



## Competitive Adsorption of O<sub>2</sub> and Toluene on the Surface of FeO<sub>x</sub>/SBA-15 Catalyst

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### ABSTRACT

The adsorption of volatile organic compounds (VOCs) and O<sub>2</sub> on the surface of the catalyst was one of the vital progresses in the plasma-catalytic oxidation of VOCs. In this work the breakthrough curves of toluene adsorption on the 3%FeO<sub>x</sub>/SBA-15 were measured under the various O<sub>2</sub> concentrations. The results showed that the breakthrough time of toluene reduced with increasing O<sub>2</sub>. Competitive adsorption was observed on the catalyst surface between O<sub>2</sub> and toluene. The catalysts adsorbed the toluene under the various O<sub>2</sub> concentrations were characterized by O<sub>2</sub> temperature-programmed desorption (O<sub>2</sub>-TPD), and X-ray photoelectron spectroscopy (XPS). The desorption amounts of O<sub>2</sub><sup>-</sup> and the Fe percentage on the catalyst surface were dependent on the O<sub>2</sub> concentration during toluene adsorption. The experimental results of pure SBA-15 and 5%MnO<sub>x</sub>/SBA-15 indicated the competitive adsorption site of O<sub>2</sub> and toluene was FeO<sub>x</sub>. In situ FTIR data of toluene adsorption on the catalyst surface indicated that the adsorption state of toluene could not be impacted by the competitive adsorption of O<sub>2</sub>, and the O<sub>2</sub> adsorbed on the catalyst could oxidize toluene.

**Keywords:** O<sub>2</sub> adsorption; Toluene adsorption; Competitive adsorption; Oxygen source.

### INTRODUCTION

VOCs are one of the most common precursors of dust-haze (Huang *et al.*, 2015; Vullo, 2016), and have adverse effects on the environment and human health (Sultana *et al.*, 2015; Wu *et al.*, 2015; Zhu *et al.*, 2016). Consequently, considerable attention has been paid to develop methods for removing VOCs. The non-thermal plasma (NTP) combined with the catalyst technology emerged as a promising method in recent years (Lee *et al.*, 2015; Trinh *et al.*, 2015a, b; Stasiulaitiene *et al.*, 2016). In this system, VOCs adsorption on the catalyst is a very important factor because VOCs residual time and reaction with active plasma species in the discharge region will be increased as a result of the catalyst appeared (Sultana *et al.*, 2015). Many researchers observe a positive relationship between catalyst adsorption ability and VOCs degradation. As catalyst adsorption performance increase, so will get the better VOCs degradation (Lu *et al.*, 2015; Pangilinan *et al.*, 2016; Wang *et al.*, 2016). O<sub>2</sub> as an essential for VOCs complete oxidation (Vandenbroucke *et*

*al.*, 2011) can be adsorbed by the catalyst (Chen *et al.*, 2004). In this co-adsorption system, Zhang *et al.* (2011) reported the competitive adsorption phenomena between O<sub>2</sub> and toluene on the catalyst surface. Nevertheless, this phenomenon is very important to explain the VOCs removal mechanism in the system of NTP assisted catalyst. However, there is little research on this problem. Therefore, the present study was conducted to investigate the competitive adsorption between O<sub>2</sub> and toluene on the catalyst surface.

To explore the competitive adsorption between O<sub>2</sub> and toluene, 3% iron loading on SBA-15 was selected as a catalyst because it showed a good performance for toluene and O<sub>2</sub> adsorption (Lu *et al.*, 2015; Zeng and Bai, 2016). The adsorption breakthrough curves of toluene were measured under the condition of various O<sub>2</sub> concentrations. In order to identify the adsorption site, the catalysts after the toluene adsorption in various O<sub>2</sub> concentrations were characterized by O<sub>2</sub>-TPD, XPS. Moreover, in situ FTIR of toluene adsorption under different O<sub>2</sub> concentrations was applied to investigate the effect of O<sub>2</sub> adsorption on the toluene adsorption and oxidation.

