



## NO Reactions Over Ir-Based Catalysts in the Presence of O<sub>2</sub>

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Received 21 January 2011; Accepted 12 April 2011

**Abstract:** The behaviour of a series of Ir-based catalysts supported on SiO<sub>2</sub>, ZSM-5 and  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> with various Ir loadings prepared by impregnation method was conducted by temperature programmed reaction (TPR) technique. The result implies that NO is oxidized to NO<sub>2</sub> while simultaneously being reduced to N<sub>2</sub> or N<sub>2</sub>O in the NO reactions over iridium catalysts. The surface active phase over iridium catalysts that promote the NO reactions is IrO<sub>2</sub>. The catalytic activity increases with the increase of the Ir loading and support materials have a little effect on the catalytic activity. When the loading is less than 0.1%, the catalytic activity was found to be dependent on the nature of support materials and in order: Ir/ZSM-5>Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>>Ir/SiO<sub>2</sub>. When the loading is higher than 0.1%, the catalytic activity for NO oxidation is in order: Ir/ZSM-5>Ir/SiO<sub>2</sub>>Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, which is correlated with Ir dispersion on the surface of support materials and the catalytic activity for NO reduction is in sequence: Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>>Ir/SiO<sub>2</sub>>Ir/ZSM-5, which is attributed to the adsorbed-dissociation of NO<sub>2</sub>. Compared to Pt/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> catalyst is more benefit for the NO reduction.

**Keywords:** Ir, NO oxidation, NO reduction, Pt

### Introduction

With the increase concerns about energy crisis and global warming, more severe requirements about the emission of greenhouse gas CO<sub>2</sub> and conservation of energy have been progressively brought forward. In this context, particular concern has been addressed to the lean burn which can greatly reduce the CO and hydrocarbon as well as improve utilization and economy of fuel. In addition, the automotive industry is currently facing serious challenges to meet the specific requirements of future regulations concerning NOx. However, the conventional three-way catalysts are not effective for NOx reduction due to

the preferential oxidation of reductants with excess oxygen under lean burn condition. Hence, the catalytic removal of NO<sub>x</sub> under excess oxygen conditions is an issue full of challenges in catalytic science.

In the past years, several technologies have been developed in order to catalytic removal of NO<sub>x</sub> under rich-oxygen environment including the catalytic decomposition, selective catalytic reduction, storage and catalytic reduction. Among these catalytic systems, noble metal catalysts have drawn many researchers' eyes owing to their high activity at low temperature and the strong resistance to poisoning by SO<sub>2</sub> and H<sub>2</sub>O<sup>1-15</sup>. Now, more and more attentions have been put on the activity of iridium catalysts<sup>5-10</sup>.

Ir-based catalysts show high catalytic activity and N<sub>2</sub> selectivity when NO reduced with hydrocarbon in rich-oxygen environment. Among Pt, Pd, Rh and Ir investigated in the reduction of NO by CO under excess oxygen, Ir-based catalysts show the highest catalytic activities<sup>7-10</sup> and the presence of SO<sub>2</sub> can promote NO reduction<sup>9,10</sup>. However, few researches has been reported for the direct catalytic reaction of NO over Ir-based catalysts in the presence of O<sub>2</sub>. In this work, we investigated the NO reactions over Ir-based catalysts in the presence of O<sub>2</sub> and discussed the effect of Ir loading and support material on the NO reactions.

## Experimental

The catalysts were prepared by iso-volumetric impregnation with aqueous solutions of H<sub>2</sub>IrCl<sub>6</sub>·6H<sub>2</sub>O (Shanghai Jiuyue Chemical Co., Ltd.) and the Ir content is 0.02wt.%, 0.1wt.%, 1wt.% and 5wt.%. The support materials used are ZSM-5 (Nakai University, Si/Al=50), active  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> (Dalian Luming Nanometer Material Co., Ltd, 200~500 nm, 160 m<sup>2</sup>/g) and SiO<sub>2</sub> (Qingdao Haiyang Chemical Co., Ltd, 0.125~0.425  $\mu$ m, 460 m<sup>2</sup>/g). All the materials were dried at 110 °C for 12 h after left one day at room temperature and finally calcined at 500 °C for 3 h in air. The powder catalysts were pressed into pellets at 10 Mpa, crushed and sieved to obtain granules of 0.250-0.425 mm for catalytic activity measurement. For comparison, 5% Pt/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> was prepared by the iso-volumetric impregnation of  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> with an aqueous solution of H<sub>2</sub>PtCl<sub>6</sub>·6H<sub>2</sub>O (Shanghai Jiuyue Chemical Co., Ltd.).

