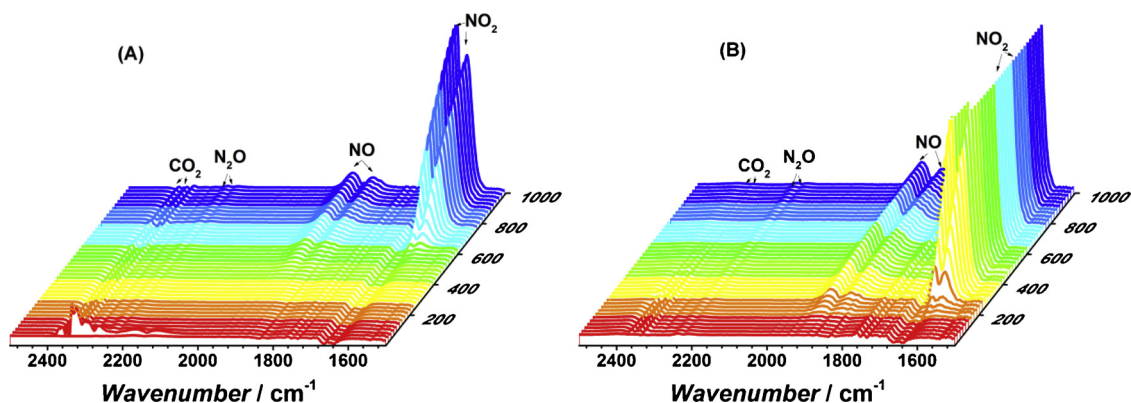


Fig. 8. FT-IR response during (0.2% NO + 5% O<sub>2</sub>) exposure over at 400 °C C<sub>3</sub>H<sub>6</sub> reduced Rh/K/CZ (A)1st and (B) 4th cycle of NO reduction experiments.

1971 cm<sup>-1</sup> were appeared, which were the same species as peaks at 2160 and 2036 cm<sup>-1</sup> due to the isotope shift. Neither the peaks at 2160 and 2036 cm<sup>-1</sup> nor at 2143 and 1971 cm<sup>-1</sup> were not observed during the H<sub>2</sub> gas stream over pre-nitrated Rh/K/CZ. Therefore, the peaks of 2143 and 1971 cm<sup>-1</sup> (2160 and 2036 cm<sup>-1</sup>) were confirmed containing N and C, which could be assigned to the surface CNO or NC species [26,27].

### 3.2.4. H<sub>2</sub> and C<sub>3</sub>H<sub>6</sub> pulses over pre-oxidised and <sup>15</sup>NO pre-nitrated Rh/K/CZ samples in TAP

Fig. 11A shows the results of the H<sub>2</sub> pulse over the pre-oxidised fresh Rh/K/CZ sample at 400 °C. The pulse of H<sub>2</sub> led to the H<sub>2</sub>O formation. H<sub>2</sub> experienced full conversion and started to breakthrough after pulse number 300. For the pre-nitrated Rh/K/CZ, as shown in Fig. 11B, the pulse of H<sub>2</sub> firstly led to the formation of NO, H<sub>2</sub>O, and <sup>15</sup>NH<sub>3</sub>. The N<sub>2</sub> formation started from pulse number 100 and disappeared at pulse number 400. H<sub>2</sub> did not show a full conversion from the beginning of H<sub>2</sub> pulse. The H<sub>2</sub> conversion increased from pulse number 100 till full conversion at the pulse number of 300, subsequently, its conversion gradually declined.

The reduction of <sup>15</sup>NO pre-nitrated Rh/K/CZ was also performed by pulsing C<sub>3</sub>H<sub>6</sub>. As shown in Fig. 12, C<sub>3</sub>H<sub>6</sub> showed 50% conversion at the beginning of the C<sub>3</sub>H<sub>6</sub> pulse, followed by a C<sub>3</sub>H<sub>6</sub> conversion increase to 100% conversion at pulse number 40. C<sub>3</sub>H<sub>6</sub> showed full conversion between pulse number 40 and 200, followed by a C<sub>3</sub>H<sub>6</sub> conversion decline. <sup>15</sup>N<sub>2</sub>, H<sub>2</sub>O, and <sup>15</sup>NH<sub>3</sub> were formed during the first 100 C<sub>3</sub>H<sub>6</sub> pulses. <sup>15</sup>NO and <sup>15</sup>N<sub>2</sub> formation diminished at the end of 100 C<sub>3</sub>H<sub>6</sub> pulses and subsequently the C<sub>3</sub>H<sub>6</sub> oxidation reaction led to the formation of CO<sub>2</sub>, CO, and H<sub>2</sub>.