### EXPERIMENTAL

#### Catalyst Preparation

3% FeO<sub>x</sub>/SBA-15 (wt. %) and 5% MnO<sub>x</sub>/SBA-15 (wt. %)

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catalysts were prepared via an impregnation method using SBA-15 (Nanjing XFNANO Materials Tech Co., Ltd) as support. Iron nitrate and manganese acetate ethanol solution of desired concentration were used as Fe and Mn precursors, respectively. The impregnated sample was stirred for 24 h at room temperature, and the solvent was then removed by evaporation at 60°C. The residue was dried in an oven at 120°C for 12 h, followed by calcination at 500°C for 4 h. Pure SBA-15 support was treated in the same way for comparison in this study.

### Adsorption Breakthrough Curves of Toluene

Experiments of toluene adsorption were carried out at room temperature and atmospheric pressure. Toluene vapor was produced by passing dry N<sub>2</sub> through pure liquid toluene kept in ice/water (0°C). The adsorption gas was mixed by N<sub>2</sub> and O<sub>2</sub>, and their rates were adjusted by mass flow controllers. At last, the adsorption gas containing 100 ppm toluene passed through catalyst bed at a rate of 300 mL min<sup>-1</sup>. Concentrations of toluene in the outlet gas were recorded using an online gas chromatograph (GC-2014C, Shimadzu).

### O<sub>2</sub>-TPD

Initial, the catalyst adsorbed toluene in various O<sub>2</sub> concentrations at room temperature and atmospheric pressure, until adsorption saturation. The O<sub>2</sub>-TPD performance was measured using Micromeritics AutoChem 2920 equipment. The analysis procedure was as follows: 100 mg sample was pretreated at 300°C using high-purity He (30 mL min<sup>-1</sup>) for 30 min, and then cooled down to 60°C. Subsequently, the flow of O<sub>2</sub>-He mixture (5% O<sub>2</sub> by volume) was switched on for 60 min. High-purity He was then switched on and waited until the system stabilized. Then the sample was heated up to 800 °C at a rate of 10 °C min<sup>-1</sup>.

### XPS

The catalyst adsorbed toluene in various O<sub>2</sub> concentrations at room temperature and atmospheric pressure. Until adsorption saturation, the XPS performance was measured using an ESCALAB 250 spectrometer (Thermo Fisher Scientific, USA) equipped with a hemispherical electron analyzer, employing an Mg K $\alpha$  radiation source (1253.6 eV) of 25 W. All binding energies were referenced to the C 1s line at 284.6 eV, which provided an accuracy of  $\pm 0.48$  eV within the full scanning range of 0 to 1100 eV. XPS peak 4.1 software was used for curve fitting.

### In Situ FTIR

In situ FTIR spectra was recorded using a Nicolet 6700 spectrometer equipped with a mercury-cadmium-telluride (MCT) detector cooled by liquid nitro-gen. The catalyst was pretreated at 300°C using high-purity Ar (100 mL min<sup>-1</sup>) for 60 min, and then cooled down to the room temperature. Subsequently, toluene-N<sub>2</sub>-O<sub>2</sub> mixture (100 ppm toluene) was introduced into the IR cell. Until toluene adsorbed saturation, the high-purity Ar was introduced for 20 min, and then the sample was heated up to 150°C. The infrared spectra were collected with a resolution of 2 cm<sup>-1</sup> and 64 scans in the region of 650–4000 cm<sup>-1</sup>.