Phase identification of fresh catalysts was analyzed by XRD analyzer. The structure of iridium and platinum were measured using TEM (JEOL, JEM-2010) at an acceleration voltage of 200 keV. The iridium dispersions were measured using a Pulse chemisorb apparatus by means of hydrogen chemisorption, assuming the ratio of surface Ir to the adsorbed hydrogen atom of 1 to 1. In order to get reproducible iridium dispersion values, several cycles of hydrogen titration were applied prior to the determination of the amount of hydrogen being chemically adsorbed on the iridium of the catalysts.

### *Catalytic activity measurements*

In a fixed-bed continuous flow reactor, catalytic activity was evaluated by temperature programmed reaction (TPR) technique. The catalyst granules (0.05 g) were carefully fixed in a tubular quartz reactor (6 mm i.d.). The reaction gas which contains NO (420 ppm) and O<sub>2</sub> (4.4vol. %) with He as the balance gas was fed through the catalyst bed at a flow rate of 100 mL/min. The reaction temperature was monitored by thermocouple directly inserted into the region of the catalyst bed and controlled by a PID-regulation system (Bachy, CKW-2200). The reaction temperature was raised at a rate of 4 °C /min from 100 °C to 750 °C. The concentrations of NO, NO<sub>2</sub> and NO<sub>x</sub> (=NO+NO<sub>2</sub>) were continuously detected by Nitrogen Oxides Analyzer (Australian Ecotech, EC-9841B).

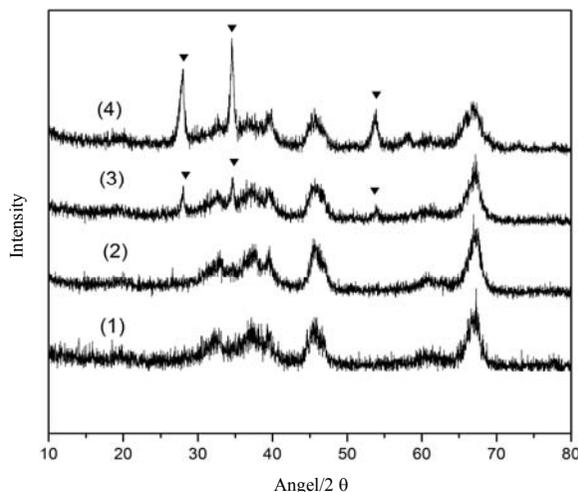
In order to evaluate the catalytic performance in the NO catalytic reaction, the maximal conversion ratio and the corresponding conversion temperature during the NO oxidation and NO reduction are adopted. In the NO oxidation, they are the maximal oxidation conversion ratio ( $\eta_o$ ) estimated by the ratio of NO<sub>2</sub> formation to NO in the reaction gas (420 ppm) together with the corresponding temperature named as  $T_o$ . In the NO reduction, the maximal reduction conversion ratio ( $\eta_R$ ) obtained by the ratio of the maximal NOx concentration reduced to NO in the reaction gas with the corresponding temperature named as  $T_R$  are adopted.

Temperature programmed desorption (TPD) was done after TPR experiment. Temperature need to be cooled to room temperature in the same gas stream as TPR system and the catalyst bed was then purged in He for about 1 h. When the signal of NO and NO<sub>2</sub> from the detector had dropped to zero, TPD experiment was started in He stream with same flow rate and heating rate as that in the activity experiments.

## Results and discussion

### Characterizations of catalysts

Figure 1 shows the XRD results of Ir-based catalysts supported on  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> with different loadings. From the XRD patterns, there are no differences among 0.02wt.%, 0.1wt.% and blank  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, and the diffraction peaks of iridium are absent. The weak peaks of IrO<sub>2</sub> are observed when the loading is 1wt.% and the peaks of IrO<sub>2</sub> strengthen as the loading increases to the 5 wt.%. Hence, IrO<sub>2</sub> is the active phase, which is consistent with the crystal phase of catalysts unreduced by H<sub>2</sub> and the absence of IrO<sub>2</sub> peaks with low contents reveals the high dispersive state of IrO<sub>2</sub>.