### 3.2.5. <sup>15</sup>N<sub>2</sub> response comparison during <sup>15</sup>NO pulse over H<sub>2</sub> reduced Rh/CZ and Rh/K/CZ

Fig. 13A shows the <sup>15</sup>N<sub>2</sub> response during the first 90 <sup>15</sup>NO pulses over H<sub>2</sub> pre-reduced fresh Rh/K/CZ, where all the NO was converted, i.e., NO signal did not have a response. The <sup>15</sup>N<sub>2</sub> showed a sharp response at the first <sup>15</sup>NO pulse; then, the response became broader with the intensity decreasing during the subsequent <sup>15</sup>NO pulses. Additionally, the N<sub>2</sub> peak was at t = 0.056 s during the 1st <sup>15</sup>NO injection, and the peak shifted to t = 0.126 s at the 90th <sup>15</sup>NO injection. <sup>15</sup>N<sub>2</sub> peak shifted to a later time during NO pulse sequence, indicating the slower and slower <sup>15</sup>N<sub>2</sub> formation rate with <sup>15</sup>NO pulses. The pulses of <sup>15</sup>NO would lead to the Rh/K/CZ was nitrated. After the <sup>15</sup>NO pulses, C<sub>3</sub>H<sub>6</sub> was used as a reductant to reduce the nitrated Rh/K/CZ. Both Fig. 13B and C show the <sup>15</sup>N<sub>2</sub> responses during the <sup>15</sup>NO pulses over a C<sub>3</sub>H<sub>6</sub> pre-reduced nitrated Rh/K/CZ sample at the 2nd and 3rd <sup>15</sup>NO pulsing cycles, respectively. Both Fig. 13B and C show that the N<sub>2</sub> response became broader with pulse number, indicating that <sup>15</sup>N<sub>2</sub> formation rate became slower and slower. In contrast, over the Rh/CZ sample, <sup>15</sup>N<sub>2</sub> responses hardly changed during the <sup>15</sup>NO pulses as the indicated <sup>15</sup>NO pulses number.

## 4. Discussion

Potassium (or barium) is a common ingredient in NSR catalyst, acting as the NO<sub>x</sub> storage component during the fuel-lean stage of the engine operation. The general problems of NSR technology are narrow operating temperature window, low space velocity, N<sub>2</sub>O formation, NH<sub>3</sub> formation, and NO<sub>x</sub> slip. The problems are mainly caused by the NO<sub>x</sub> storage and release materials. The Di-Air system showed a broader

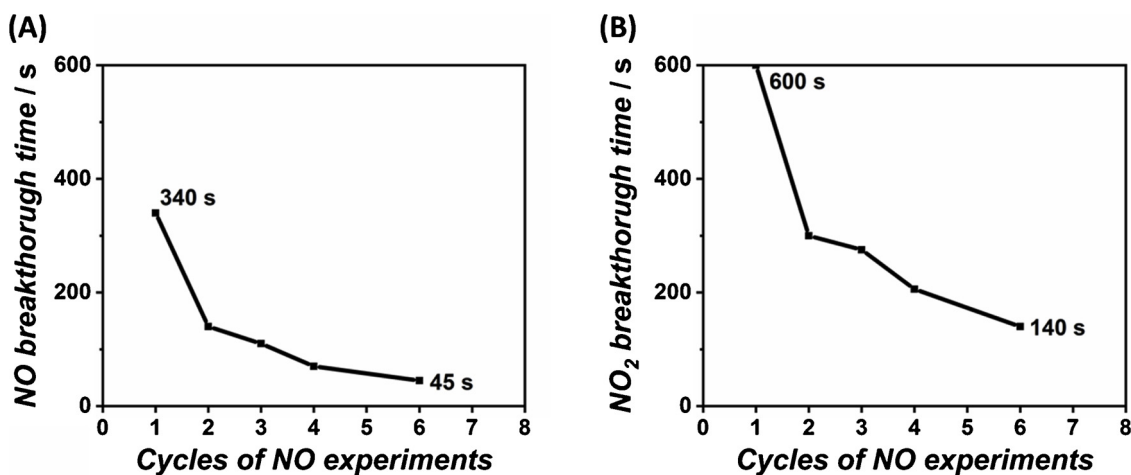


Fig. 9. NO and NO<sub>2</sub> breakthrough time versus the number of NO experiment cycles during (0.2% NO + 5% O<sub>2</sub>) exposure over C<sub>3</sub>H<sub>6</sub> reduced Rh/K/CZ at 400 °C.

