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Combination effect of activated carbon with TiO_2 for the photodegradation of binary pollutants at typical indoor air level

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Abstract

Previously we identified that residence time and water vapor are the vital parameters that affect the photodegradation of indoor air pollutants at parts-per-billion (ppb) levels using TiO_2. The presence of water vapor competes with pollutants for adsorption sites on TiO_2 thus reducing the pollutant removal rate. By immobilizing TiO_2 on activated carbon (AC), a satisfactory pollutant removal rate is achieved even at high water vapor levels. This study further examines the effect of TiO_2 immobilized on AC by co-injecting binary pollutants simultaneously since the presence of other pollutants might have an inhibition effect on the photocatalytic activity under different humidity levels. 200 parts-per-billion NO, 20 ppb BTEX and 200 ppb SO_2 were co-injected under different residence time and humidity levels to investigate their mutual effect on TiO_2 and TiO_2 immobilized on AC. Results showed that no significant pollutant removal difference was observed between TiO_2 and TiO_2 immobilized on AC at longer residence time. The presence of BTEX only reduced NO conversion by 5%. At evaluated humidity levels, however, a significant different pollutant removal rate was observed. The presence of BTEX reduced NO conversion by more than 10%. The use of TiO_2 on AC, reduced both the competition effect of the pollutant and water vapor on TiO_2. The inhibition effect of BTEX and SO_2 on NO conversion was significantly reduced when TiO_2 immobilized on AC compared to TiO_2 only. The by-product, NO_2, from the photodegradation of NO, was also reduced despite the presence of SO_2 and BTEX under high humidity level.

Keywords: VOCs; BTEX; NO; SO_2; Photocatalysis; Air purification

1. Introduction

Indoor air pollution is a serious problem especially in urban cities. Pollutants such as NO_x, SO_2 and VOCs cause adverse health impacts on occupants. This phenomenon is known as Sick Building Syndrome (SBS) [1]. Indoor air pollutants such as VOCs come from wall finishings [2] and nearby vehicular emissions [3]. Such gaseous pollutants are commonly removed by the adsorbent such as activated carbon (AC) installed in the inlet fresh air intake. However, the use of adsorbents merely transfer pollutants from the gaseous phase to the solid phase and causes a disposal and regeneration problem. Improper maintenance of these filters may even become a source of VOCs [4].

Advanced oxidation process (AOP) such as photocatalysis is a promising technology for air purification. Photodegradation occurs at room temperature and pressure and actually oxidizes pollutants to H_2O and CO_2 [5–15]. Recently, studies showed [16,17] that at high humidity levels the removal of air pollutants is significantly reduced when the pollutant concentration is at parts-per-billion (ppb) level such as those in indoor environment. By immobilizing TiO_2 on adsorbent, the pollutant removal rate was largely increased [18–24].

The aim of this study is to evaluate whether the inhibition effect owing to the presence of other pollutants or the presence of water vapor is more serious. Previously we reported that the use of TiO_2 immobilized on AC filter for air purification using single pollutant such as NO and BTEX at ppb levels [25]. However, studies showed that competition effects between binary pollutants were observed for adsorption on AC [26,27] and photodegradation on TiO_2 [28,29]. Thus, it is of interest to investigate the photodegradation of binary pollutants by using TiO_2 immobilized on AC. Two hundred parts-per-billion SO_2 [30], 200 ppb NO [31,32] and 20 ppb BTEX [33,34] were selected as target pollutants as these pollutants commonly exist in indoor environment. Sensitive analyses were conducted for the binary photodegradation of NO with BTEX and NO with SO_2 under different residence time and levels of humidity. To the best of our knowledge, no study has been reported on the photodegradation of binary pollutants at ppb level using TiO_2 immobilized on AC.