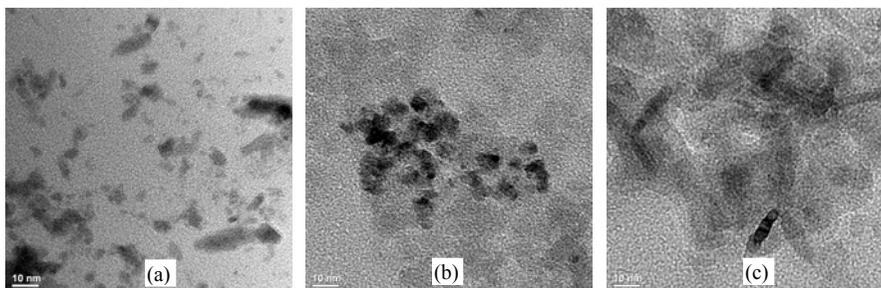


**Figure 1.** XRD patterns of Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> with different Ir contents: (1) zero, (2)0.1wt.%, (3) 1wt.% and (4) 5wt.%. IrO<sub>2</sub> (▼)

Figure 2 shows TEM images of 1wt.% Ir over different supports. From it, we can find that Ir particles are well dispersed over the surface of ZSM-5 and accumulative over the surface of  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>.

Table 1 gives the hydrogen chemisorption over 1wt.% Ir/SiO<sub>2</sub> and 5wt.% Ir supported on SiO<sub>2</sub>,  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and ZSM-5. H<sub>2</sub> chemisorption is corresponding to the number of Ir atoms

exposed on the surface per gram of catalysts. From Table 1, with the increase of Ir content, the number of Ir atoms exposed on the surface becomes larger and there are more Ir atoms exposed on the surface over Ir/ZSM-5 with the same content.



**Figure 2.** TEM images of 1wt.% Ir over (a) ZSM-5, (b) SiO<sub>2</sub>, (c)  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>.

**Table 1.** Ir dispersion over catalysts

Catalyst	1%Ir/SiO <sub>2</sub>	5%Ir/SiO <sub>2</sub>	5%Ir/ $\gamma$ -Al <sub>2</sub> O <sub>3</sub>	5%Ir/ZSM-5
Amount of H <sub>2</sub> adsorption, $\mu\text{mol} \cdot \text{g}^{-1}_{\text{cat}}$	19.4	101.95	29.66	111.42

#### *Reactions of NO over Ir/ZSM-5*

Figure 3 shows the TPR results of NO reaction over Ir/ZSM-5. From Figure 3(a), we can find that the concentration of NO<sub>2</sub> begins to increase at 300 °C while NO decrease simultaneously over 0.1wt.% Ir/ZSM-5, implying that only part of NO is oxidized to NO<sub>2</sub>(equation (1)). The concentration of NO<sub>2</sub> reaches the maximum at 390 °C and then decreases as the temperature increases limited by the thermodynamic equilibrium among NO, NO<sub>2</sub> and O<sub>2</sub><sup>16</sup>. In Figure 3(b), the concentration of NO<sub>x</sub> (=NO+NO<sub>2</sub>) over 0.1wt.% Ir/ZSM-5 decreases from 300 °C, reaches the lowest at 390 °C and then increases as the temperature continue to increase. From Figure 3, it is obvious that the NO<sub>x</sub> reduction is related to the oxidation of NO to NO<sub>2</sub> over 0.1wt.% Ir/ZSM-5. Wang *et al.*<sup>8</sup> gave a research on TPD of NO after co-adsorption with O<sub>2</sub> over 0.1wt.% Ir/ZSM-5 using GC-MS technique and found that peaks of N<sub>2</sub> and N<sub>2</sub>O formed around 395 °C. Apparently, the temperature at which NO<sub>x</sub> reaches the lowest concentration in our experiment is consistent with that of N<sub>2</sub> and N<sub>2</sub>O formed in Wang's report<sup>8</sup>, which implied that the NO<sub>x</sub> reduced over Ir/ZSM-5 was transformed into N<sub>2</sub> and N<sub>2</sub>O. Since the reduction of NO<sub>x</sub> associates with NO<sub>2</sub> formation, it can be attributed to NO<sub>2</sub> adsorbed-decomposed to adsorbable NO (NO(ad))<sup>15,17</sup> and then decompose to N<sub>2</sub>(N<sub>2</sub>O) (equation (2)-(3)). Thus, not only the oxidation of NO to NO<sub>2</sub> occurred over Ir-based catalysts, but also the reduction of NO<sub>2</sub> adsorbed-dissociation to N<sub>2</sub> (or N<sub>2</sub>O) took place, simultaneously.