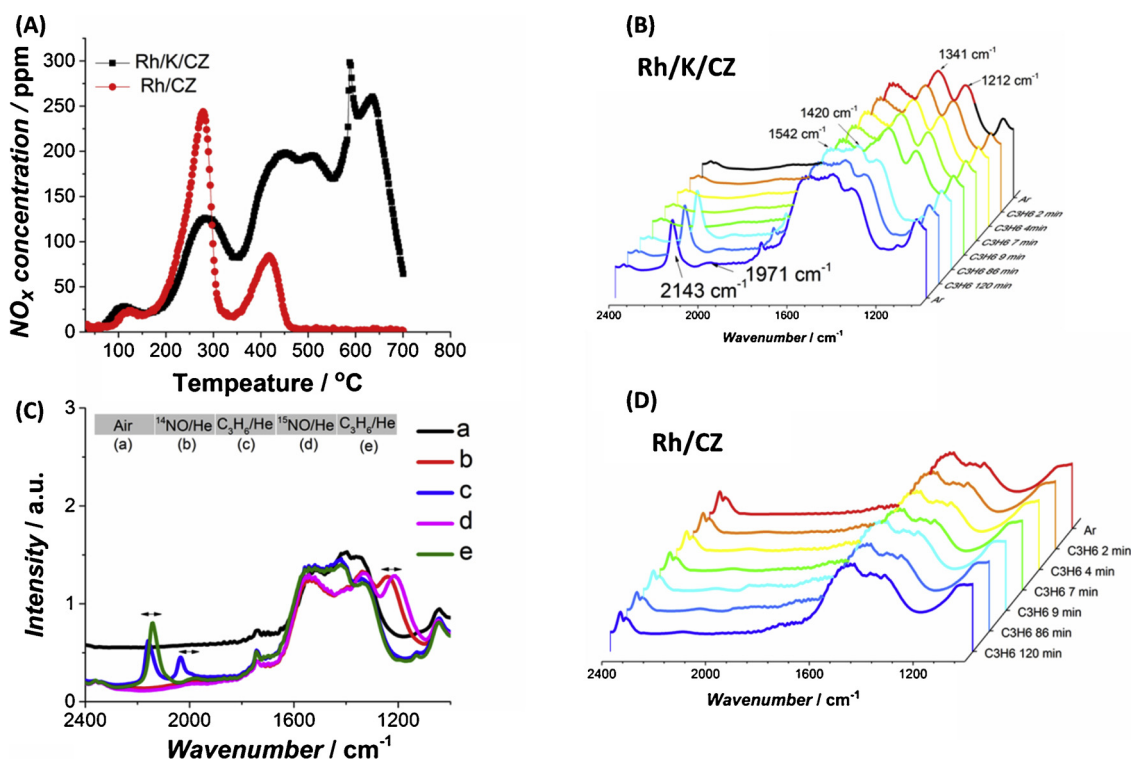


Fig. 10. (A) NO<sub>x</sub>-TPD in He recorded after exposure to (0.5% NO + 5%O<sub>2</sub>)/He at 200 °C over Rh/CZ and Rh/K/CZ, *in-situ* Drift spectra during C<sub>3</sub>H<sub>6</sub>/Ar over <sup>15</sup>NO pre-nitrated (B) Rh/K/CZ and (D) <sup>15</sup>NO Rh/CZ, (C) isotope gas switching experiment over Rh/K/CZ.

operating temperature window (up to 800 °C) and higher space velocity (up to 120.000 L/L/h), where the storage component hardly can have a role in the NO<sub>x</sub> reduction. From our previous work, we have found that the oxygen anion vacancies in ceria are responsible for the decomposition of NO into N<sub>2</sub>, thereby, re-oxidising these defect centres. The delayed oxidation of the carbon deposits by the oxygen species originating from the lattice oxygen will in practice maintain a reduced surface state of the ceria during the fuel-lean conditions. These carbon deposits (created from the fuel injection), therefore, can be seen as a stored reductant with a delayed (buffer) function. The loading of Rh (noble metal) is mainly to lower the fuel activation temperature, to lower the ceria support reduction temperature, and to accelerate N<sub>2</sub> formation rate. Although potassium and barium are ingredients in the Di-Air catalyst composition, it is necessary to investigate the role of these NO<sub>x</sub> storage materials. What will be the exact role of these components and what will be the consequence by the addition. The discussion will be focused on the comparison between catalysts with and without potassium loading from the perspectives of catalyst

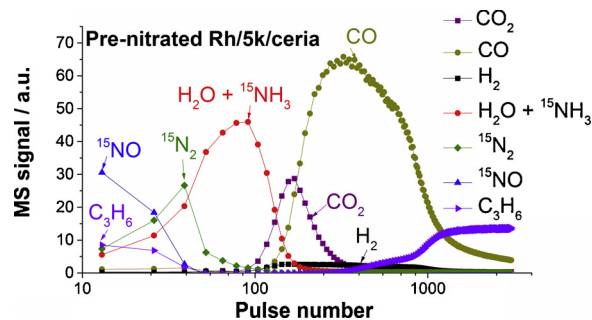


Fig. 12. C<sub>3</sub>H<sub>6</sub> over <sup>15</sup>NO pre-nitrated Rh/K/CZ at 450 °C, Ne was used as internal standard.

performance stability, NO slip, NH<sub>3</sub>- and N<sub>2</sub>O- formation and in the end the effectiveness of the NO conversion into the selectivity of the N<sub>2</sub> formation.