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2. Experimental

2.1. Reagents and catalyst

The detailed experimental setup has been described elsewhere [25]. BTEX (Spectra gases) with a mixing ratio of 1:1:1:1, NO (BOC gases) and SO_2 (BOC gases) were used as the reactant gas and acquired from a compressed gas cylinder at concentrations of 1 ppm ± 2%, 10 ppm ± 5% and 50 ppm ± 2%, respectively, with nitrogen as balanced gas with traceable National Institute of Standards and Technology (NIST) standard. TiO_2 (Degussa P-25) was used as a photocatalyst. The catalyst was used as received without any pretreatment. Water suspension with 5% of TiO_2 was coated on a glass fiber filter (Whatman) over an area of 20 cm × 12 cm, as a supporting substrate (denoted as TiO_2 filter). It was then calcinated at 120 °C for 1 h with a temperature gradient of 5.5 °C/min. The same procedure was followed for TiO_2 loaded on an activated carbon filter which is acquired from a local company (TiO_2/AC), except an activated carbon filter (23.085 g ± 0.5%) was used instead of a glass fiber filter. The Brunauer–Emmett–Teller (BET) surface area of the activated carbon extracted from the activated carbon filter is 1115 m^2/g. The surface area of the glass fiber filter is identical to the activated carbon, which is 20 cm × 21 cm. The amount of TiO_2 imposed is determined by the weight difference before and after the coating procedure. In all experiments, the weight of TiO_2 imposed is 1.64 g ± 5%. The scanning electron micrographs of the TiO_2 filter [16] and the TiO_2/AC filter [25] are shown elsewhere.

2.2. Reactor and experimental setup

A reactor with a volume of 18.6 l (20.1 cm (H) × 44.2 cm (L) × 21 cm (W)) with its surface coated by a Teflon film (BYTAC Type AF-21) was used for this study. Illumination was provided by a 6 W UV lamp (Cole-Parmler) which emits a primary wavelength at 365 nm and its intensity was determined by a UV meter (Spectroline DRC-100X). The UV lamp was horizontally placed at the upper part of the reactor, 14 cm from both ends. UV intensity measured in all experiments was 750 $\mu W/cm^2$. The TiO_2 coated filter was supported by a Teflon film and fixed horizontally with a vertical distance of 5 cm between the UV lamp. Stainless steel sampling ports and Teflon tubing were used to connect the reactor and the analytical instruments.