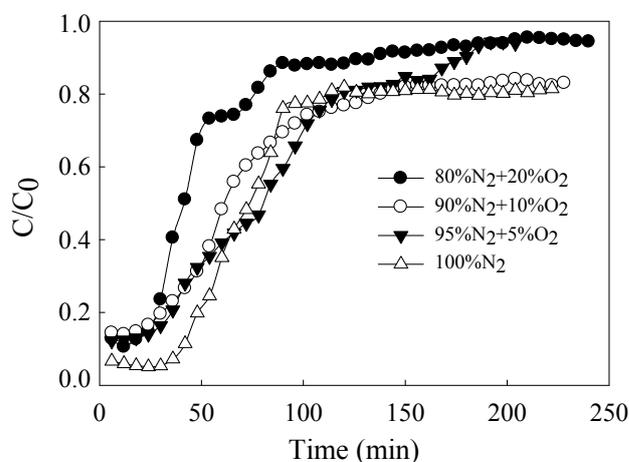
## RESULTS AND DISCUSSION

### Adsorption Breakthrough Curve of Toluene

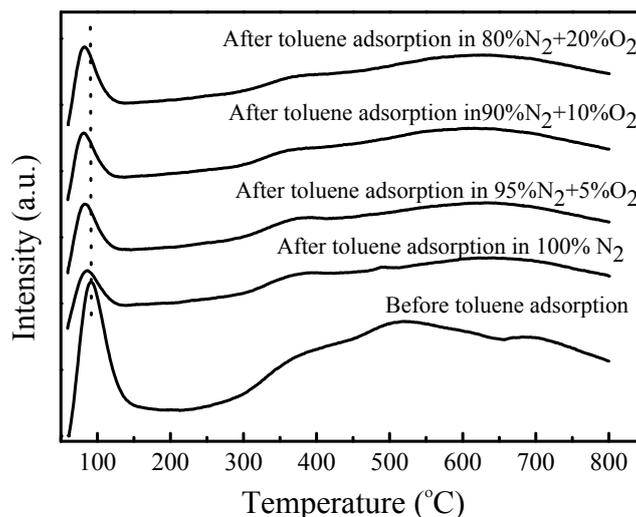
The adsorption breakthrough curves of toluene on the 3%FeO<sub>x</sub>/SBA-15 catalyst were presented in Fig. 1. The outlet toluene concentration was very low and the breakthrough curves were close to a straight line at first. Then the outlet toluene concentration was significant increased with the extension of adsorption time, finally reached a value of steady state (Fig. 1). The time that the toluene concentration increased was defined as the breakthrough time (Zhao *et al.*, 2011). The breakthrough time of toluene displayed an obvious difference at the different O<sub>2</sub> concentration streams, the following sequence was 100%N<sub>2</sub> (36 min) > 95%N<sub>2</sub> + 5%O<sub>2</sub> (24 min)  $\approx$  90%N<sub>2</sub> + 10%O<sub>2</sub> (24 min) > 80%N<sub>2</sub> + 20%O<sub>2</sub> (18 min). Our previous work found that the 3%-Fe-loading catalyst could adsorb O<sub>2</sub> on the surface and oxidize Fe<sup>2+</sup> into Fe<sup>3+</sup> (Lu *et al.*, 2015). This type of O<sub>2</sub> could quickly occupy the adsorption site, reduced the amount of toluene adsorption, so that the breakthrough time decreased when O<sub>2</sub> concentration increased. Those results indicated that O<sub>2</sub> provided competitive adsorption with toluene on the 3%FeO<sub>x</sub>/SBA-15 catalyst.

### O<sub>2</sub>-TPD

O<sub>2</sub>-TPD profiles could provide useful information on the behavior of oxygen in composite oxide materials. The O<sub>2</sub>-TPD profiles of fresh 3% FeO<sub>x</sub>/SBA-15 catalyst and after toluene adsorbed in various background gases were measured. In the TPD curves of various samples (Fig. 2), the peak emerged at 80°C could be ascribed to desorption of weak adsorption molecular oxygen (O<sub>2</sub><sup>-</sup>) from the catalyst surface (Li *et al.*, 2008; Ma *et al.*, 2013). Quantitative evaluation of this desorption peak (Table 1) revealed that desorption amount of O<sub>2</sub><sup>-</sup> from the catalyst, after it adsorbed toluene drastically dropped compared to the fresh catalyst. The degree of reduction depended on the O<sub>2</sub> concentrations when toluene adsorbed. Simultaneously, the intensity of



**Fig. 1.** Adsorption breakthrough curves of toluene on the 3%FeO<sub>x</sub>/SBA-15 catalyst under different O<sub>2</sub> concentrations (Initial concentration of toluene: 100 ppm, gas flow: 300 mL min<sup>-1</sup>).