#### *Catalytic activity*

Figure 3, Figure 4 and Figure 5 are TPR profiles of NO, NO<sub>2</sub> and NO<sub>x</sub> over Ir/ZSM-5, Ir/SiO<sub>2</sub> and Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> respectively and the evaluation parameters are tabulated in Table 2. Compared with Ir-based catalysts, blank supports show negligible activity. Over the same support materials, with increase of Ir content, the oxidation activity together with the reduction activity of NO both increase. With the same Ir content, Ir/ZSM-5 is more beneficial

for the NO oxidation but Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> is more conducive to NO reduction. Therefore, Ir-based catalysts play an important role in the NO reaction and the loading of Ir and support materials are of important effect on the activities of Ir-based catalysts.

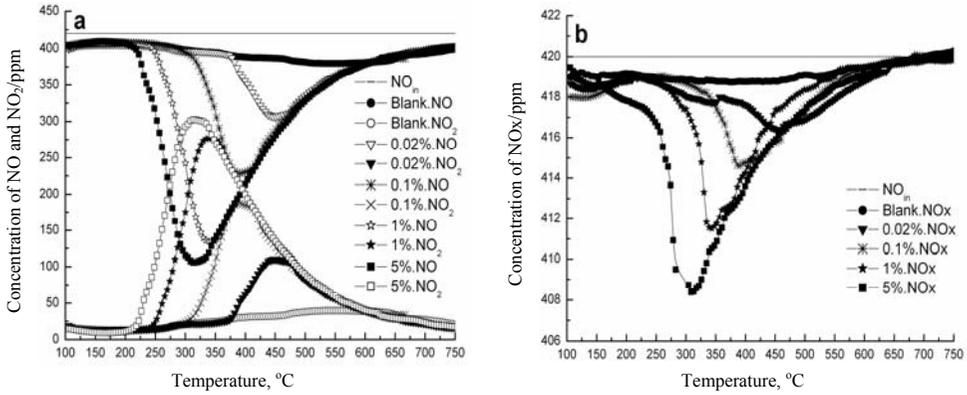
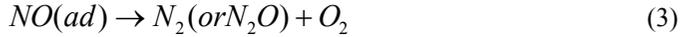