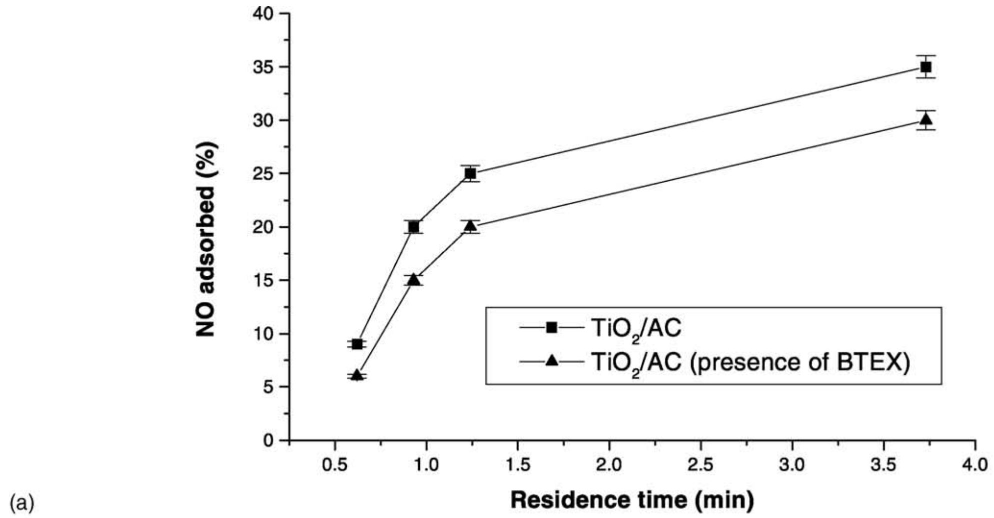
A zero air generator (Thermo Environmental Inc., Model 111) was used to supply the air stream. The desired humidity of the flow was controlled by passing the zero air stream through a humidification chamber. The reactant stream and the zero air stream were connected to a mass flow calibrator (Advanced Pollution Instrumentation Inc., Model 700). The gas streams were pre-mixed by a gas blender and the desired flow was controlled by a mass flow controller inside the calibrator. After the inlet and the outlet concentration of the target pollutants achieved equilibrium (1 h), the UV lamp was turned on and initiated the reaction. The concentration of NO was continuously measured by a Chemiluminescence NO analyzer (Thermo Environmental Instruments Inc., Model 42c), which monitors NO, NO_2, and NO_x at a sampling rate of 0.7 l/min. SO_2 was continuously measured by a Pulsed Fluorescence SO_2 analyzer (Thermo Environmental Instruments Inc., Model 43b) at a sampling rate of 0.4 l/min. Pre-cleaned Summa canisters were evacuated for VOCs sampling. Constant VOCs sampling time was achieved using a mass flow controller. Samples of VOCs were collected at designated times during the experiment. After collection, the canister sample was first concentrated by a Nutech Cryogenic Concentrator (Model 3550A), and the trapped VOCs were separated and analyzed by Hewlett-Packard Gas Chromatograph (Model HP 6890) and quantified by a Mass Selective Detector (Model HP5973). After analysis, the canister was sequentially evacuated and pressurized with humidified zero air until all compounds detected were smaller than 0.2 ppb. TO-14 (Toxi-Mat-14M Certified Standard, Matheson) standard gas was analyzed using the GC/MS system seven times at 0.2 ppb to obtain the method detection limits [33].

3. Results and discussion

3.1. Binary adsorption of NO and BTEX

Fig. 1(a) shows the adsorption of NO with and without the presence of BTEX at a humidity level of 2100 ppmv under different residence time. Each experiment set was conducted four times and the average value was reported. Previous study [25] showed that no difference in the amount of NO and BTEX adsorbed between TiO_2/AC and AC filter. Thus, only TiO_2/AC was studied for the adsorption test. No adsorption was found for NO and BTEX for TiO_2 filter with the experimental error. The amount adsorbed was determined by the pollutant concentration difference between the inlet stream and the outlet stream. The amount of NO adsorbed increased with increasing residence time despite the presence of BTEX. With the presence of BTEX, the amount of NO adsorbed was reduced by 5%. This agrees with the findings, of which, study [35] showed that the existence of other pollutants decreased the adsorption capacity of a pollutant. Fig. 1(b) shows the influence of NO on the adsorption of BTEX with the same experimental conditions of Fig. 1(a). No significant difference in the amount of BTEX adsorbed on TiO_2/AC was observed. Study [36] also reported that the amount of benzene, toluene and *o*-xylene adsorbed on AC is similar. As in the case of NO, the presence of NO approximately reduced 5% of the adsorption capacity of BTEX.

Fig. 2(a) shows the adsorption of NO with and without the presence of BTEX at a residence time of 1.2 min under different humidity levels. The presence of water vapor inhibited the adsorption of NO. The inhibition effect is more significant when the humidity level increased beyond