**Fig. 2.** O<sub>2</sub>-TPD profiles of fresh 3%FeO<sub>x</sub>/SBA-15 catalyst and after toluene adsorption in different background gases.

**Table 1.** Desorption amount of O<sub>2</sub><sup>-</sup> on the fresh 3%FeO<sub>x</sub>/SBA-15 catalyst and after toluene adsorption in various background gases.

Back ground gas of adsorption	Total O <sub>2</sub> <sup>-</sup> (mmol g <sup>-1</sup> )
Before adsorption	0.18629
100%N <sub>2</sub>	0.05367
95%N <sub>2</sub> + 5%O <sub>2</sub>	0.06099
90%N <sub>2</sub> + 10%O <sub>2</sub>	0.05762
80%N <sub>2</sub> + 20%O <sub>2</sub>	0.07171

this peak showed the minimum for the sample of toluene adsorption at the pure N<sub>2</sub>. Whereas, the peak was arising as O<sub>2</sub> concentration increased. For this phenomenon, there were two main reasons: (i) Oxygen that adsorbed on the catalyst surface during toluene adsorption desorbed from the catalyst surface; (ii) The adsorbed toluene was oxidized by the adsorbed O<sub>2</sub> during the pretreatment procedure (O<sub>2</sub>-TPD, pretreated at 300°C), so the adsorption sites occupied by the toluene were released. And those sites were re-adsorbed by the O<sub>2</sub> which came from O<sub>2</sub>-He mixture (O<sub>2</sub>-TPD, O<sub>2</sub>-He mixture was switched for 60 min). Finally, improved O<sub>2</sub><sup>-</sup> desorption amount. Whatever the results, these indicated that O<sub>2</sub> and toluene had the competitive adsorption on the 3%FeO<sub>x</sub>/SBA-15 catalyst surface.

Simultaneously, the temperature of this peak shifted lower compared to the fresh catalyst, and the lowest was observed at the pure N<sub>2</sub> as the background gas of toluene adsorption. This implied that the lattice oxygen activity might be improved when the oxygen adsorbed on the catalyst surface. It was beneficial for the complete oxidation of toluene.

To better understand the competitive adsorption of O<sub>2</sub> and toluene on the FeO<sub>x</sub>/SBA-15 catalyst, an additional experiment was carried out with pure SBA-15 and 5%MnO<sub>x</sub>/SBA-15 adsorbed toluene in the feed gases of 100%N<sub>2</sub> and 80%N<sub>2</sub> + 20%O<sub>2</sub> (Fig. 3). No significant difference was observed between the spectra acquired with different background gases, suggested that there was no competitive adsorption of O<sub>2</sub> and toluene on the pure SBA-15 and 5%MnO<sub>x</sub>/SBA-