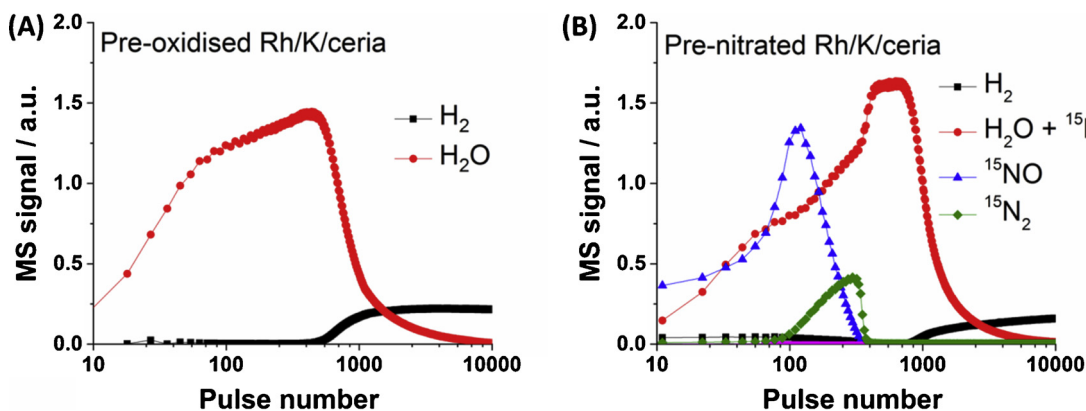


Fig. 11. H<sub>2</sub> over NO pre-oxidised (A) and <sup>15</sup>NO pre-nitrated Rh/K/CZ at 450 °C, Ar was used as internal standard.

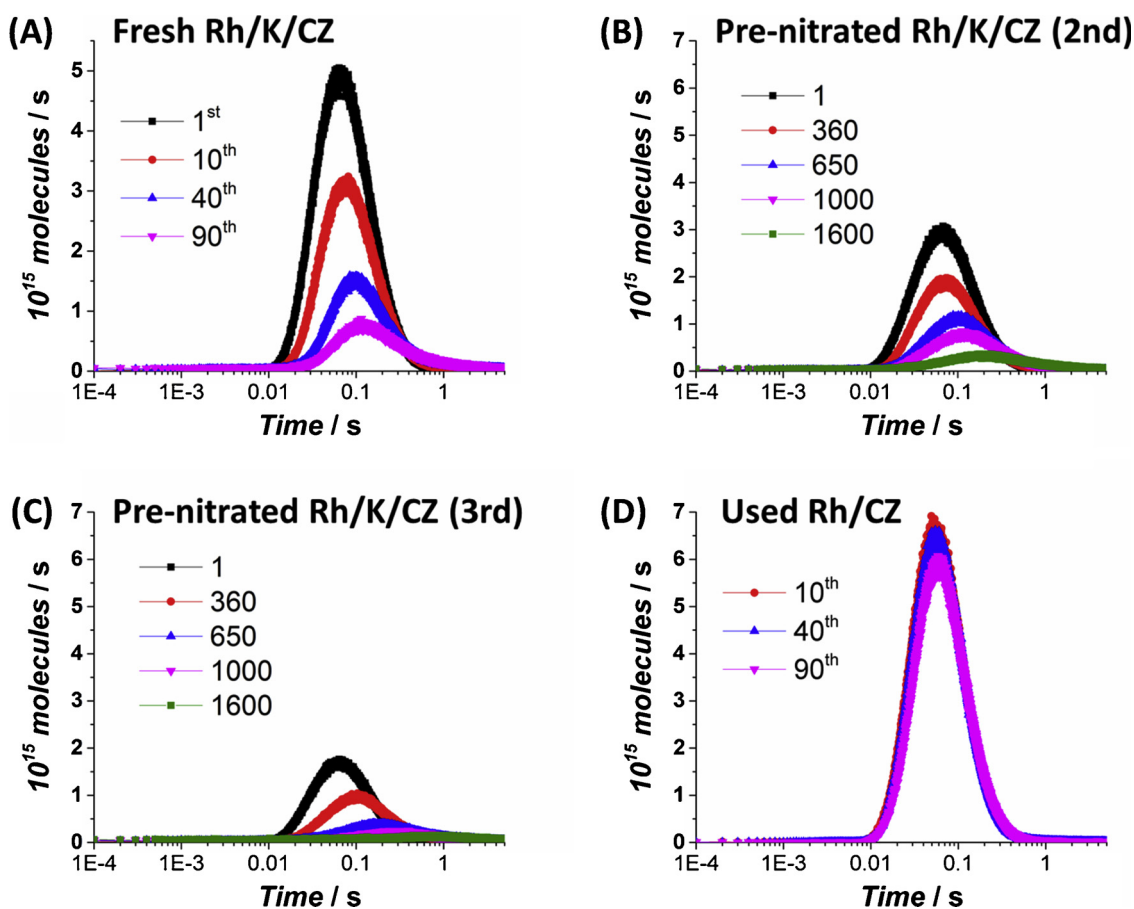


Fig. 13.  $^{15}\text{N}_2$  response during  $^{15}\text{NO}$  pulses over (A)  $\text{H}_2$  pre-reduced Rh/K/CZ (fresh), (B)  $\text{C}_3\text{H}_6$  pre-reduced Rh/K/CZ (pre-nitrated, 2nd cycle), (C)  $\text{C}_3\text{H}_6$  pre-reduced Rh/K/CZ (pre-nitrated, 3rd cycle), and (D)  $\text{H}_2$  pre-reduced Rh/CZ (both used and fresh).