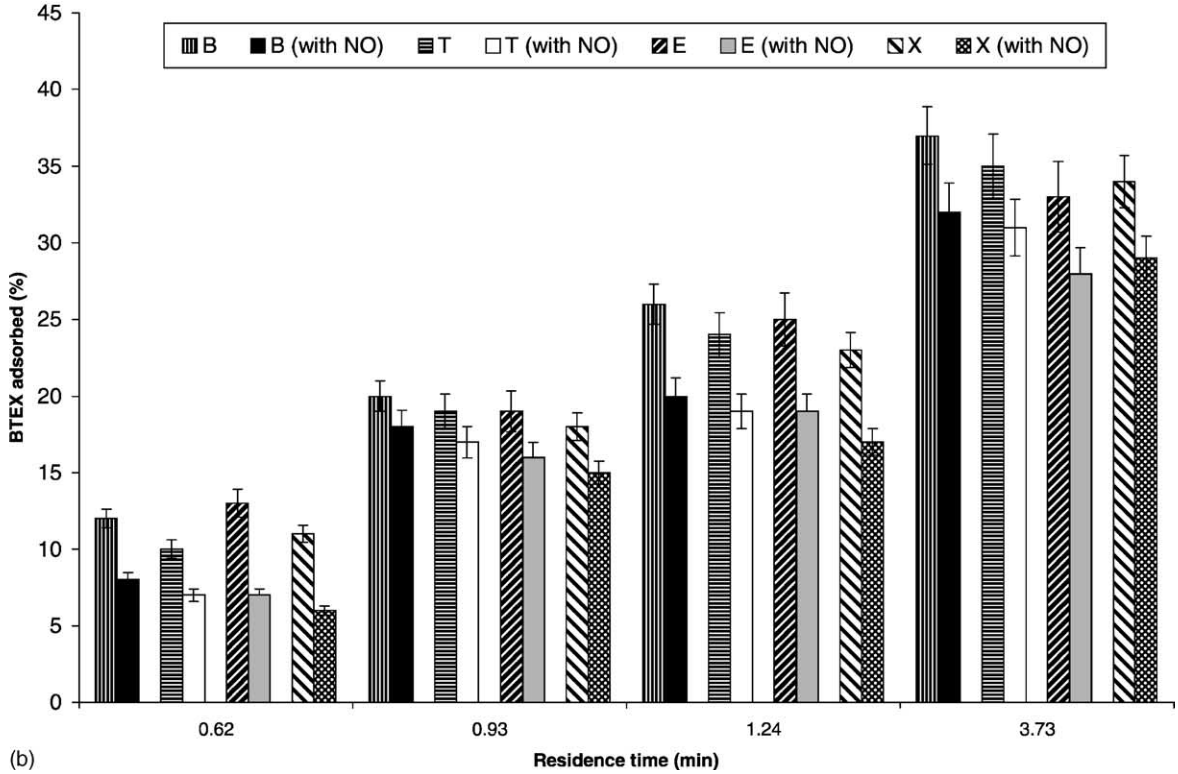


Fig. 1. (a) Amount of NO adsorbed with and without the presence of BTEX under different residence time. (■) TiO_2/AC; (▲) TiO_2/AC with the presence of BTEX. Experimental conditions: 200 ppb NO; 20 ppb BTEX; humidity level 2100 ppmv; (b) amount of BTEX adsorbed with and without the presence of NO under different residence time. Experimental conditions: 200 ppb NO; 20 ppb BTEX; humidity level 2100 ppmv.

15,000 ppmv. Studies [35,37] also showed that the inhibition effect of water vapor becomes significant when the humidity level increases beyond 20,300 ppmv. Although the presence of BTEX inhibited the adsorption of NO on AC, the inhibition effect is not significant compared to the presence of water vapor. Fig. 2(b) shows the adsorption of BTEX with and without the presence of NO with the same experimental conditions of Fig. 2(a). The increase in humidity level inhibited the adsorption of BTEX. The presence of NO inhibited the adsorption of BTEX despite the levels of humidity.