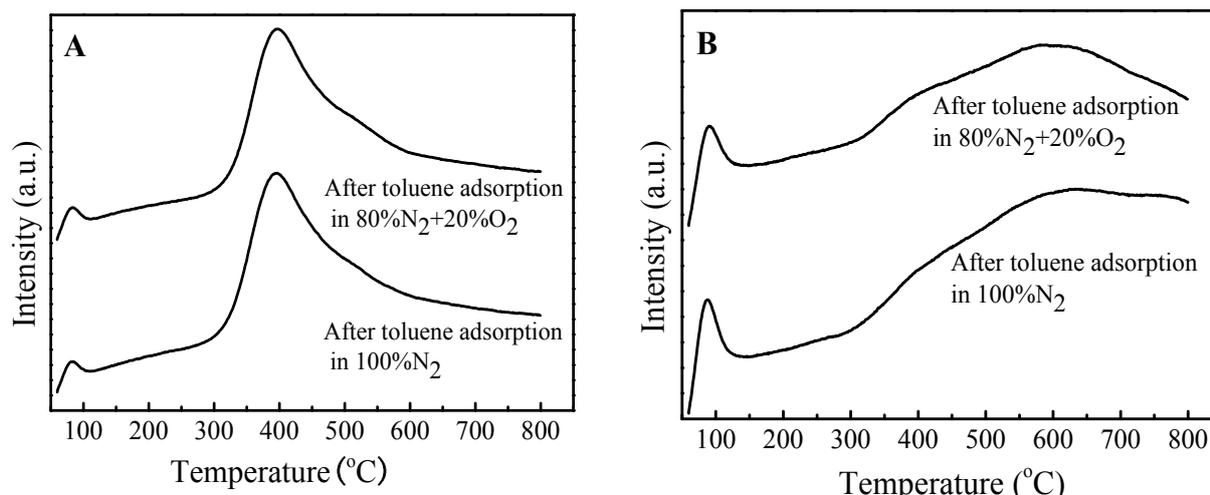
15 catalysts surface. This indicated that FeO<sub>x</sub> was the competitive adsorption site of O<sub>2</sub> and toluene.

#### **Effect of O<sub>2</sub> Concentration on the Atomic Surface Compositions of Catalyst**

Atomic surface compositions of catalysts were obtained via XPS (Table 2, Fig. 4). The results showed that the O, Fe, Fe<sup>2+</sup> and Fe<sup>3+</sup> content had been changed as the toluene adsorbed (Table 2). Compared to the fresh catalyst, the percentage of Fe<sup>2+</sup> increased when the adsorbed gas was 100%N<sub>2</sub>, while decreased as the background gas containing O<sub>2</sub>. However, Fe<sup>3+</sup> content showed the opposite tendency, decreased in the 100%N<sub>2</sub>, increased as the background gas containing O<sub>2</sub>, and the 20%O<sub>2</sub> showed the maximum. Previous study showed that the toluene could adsorb on the catalyst surface of metal ion (Liu *et al.*, 2005). Therefore, when the background gas was pure N<sub>2</sub>, the toluene could be adsorbed on the Fe<sup>2+</sup> or Fe<sup>3+</sup> site, resulting in the decrease of Fe ion concentration on catalyst surface. Subsequently, the Fe<sup>2+</sup> and O located on the catalyst subsurface moved to the catalyst surface, and brought out the increase of Fe<sup>2+</sup>, O and Fe content on the catalyst surface (Table 2). Another hand, O<sub>2</sub> had the competitive adsorption with toluene on the 3%FeO<sub>x</sub>/SBA-15 (Figs. 2 and 3). Therefore, when the background gas contained O<sub>2</sub>, the O<sub>2</sub> could be adsorbed on the Fe<sup>2+</sup> and oxidized Fe<sup>2+</sup> into Fe<sup>3+</sup> (Lu *et al.*, 2015), resulting in the increase of Fe<sup>3+</sup> (Table 2). This result further demonstrated that the O<sub>2</sub> and toluene appeared the competitive on the FeO<sub>x</sub>/SBA-15 surface, and the Fe<sup>2+</sup> was one of the competitive adsorbed sites.

At the same time, the XPS spectra for Fe 2p (Fig. 4) shifted lower after adsorbed toluene, especially fit adsorbed toluene in the 90%N<sub>2</sub> + 10%O<sub>2</sub>. This could be attributed to the existence of FeSi or FeSi<sub>2</sub> (Li *et al.*, 2015). This indicated that the toluene adsorption could increase the interaction between Fe and supporter, which benefitted the performance of catalyst activity.