#### 4.1. The effect of potassium on the stability of catalyst performance

$\text{C}_3\text{H}_6$  was used to reduce the catalyst to mimic the consequence of fuel injection in the Di-Air system [14]. The Rh lowered the  $\text{C}_3\text{H}_6$  oxidation temperature over the CZ [14]. At the temperature below  $450^\circ\text{C}$ , the reduction of CZ support was not favoured [14]. By loading Rh, the reduction of CZ by  $\text{C}_3\text{H}_6$  at  $450^\circ\text{C}$  was obtained around 3 hypothetical reduced CZ layers with additional carbon deposition.

The reactivity of NO reduction was investigated in a flow reactor under atmospheric pressure. Prior to the NO reduction experiments, 1.25%  $\text{C}_3\text{H}_6/\text{He}$  was used to pre-treat the Rh/K/CZ and Rh/CZ at  $450^\circ\text{C}$  for 2 h before each cycle of NO experiments, as shown in the experimental scheme (Scheme 1). The pre-treatment by  $\text{C}_3\text{H}_6$  led to the reduction of CZ support and deposition of carbon on the catalyst surface [16]. The  $\text{H}_2$ -TPR experiment (Fig. 2B) showed significant changes in reduction peak position between Rh/CZ and Rh/K/CZ. Therefore, the addition of potassium hardly changed the lattice oxygen reactivity. The amount of  $\text{H}_2$  consumption over Rh/K/CZ was almost two times of that over Rh/CZ. For K-containing NSR catalyst, several kinds of K species can be existed in the form of  $\text{K}_2\text{O}$ ,  $\text{KOH}$ , and  $\text{K}_2\text{CO}_3$  [28]. The  $\text{K}_2\text{CO}_3$  could be reduced to  $\text{CO}_2$  and  $\text{H}_2\text{O}$  at lower temperature, around  $200^\circ\text{C}$ , initiated by surface hydroxyl groups [29,30]. Therefore, separately from the contribution of the reduction of CZ support, the  $\text{H}_2$  consumption was accounted for the reduction of surface carbonate.

The results of Fig. 3A showed the reduction of NO into  $\text{N}_2$  over the  $\text{C}_3\text{H}_6$  pre-reduced Rh/CZ. The FT-IR spectra (Fig. 3B) confirmed the formation of CO and  $\text{CO}_2$  and excluded the formation of  $\text{NO}_2$  and  $\text{N}_2\text{O}$  during the first 460 s, where NO was completely converted. The conversion of NO into  $\text{N}_2$  was confirmed by the  $^{15}\text{NO}$  experiment, as reported in our previous work [17].

The oxygen vacancies were the catalytic sites for the NO reduction into  $\text{N}_2$ . The reduction of NO resulted in a re-oxidation of the reduced Rh/CZ. Subsequently, the oxygen from the (re-oxidised) CZ lattice was further reacted with the deposited carbon to form CO and  $\text{CO}_2$ , thus additional oxygen vacancies were created and the new oxygen vacancies were used for additional NO reduction. NO appeared in the exit exhaust stream after 460 s. In the time frame from 450 s till 1500 s the rest of carbon deposited was oxidised. From 1500 s onwards NO was partially converted into  $\text{NO}_2$ . As shown in Fig. 3D, the complete NO conversion time interval remained the same during the 4 cycles and indicated the high stability of Rh/CZ sample during the  $\text{C}_3\text{H}_6$  pre-treatment and NO reduction process.

In the presence of potassium the overall product evolution profile for the  $\text{C}_3\text{H}_6$  reduced Rh/K/CZ catalyst during the NO reduction was similar to that of Rh/CZ over fresh sample. This was due to the oxygen vacancies playing a role in NO reduction. The NO, however, started to break through at  $t = 750$  s (Fig. 4), which was 290 s longer than the NO over Rh/CZ. The extended duration of the NO conversion was due to the presence of potassium, which could adsorb additional NO as potassium nitrite and nitrate [31]. The difference between the fresh and the used Rh/K/CZ was significant. The NO breakthrough time dropped from 750 s for the 1st cycle to 450 s for the 4th cycle (Fig. 5). Potassium was common ingredient in the NSR system to store  $\text{NO}_x$  during the fuel lean stage.