3.2. *Photodegradation of SO_2 by TiO_2 and TiO_2/AC*

Prior to the investigation of binary photodegradation of NO with SO_2 and BTEX, it is necessary to examine the photodegradation of SO_2 by TiO_2 and TiO_2/AC. Previously

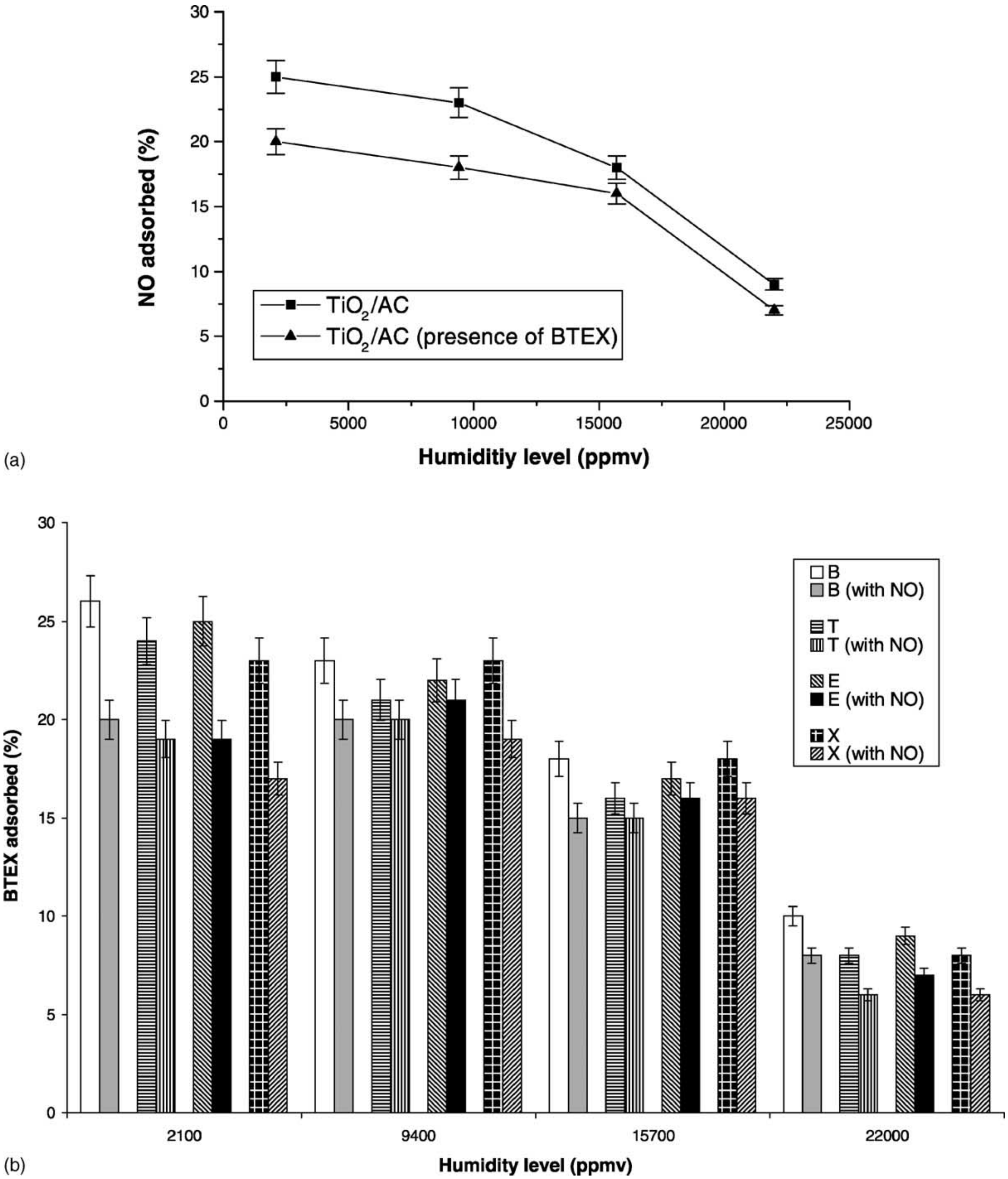


Fig. 2. (a) Amount of NO adsorbed with and without the presence of BTEX under different levels of humidity. (■) TiO_2/AC; (▲) TiO_2/AC with the presence of BTEX. Experimental conditions: 200 ppb NO; 20 ppb BTEX; residence time 1.2 min; (b) amount of NO adsorbed with and without the presence of BTEX under different levels of humidity. Experimental conditions: 200 ppb NO; 20 ppb BTEX; residence time 1.2 min.