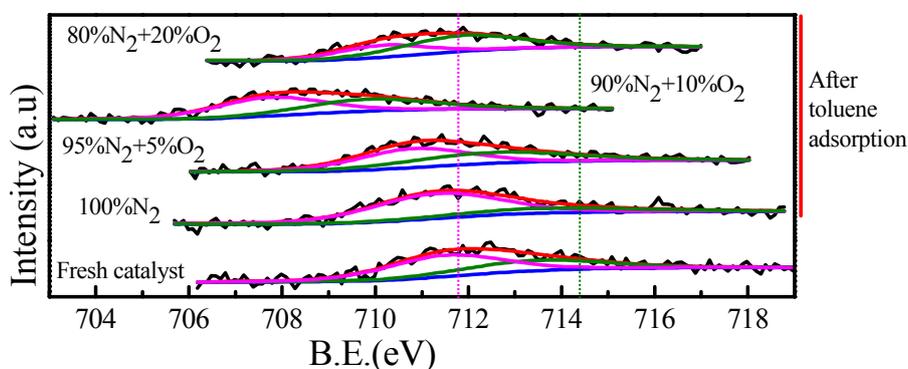
Thus, based on those results, the schematic diagram of competitive adsorption of O<sub>2</sub> and toluene on FeO<sub>x</sub>/SBA-15



**Fig. 3.** O<sub>2</sub>-TPD profiles of (A) SBA-15 and (B) 5%MnO<sub>x</sub>/SBA-15 after toluene adsorption in different background gases.

**Table 2.** Atomic surface compositions of fresh 3%FeO<sub>x</sub>/SBA-15 catalyst and after adsorbed toluene under various background gases as obtained via XPS.

Catalyst	Atomic Composition (%)			Fe %	
	Si	O	Fe	Fe <sup>3+</sup>	Fe <sup>2+</sup>
Fresh	25.74	73.56	0.70	37.02	62.98
After toluene adsorption in 100%N <sub>2</sub>	24.90	74.16	0.94	21.00	79.00
After toluene adsorption in 95%N <sub>2</sub> + 5%O <sub>2</sub>	25.29	73.93	0.78	45.84	54.16
After toluene adsorption in 90%N <sub>2</sub> + 10%O <sub>2</sub>	25.24	73.90	0.86	42.85	57.15
After toluene adsorption in 80%N <sub>2</sub> + 20%O <sub>2</sub>	25.25	74.02	0.73	63.41	36.59



**Fig. 4.** Fe 2p core level XPS spectra of fresh FeO<sub>x</sub>/SBA-15 catalyst and after adsorbed toluene under various background gases.

was proposed, as shown in Fig. 5. The O<sub>2</sub> and toluene adsorbed on the site of Fe<sup>2+</sup> loading on the catalyst surface, resulted in the decrease of Fe<sup>2+</sup> ion concentration on catalyst surface. Consequently, the Fe<sup>2+</sup> located on the catalyst subsurface moved to the catalyst surface. At the same time, Fe<sup>2+</sup> could be oxidized into Fe<sup>3+</sup> as the gas containing O<sub>2</sub>.

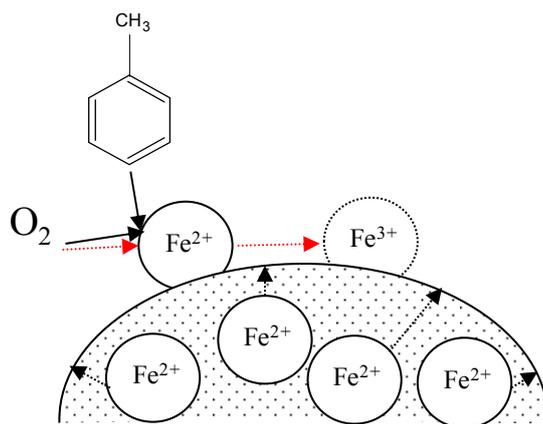
#### *In Situ FTIR*

In situ FTIR studies provided real-time monitoring of transient events occurring on the catalyst during toluene adsorption. In this study, a set of FTIR spectra were obtained during toluene adsorption over 3% FeO<sub>x</sub>/SBA-15 in different O<sub>2</sub> concentrations (Fig. 6). Fig. 6(A) was the IR transmittance