For the Rh/K/CZ catalyst the fresh and pre-nitrated surface affected the  $\text{C}_3\text{H}_6$  reactivity. Apparently, less CO was formed during the NO gas stream over the used Rh/K/CZ sample (Fig. 4 and 5). The less CO formation indicated the low reactivity of  $\text{C}_3\text{H}_6$  for a recycled 'potassium' catalyst. The BET surface of Rh/K/CZ before and after the reaction remained similar, therefore, the reactivity difference between the fresh

and used Rh/K/CZ was ascribed to the nitrate or nitrite formation. The formation of nitrate or nitrite was confirmed by the *in-situ* Drift as shown in Fig. 10B. A long NO admission time led to nitrites and slowly transformation into nitrates. The formation of nitrate and nitrite species stabilised the CZ lattice oxygen reducibility, which caused to a low C<sub>3</sub>H<sub>6</sub> reactivity. The addition of alkali metals into V<sub>2</sub>O<sub>5</sub>/CeO<sub>2</sub> catalysts led also to the deactivation for the selective catalytic reduction of NO<sub>x</sub> with NH<sub>3</sub> in the SCR reaction. Potassium decreased the surface acidity and lowered the reducibility of the ceria and V<sub>2</sub>O<sub>5</sub>, both suppressing the NH<sub>3</sub> adsorption and NH<sub>3</sub> activity for the SCR reaction [32]. Therefore, the addition of potassium into the Rh/CZ system will lower the C<sub>3</sub>H<sub>6</sub> reactivity by the stabilisation of the ceria lattice oxygen.

In our TAP study, different reductant reactivity's over pre-oxidised and pre-nitrated Rh/K/CZ were observed. The pulsing of even the most active reductant, H<sub>2</sub>, showed different reactivity over the fresh and pre-nitrated Rh/K/CZ samples. H<sub>2</sub> showed a full conversion to H<sub>2</sub>O over the oxidised Rh/K/CZ sample, but around 80% conversion over the pre-nitrated sample (Fig. 11). The presence of nitrate/nitrite inhibited the CZ support reduction reactivity.

In the presence of gas-phase oxygen, NO transformed in nitrate-like species over the potassium sample [33]. At the temperature of 450 °C, a stronger stability of nitrate species in the form of polydentate species was formed [34]. The formation of such stable species during a long NO exposure inhibited the reaction between C<sub>3</sub>H<sub>6</sub> and Rh/CZ. As shown in Fig. 9, the NO started to breakthrough from 45 s at the 4th cycle experiment, as compared to 340 s at the 1st cycle experiment. Additionally, the NO<sub>2</sub> breakthrough time dropped. With the cycles of (NO + O<sub>2</sub>) experiments, the NO adsorption on the potassium led to a more stable polydentate nitrate species that deteriorated the reversible NO<sub>x</sub> storage capacity. More importantly, unlike the Rh/K/CZ, the NO breakthrough for Rh/CZ remained the same time during the whole NO experiment cycles (69 s), as shown in Fig. 6D. The difference behaviours in the NO breakthrough time (Figs. 6D and 9) indicated clearly that the potassium was the component for the deactivation of Rh/K/CZ in NO reactivity in cycles of NO reduction experiment. To validate this conclusion, the stability of stored NO<sub>x</sub> over Rh/K/CZ was studied both by NO<sub>x</sub>-TPD in He (Fig. 10A) and under reductant gas stream (Fig. 10B and C). The NO<sub>x</sub>-TPD showed that a broad temperature window of NO<sub>x</sub> desorption till 700 °C. The desorbed NO<sub>x</sub> up to 380 °C was likely related to the decomposition of nitrites, whereas those desorption species above 380 °C were more related to the desorption of nitrates [35]. During this temperature ramp, the nitrite species also transformed into the nitrate species. Apparently, significant amount of the adsorbed NO<sub>x</sub> was strongly adhesive to the Rh/K/CZ, which required temperature above 700 °C to completely regenerate the catalyst to be free of adsorbed NO<sub>x</sub>. Additionally, *in-situ* Drift experiments were performed to investigate the thermal stability of adsorbed NO<sub>x</sub> in the presence of reductant. As shown in Fig. 10B, the exposure of pre-nitrated Rh/K/CZ under C<sub>3</sub>H<sub>6</sub> environment led to the formation of peaks at 2143 and 1971 cm<sup>-1</sup>, which was further confirmed in Fig. 10C that these two peaks contained both N and C atoms. During the C<sub>3</sub>H<sub>6</sub> exposure, only the chelating nitrite peaks disappeared. The *in-situ* Drift experiments demonstrated that C<sub>3</sub>H<sub>6</sub> was not able to completely regenerate the N storage over the surface at the temperature of 450 °C.