Figure 3. TPR profiles of NO, NO<sub>2</sub> and NOx over Ir/ZSM-5

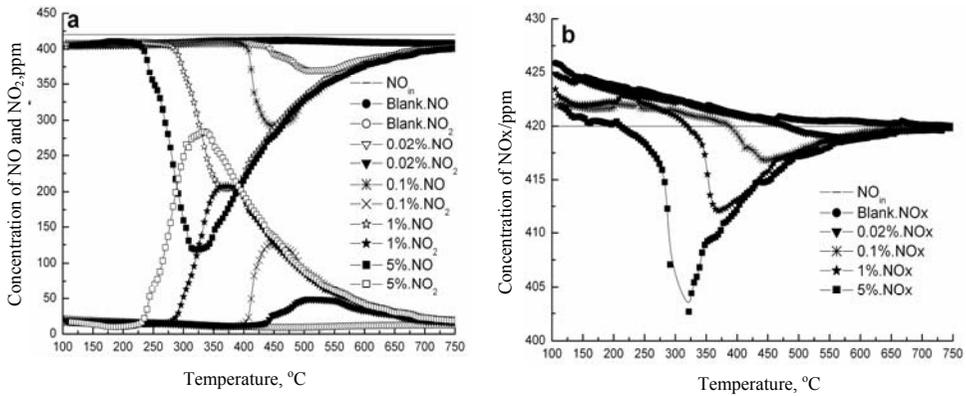


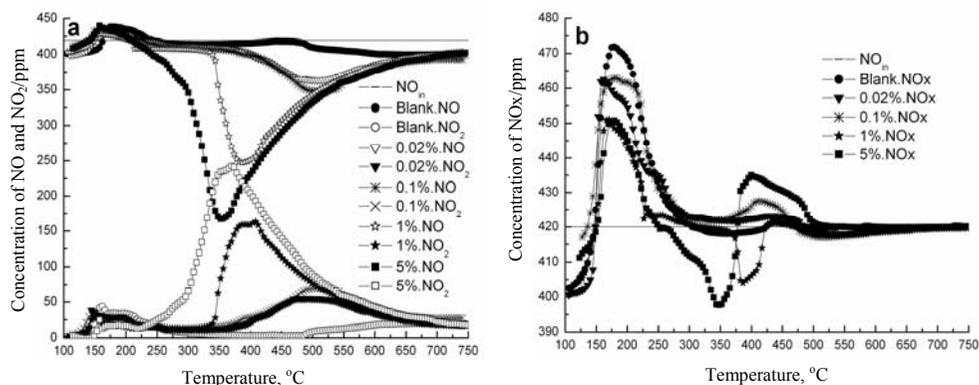
Figure 4. TPR profiles of NO, NO<sub>2</sub> and NOx over Ir/SiO<sub>2</sub>

*Effect of Ir contents*

Figure 4 shows the profiles of NO reaction over Ir/SiO<sub>2</sub>. In Figure 4(a), with the increase of Ir content, the oxidation window of NO becomes broad at low temperature,  $\eta_o$  increases and  $T_o$  moves toward low temperature. These results show that more NO oxidized to NO<sub>2</sub> as the content of Ir increases. Our result is similar to Xue’s report<sup>13</sup> that the oxidation activities of NO were observed to increase as the Pt loading increased. And this can be verified by hydrogen chemisorption over Ir/SiO<sub>2</sub> with 1wt.% and 5wt.% in Table 1. With the increase of Ir content, Ir atoms exposed on the surface increase and contribute to the oxidation of NO. In Figure 4 (b), with the increase of Ir contents, the reduction window of NO becomes broad at low temperature,  $\eta_R$  increases and  $T_R$  moves toward low temperature. These results indicate that a higher content of Ir metal is more beneficial for the

reduction of NO due to more formation of NO<sub>2</sub> and the proceeding of equation (2) and equation (3).  $T_O$  and  $T_R$  were same and this further demonstrated the association between NOx reduction and NO<sub>2</sub> production. Hence, Ir content exhibits large effect on the NO reaction over Ir/SiO<sub>2</sub> and the activities of oxidation and reduction both improve with Ir content increase.

From Figure 3 and Figure 5, with increase of Ir content, the oxidation activity together with the reduction activity of NO both increase over Ir/ZSM-5 and Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and these are similar to that of Ir/SiO<sub>2</sub>. Compared with NO reactions over Ir supported on ZSM-5 and SiO<sub>2</sub>, an obvious discrepancy over Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> is the strong desorption of NO and NO<sub>2</sub> ranging from 100 °C to 250 °C. The desorption is due to the adsorption at low temperature and this coincides with Xue *et al.*<sup>13</sup>



**Figure 5.** TPR profiles of NO, NO<sub>2</sub> and NOx over Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>

### *Effect of the support materials*

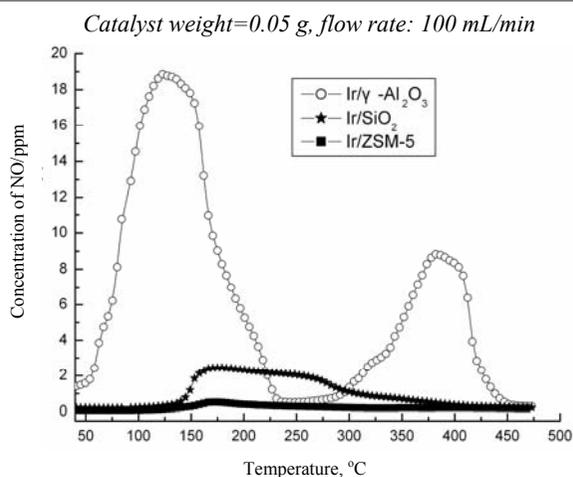
In Table 2, the activity of NO oxidation over blank supports is in order: ZSM-5 >  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> > SiO<sub>2</sub> and the reduction activities of NO are zero. This result indicates that support materials exhibited a little effect on the NO oxidation and no effect on the NO reduction. Our result about the NO oxidation is same as Xue *et al.*<sup>13</sup> report that NO oxidation primarily depends on the nature of support materials.