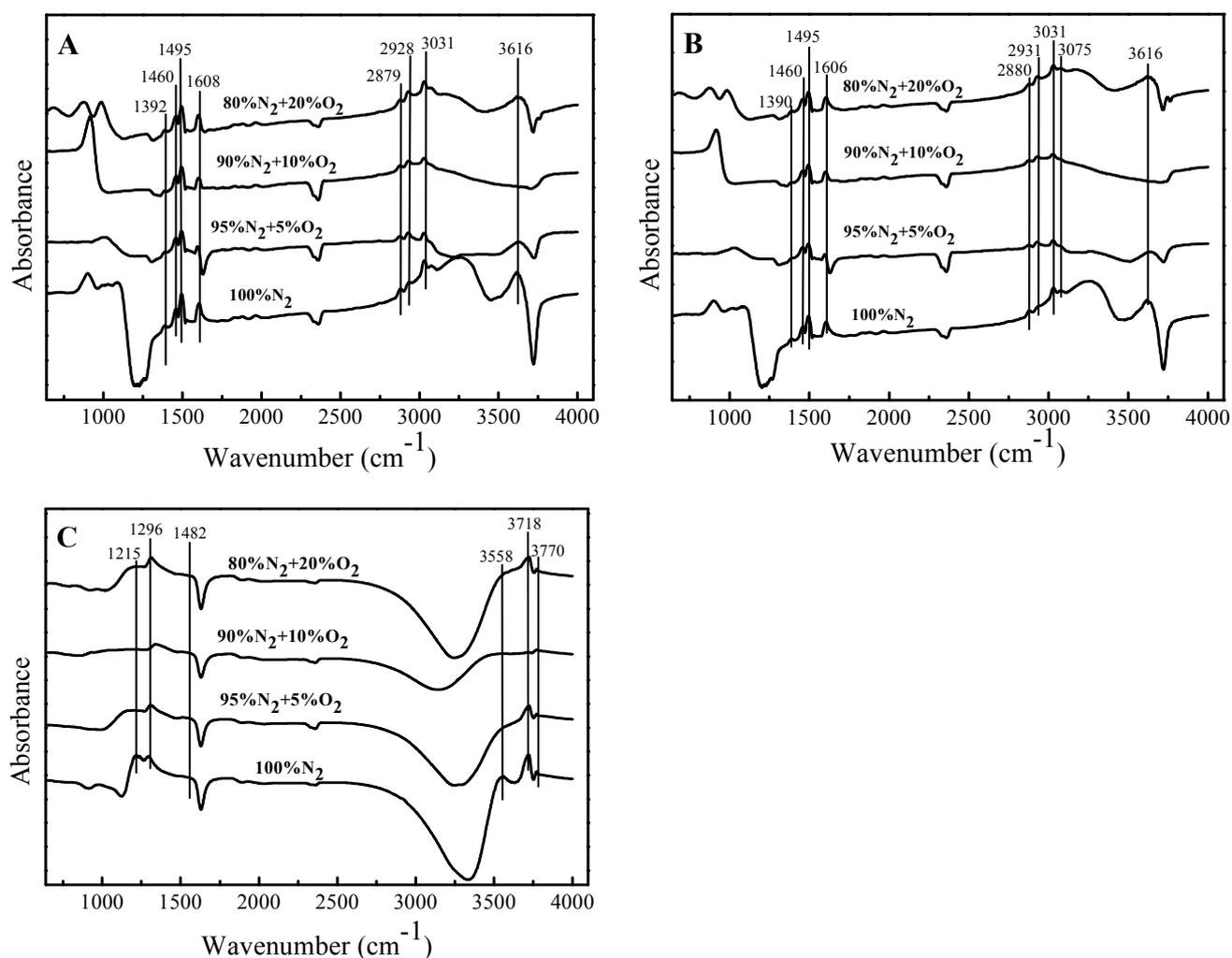
spectra of toluene adsorption over the catalyst. After adsorption saturation, the catalyst was immersed in pure Ar and purged for 20 min (Fig. 6(B)), then heated under the condition of 150°C (Fig. 6(C)).