H<sub>2</sub> and CO were regarded to have a relatively high nitrate reduction efficiency compared to that of C<sub>3</sub>H<sub>6</sub> and C<sub>3</sub>H<sub>8</sub> [36]. In the Di-Air system, fuel was used as reductant and was directly injected over the catalyst. The reaction between C<sub>3</sub>H<sub>6</sub> and pre-nitrated Rh/K/CZ showed similar reaction step. As shown in Fig. 12, the pulses of C<sub>3</sub>H<sub>6</sub> firstly led to the formation of H<sub>2</sub>O, <sup>15</sup>NH<sub>3</sub>, <sup>15</sup>N<sub>2</sub>, and <sup>15</sup>NO. The formation of CO<sub>2</sub> was secondly followed by the formation of H<sub>2</sub> and CO from pulse number of 90 indicated the participation of CZ lattice oxygen in C<sub>3</sub>H<sub>6</sub> complete reaction and cracking reaction. Therefore, C<sub>3</sub>H<sub>6</sub> needed to react with the adsorbed nitrite and nitrate species before the CZ lattice oxygen could participate in the C<sub>3</sub>H<sub>6</sub> reaction. The low reactivity of hydrocarbon towards the nitrate(s) would eventually affect the life time

of the catalyst.

#### 4.2. The effect on potassium on the NH<sub>3</sub> formation and NO slip

Regarding the ammonia formation, ammonia evolution occurred after introducing the H<sub>2</sub> and hydrocarbons over the NSR catalyst. The formation of ammonia could act as reductant to reduce NO<sub>x</sub> into N<sub>2</sub>, especially for the SCR reaction of NO<sub>x</sub> with NH<sub>3</sub>. It was well-known that both the NO<sub>x</sub> slip and NH<sub>3</sub> formation were main hurdles to the tackle in the NSR system. Therefore, a combined NSR (upstream) and SCR (downstream) DeNO<sub>x</sub> system was developed, aiming to solve the NH<sub>3</sub> and NO<sub>x</sub> challenges [37].

The pulsing of H<sub>2</sub> over a <sup>15</sup>NO pre-nitrated Rh/K/CZ led to an initial reaction between H<sub>2</sub> and surface nitrate/nitrite with formation of H<sub>2</sub>O, <sup>15</sup>NH<sub>3</sub>, <sup>15</sup>N<sub>2</sub>, and <sup>15</sup>NO (Fig. 11B). The <sup>15</sup>N<sub>2</sub> and <sup>15</sup>NO formation diminished after the pulse number 400. The reduction of CZ support led to the water formation after pulse number 400. Therefore, the reduction of pre-nitrate Rh/K/CZ by H<sub>2</sub> firstly led to the reduction of surface adsorbed nitrite and subsequently to the CZ support reduction. The formation of ammonia depended on the local coverage of chemisorbed N and H atoms [38]. The introduction of H<sub>2</sub> initially led to the NO<sub>x</sub> slip that was due to the fast NO<sub>x</sub> desorption at the temperature of 450 °C. The formation of ammonia favoured when the NO<sub>x</sub> desorption rate dropped down (from pulse number 80 to 800) and the concentration of surface H species increased. In our TAP experiment, the introduction of H<sub>2</sub> firstly led to the <sup>15</sup>NH<sub>3</sub> formation and some NO slip. The reduction of NO<sub>x</sub> into N<sub>2</sub> started from pulse number 80. <sup>15</sup>N<sub>2</sub> was formed during the pulse number 80 to 400, which could be due to the decomposition of NO<sub>x</sub> over the reduced site of Rh/K/CZ or the reduction of NO<sub>x</sub> by the formed ammonia. Similarly, the introduction of C<sub>3</sub>H<sub>6</sub> over the pre-nitrated Rh/K/CZ also led to the <sup>15</sup>NO slip and <sup>15</sup>NH<sub>3</sub> formation (Fig. 12).

#### 4.3. The effect of potassium on the N<sub>2</sub>O formation and N<sub>2</sub> formation rate

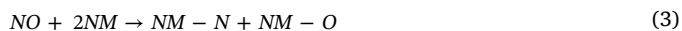
N<sub>2</sub>O formation has a large impact the NO reduction over a NSR catalyst. In our study, N<sub>2</sub>O formation was only observed over the potassium containing samples.

For Rh/CZ, during the full NO conversion time interval (t = 0–460 s), neither N<sub>2</sub>O and NO<sub>2</sub> was formed (Fig. 3). The observation of m/e = 28 indicated the reduction of NO into N<sub>2</sub>. Even 1 ppm N<sub>2</sub>O coming from the impurity in of NO gas bottle was reduced. Therefore, a reduced ceria, acting as 'oxygen black hole' [16], selectively reduced NO and traces of N<sub>2</sub>O into N<sub>2</sub>.

When the Rh/CZ was reduced, most probably associated with an oxygen vacancy linked to a Ce<sup>3+</sup> cation. The adsorption of NO over the reduced site of Ce led to NO dissociation, as described in Eq. (1), and recombination of N<sub>ads</sub> into N<sub>2</sub>, as described in Eq. (2).