From the data in Table 2, we can find that the activity is in sequence: Ir/ZSM-5 > Ir/SiO<sub>2</sub> > Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> for catalytic oxidation of NO with the Ir content of 1wt.%. Xue *et al.*<sup>13</sup> gave a research on effect of the support materials on the oxidation of NO to NO<sub>2</sub> over Pt-based catalysts and found that the catalytic activity of Pt/SiO<sub>2</sub> is higher than Pt/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, which is similar to our result. However, these results about NO oxidation over Ir-based catalysts with the content of 1wt.% were different from those obtained from blank support in the NO reactions, which gave a hint that difference in catalytic activities should be derived from discrepancy of Ir dispersion on the support surface<sup>18</sup>. Figure 2 shows the TEM images of Ir-based catalysts supported by ZSM-5, SiO<sub>2</sub> and  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> with the loading of 1wt.%. From Figure 2, it is obviously that Ir particles are well dispersed over the surface of ZSM-5 and accumulative over the surface of  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>. Table 1 gives the hydrogen chemisorption over 1wt.% Ir/SiO<sub>2</sub> and 5wt.% Ir supported on SiO<sub>2</sub>,  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and ZSM-5. From the data in Table 1, it is also confirmed Ir particles are well dispersed over the surface of ZSM-5 and accumulative over the surface of  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>. From above results, Ir particles

accumulated were not conducive to the catalytic oxidation of NO to NO<sub>2</sub>. From the comparison of catalytic reduction activities with 1 wt.% loading, it was found that  $\eta_R$  is in order: Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>>Ir/SiO<sub>2</sub>>Ir/ZSM-5 and the  $T_R$  is Ir/ZSM-5>Ir/SiO<sub>2</sub>>Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>. Obviously, the order of  $T_R$  is consistent with that of  $T_o$  and the order of  $\eta_R$  is reverse with that of  $\eta_o$ . The consistence of  $T_R$  and  $T_o$ , was attributed to the NO<sub>x</sub> reduction closely related with NO<sub>2</sub> formation. The contrary of  $\eta_R$  and  $\eta_o$  indicated that the NO reduction was related with NO<sub>2</sub> formation as well as its adsorption and dissociation. Figure 6 shows TPD profile of NO after co-adsorption over Ir/ZSM-5, Ir/SiO<sub>2</sub> and Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> with the content of 1 wt.%. From figure 6, it can be obtained that the adsorption activity is Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>> Ir/SiO<sub>2</sub>> Ir/ZSM-5, which is consist with  $\eta_R$ . These implied the adsorption-dissociation of NO<sub>2</sub> on support played an important role in NO reduction.

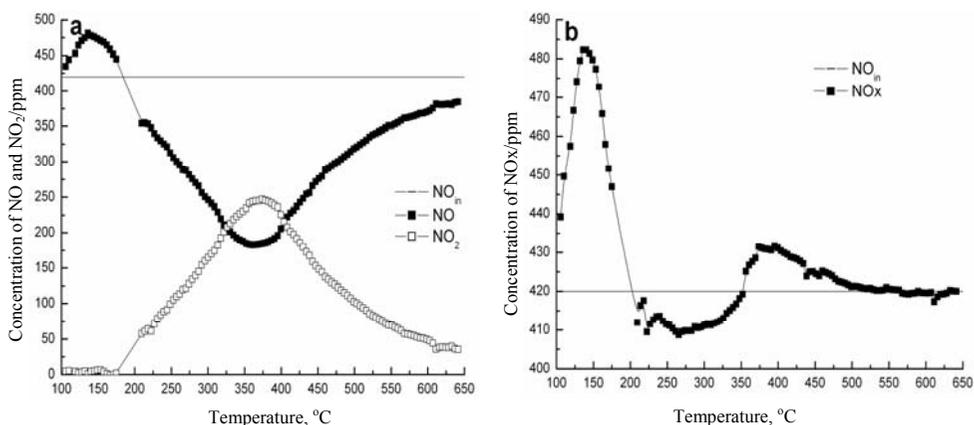
**Table 2.** Activity of catalysts for NO reaction