During toluene adsorption, strong peaks due to toluene appeared at 1392, 1460, 1495, 1608 (C = C vibrations of an aromatic ring) (Li *et al.*, 2007), 2879, 2928 (C-H vibrations of methyl) (Maira *et al.*, 2001; Eby *et al.*, 2012), and 3031 (C-H vibration of aromatic ring) (Maira *et al.*, 2001). The peaks displayed no significant shift under the different O<sub>2</sub> concentrations, indicated that the O<sub>2</sub> did not influence the toluene adsorption state.

During the Ar purge processing, vibration bands of C =



**Fig. 5.** The schematic diagram of competitive adsorption of  $O_2$  and toluene on  $FeO_x/SBA-15$ .



**Fig. 6.** In situ FTIR spectroscopy of the 3% $FeO_x/SBA-15$  catalyst (A) Toluene adsorption, (B) Ar purge after toluene adsorption, (C) 150°C heated in the pure Ar.

C (aromatic ring), C-H (methyl), and C-H (aromatic ring) were also observed. This indicated that the toluene could steadily adsorb on the catalyst surface, which agreed with the results of Table 2. After 20 min of Ar purge, the catalyst was heated in the pure Ar stream (Fig. 6(C)). The bands of

toluene adsorption disappeared, and some new peaks were formed. Two peaks at 1215  $cm^{-1}$  and 1296  $cm^{-1}$  indicated the formation of C-O-C and C-O of ester, respectively (Long et al., 2011). At the same time, the intensity of the band at 1215  $cm^{-1}$  decreased with increasing  $O_2$  concentration.

This suggested that the O<sub>2</sub> adsorbed on the catalyst surface promoted toluene oxidation and decreased the formation of ester organic by-products. The peaks at 3558 cm<sup>-1</sup> and 3718 cm<sup>-1</sup> should correspond to the bridging OH groups with toluene and the OH of the catalyst surface, respectively (Maira *et al.*, 2001; Wu *et al.*, 2014). The peak at 3558 cm<sup>-1</sup> decreased as the background gas containing O<sub>2</sub>, which was due to the reaction of toluene with O<sub>2</sub> adsorbed on the catalyst surface. Those results demonstrated that O<sub>2</sub> adsorbed on the catalyst surface could oxidize toluene.

Additionally, the peaks at 3616 cm<sup>-1</sup> should assigned to a lattice OH stretching mode (Wu *et al.*, 2014), and the intensity was the maximum under the pure N<sub>2</sub>. Our previous study found that the 3%-Fe-loading catalyst could oxidize toluene into CO<sub>x</sub> in the pure N<sub>2</sub> plasma (Lu *et al.*, 2015), one of the reasons might arise from the oxidation ability of the OH under the pure N<sub>2</sub>.

## CONCLUSIONS

In the present study, the breakthrough time of toluene in the different background gases indicated that O<sub>2</sub> could competitively adsorb with toluene on the 3%FeO<sub>x</sub>/SBA-15 catalyst, and the Fe<sup>2+</sup> was one of the adsorption sites for both O<sub>2</sub> and toluene. In situ FTIR study of toluene adsorption on the catalyst surface showed that the competitive adsorption between O<sub>2</sub> and toluene could not impact the toluene adsorption state on the catalyst surface, and the O<sub>2</sub> adsorbed on the catalyst surface could oxidize toluene.

## ACKNOWLEDGMENT

This work was carried out with the supported of “the National Natural Science Foundation of China (No.51508245, No. U1201231, No.51378218)”. We appreciate Dr. William Wen, Mr Rex Howitson and Alan Peterson for checking the English language.

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Received for review, May 7, 2016

Revised, February 2, 2017

Accepted, March 12, 2017