Reading the N<sub>2</sub>O formation during the NO reduction process, two steps were proposed for the formation of N<sub>2</sub>O over Pt and Rh in the literature [39]:



Over the Rh/CeO<sub>2</sub>-ZrO<sub>2</sub> system hardly any N<sub>2</sub>O formation was observed [40]. In the presence of noble metal, the combination of N<sub>ads</sub> into N<sub>2</sub> step was faster than the reaction between NO and N<sub>ads</sub>.

For the fresh Rh/K/CZ, a level of 25 ppm of N<sub>2</sub>O was, however, observed from t = 500 s, where a full NO conversion was observed (Fig. 4). Over the used Rh/K/CZ sample, N<sub>2</sub>O was instantly formed during the NO exposure (Fig. 5). When an excess of oxygen vacancies was available over the nitrate free Rh/K/CZ catalyst, e.g., t < 500 s in Fig. 4, NO was selectively reduced into N<sub>2</sub> and no N<sub>2</sub>O was observed.

The decreasing of the CO formation from  $t = 400$  s onwards indicated the depletion of the deposited carbon over the Rh/K/CZ sample and the largely (re-)oxidised of CZ support.  $N_2O$  started to be formed, when CO intensity largely decreased, i.e.,  $N_2O$  was formed over a less reduced Rh/K/CZ sample. This hypothesis/observation was in line with the observation over the used Rh/K/CZ sample, as shown in Fig. 5. The difference between the fresh and used Rh/K/CZ sample was the adsorption of  $NO_x$  over the K on the used Rh/K/CZ, which had a significant influence on the  $C_3H_6$  reactivity and the CZ support reduction, as described in Section 4.1. To sum up, the addition of potassium into the CZ catalyst clearly led to a significant  $N_2O$  formation.

For a NSR catalyst, the stored  $NO_x$  over potassium or barium component was supposed to be converted into  $N_2$ , but  $N_2O$  was commonly observed.  $N_2O$  was both formed during the lean/rich switching transient. The formation of  $N_2O$  during the fuel rich conditions was attributed to either the incomplete reduced catalyst sites or the reaction between reductants and intermediates. While the  $N_2O$  formation during the rich to lean switching originated from the oxidation of the reduction intermediates remaining on the surface, which included adsorbed ammonia,  $NH_4NO_3$ , or isocyanates. In our experimental protocol, lean/rich switching transients were not really existed and the  $N_2O$  formation was also not only observed during the switching of reaction conditions. Therefore, the formation of  $N_2O$  could not completely be attributed to the decomposition of ammonia,  $NH_4NO_3$ , or isocyanates.

Different reaction rates of NO dissociation and  $N_{ads}$  combination into  $N_2$  might explain the  $N_2O$  formation by the addition of potassium to Rh/CZ catalyst, as shown in Eqs. (1–4).  $N_2O$  can be formed via recombination of NO, adsorption over the surface, and with N, left over the surface. Therefore, the relative reaction rate among the N recombination into  $N_2$ , surface concentration of NO, and NO dissociation rate are critical to the  $N_2O$  formation. In order to understand the process of the NO reduction over the potassium containing sample, NO pulses experiments over a  $H_2$  reduced Rh/CZ and Rh/K/CZ were performed. The  $N_2$  response during the  $^{15}NO$  pulses can provide information on the NO reduction process.

The results of TAP experiment by pulsing  $^{15}NO$  over a  $H_2$  reduced Rh/CZ showed that a fast N species (re)combination into  $N_2$ . There was hardly N-species left over the Rh/CZ surface during each NO injection. However, the injection of  $^{15}NO$  over a  $H_2$  reduced Rh/K/CZ led to a slower  $N_2$  formation rate as compared to that over the Rh/CZ sample (Fig. 13). The  $N_2$  formation slowed down during the  $^{15}NO$  pulses. Since no  $^{15}NO$  was observed by the MS during the  $^{15}NO$  injection, the slower  $N_2$  formation rate was due to slow N-species (re)combination process. Therefore, when the reaction was performed under the atmosphere pressure and under high space velocity, the adsorbed N-species combined with the NO to form  $N_2O$  over the potassium containing catalyst.

## 5. Conclusions

To summarise the addition of potassium into the Rh/CZ catalyst deteriorated performance of the catalysts. Over a clean Rh/K/CZ catalyst, the initial NO conversion performance, including the NO reduction and storage, was determined both by the rate of  $NO_x$  storage capacity and the oxygen vacancies capacity. The  $NO_x$  stored over Rh/K/CZ in the previous lean phase could not be regenerated sufficiently upon  $C_3H_6$  exposure and the levels of stored (unreduced)  $NO_x$  gradually increased from one cycle to the next, resulting in deteriorating performance of the potassium containing catalysts. Besides, the well-known problems of  $NO_x$  slip and  $NH_3$  formation over the NSR the addition of potassium led to the  $N_2O$  formation and slowed down the reaction rate of  $N_{ads}$  combination into  $N_2$ . It is, therefore, recommended for an efficient Di-Air  $NO_x$  abatement technology to avoid the addition of potassium to the noble metal ceria (Rh/CZ) catalyst system.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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