Catalyst	$\eta_o$ %	$T_o$ °C	$\eta_R$ %	$T_R$ °C
Blank SiO <sub>2</sub>	0		0	
0.02% Ir/SiO <sub>2</sub>	11.7	512	a little	
0.1% Ir/SiO <sub>2</sub>	30.0	446	1.2	446
1% Ir/SiO <sub>2</sub>	49.5	369	2.1	369
5% Ir/SiO <sub>2</sub>	67.5	321	4.1	321
Blank $\gamma$ -Al <sub>2</sub> O <sub>3</sub>	4.8	>600	0	
0.02% Ir/ $\gamma$ -Al <sub>2</sub> O <sub>3</sub>	13.0	507	a little	
0.1% Ir/ $\gamma$ -Al <sub>2</sub> O <sub>3</sub>	16.5	500	1.5	500
1% Ir/ $\gamma$ -Al <sub>2</sub> O <sub>3</sub>	38.8	386	3.8	386
5% Ir/ $\gamma$ -Al <sub>2</sub> O <sub>3</sub>	57.7	352	5.3	352
Blank ZSM-5	9.4	>550	0	
0.02% Ir/ZSM-5	26.1	451	a little	451
0.1% Ir/ZSM-5	44.7	391	1.0	391
1% Ir/ZSM-5	65.9	339	2.0	339
5% Ir/ZSM-5	72.1	313	2.8	313
5% Pt / $\gamma$ -Al <sub>2</sub> O <sub>3</sub>	58.8	361	a little	



**Figure 6.** TPD profiles of NO after co-adsorption of NO and O<sub>2</sub> over Ir/ZSM-5, Ir/SiO<sub>2</sub> and Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>

The NO oxidation ability with the content of 0.02wt.% is in order: Ir/ZSM-5 > Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> > Ir/SiO<sub>2</sub>, which is similar to that of blank supports. And the activities of NO reduction are weak. These were attributed to the nature of support materials which played an important role when the Ir content was low. The NO oxidation activity with 0.1wt.% and 5wt.% is Ir/ZSM-5 > Ir/SiO<sub>2</sub> > Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and the NO reduction activity is Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> > Ir/SiO<sub>2</sub> > Ir/ZSM-5, which are similar to those of Ir-based catalysts with the content of 1wt.%.



**Figure 7.** TPR profiles of NO, NO<sub>2</sub> and NO<sub>x</sub> over 5wt.% Pt/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>

#### *Comparison between Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and Pt/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>*

Figure 7 shows TPR profiles of NO, NO<sub>2</sub> and NO<sub>x</sub> over 5% Pt/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>. From the data in Table 2, NO oxidation over 5wt.% Pt/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> reaches the maximal conversion at 361 °C and the conversion ratio is 58.8%, which are accordant with Xue<sup>13</sup>. Compared with 5wt.% Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> in Figure 4 (a), although NO oxidation activity over Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> is lower than that of Pt/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> at low temperature, the maximal oxidation conversion is similar to Pt/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>. Comparing Figure 7 (b) with Figure 4 (b), NO reduction conversion over Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> is higher than that over Pt/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>. Hence, Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> is more beneficial for NO reduction than Pt/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and this result is accordant with Wang *et al.*<sup>8</sup>.

### **Conclusion**

A series of TPR and TPD experiments were carried out in order to give a research on the NO reactions over Ir-based catalysts in the presence of O<sub>2</sub>. The oxidation of NO to NO<sub>2</sub> together with the reduction of NO<sub>2</sub> to N<sub>2</sub> (or N<sub>2</sub>O) through adsorption and decomposition were observed over Ir-based catalyst and IrO<sub>2</sub> is the surface active phase in the NO reactions by XRD analysis. Ir content and support materials both exhibited an effect on the NO reaction over Ir-based catalysts. The activities of the oxidation and reduction of NO increased as Ir loading increased. When the loading less than 0.1wt.%, NO oxidation activity is Ir/ZSM-5 > Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> > Ir/SiO<sub>2</sub> mainly depended on the nature of support materials. While the loading greater than 0.1wt.%, the NO oxidation activity is Ir/ZSM-5 > Ir/SiO<sub>2</sub> > Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> which was lied on the Ir dispersion over support materials and the NO reduction activity is Ir/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> > Ir/SiO<sub>2</sub> > Ir/ZSM-5 which was relied on the adsorbed-dissociation of NO<sub>2</sub> over Ir-based catalysts. Compared with Pt catalysts, Ir-based catalyst is more beneficial for NO reduction.

### Acknowledgment

This work was supported by Natural Scientific Research Innovation Foundation in Harbin Institute of Technology (No.2008), "Double Hundred" Plan of Shenzhen (No.2008) and National Natural Science Foundation of China (No. 20907012).

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