we reported that no photodegradation of SO_2 was observed by using TiO_2 powder only [38]. Fig. 3 shows the SO_2 removal by TiO_2 and TiO_2/AC. The removal (%) is calculated by:

$$\text{removal (\%)} = \frac{\text{initial concentration} - \text{final concentration}}{\text{initial concentration}} \times 100\% \quad (1)$$

where initial concentration is the inlet pollutant concentration and final concentration is the photo-steady-state concentration at an irradiation time of 120 min. The removal of SO_2 increased with increasing humidity using TiO_2, whereas a decreasing trend was observed for TiO_2/AC. At a humidity level of 22,000 ppmv, the TiO_2 filter adsorbed 14% SO_2 more than TiO_2/AC. The glass fiber filter, used as the supporting substrate, adsorbed more than 75% of SO_2. However,

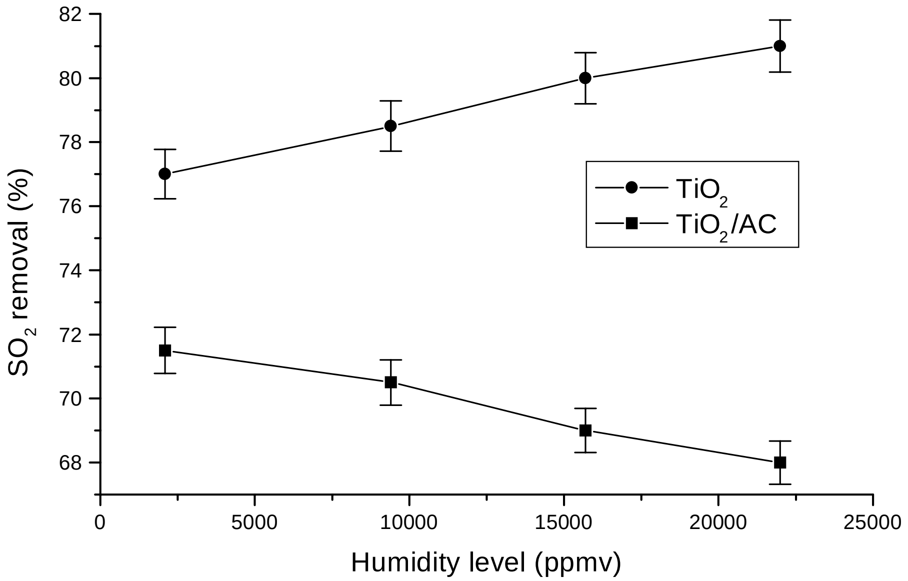


Fig. 3. SO_2 removal using TiO_2 and TiO_2/AC under different humidity levels. (●) TiO_2; (■) TiO_2/AC. Experimental conditions: 200 ppb SO_2; residence time 1.2 min.

no adsorption was observed for TiO_2 powder only (without the use of glass fiber filter as supporting substrate) within the experimental error. The SO_2 removal increased from 77 to 80% when the humidity level increased from 2100 to 22,000 ppmv. The adsorption of SO_2 on the glass fiber filter is owing to the formation of sulfate ion. The concentration of the sulfate ion increased with increasing humidity [38]. An opposite trend was observed when using TiO_2/AC. The SO_2 removal decreased from 71 to 68% when the humidity level increased from 2100 to 22,000 ppmv. This is probably due to the competition between the SO_2 and water vapor for adsorption sites on activated carbon. Studies showed that the presence of water vapor inhibited the adsorption of NO [39], benzene [40] and VOCs [37] on activated carbon.

3.3. Binary photodegradation of NO and BTEX by TiO_2 and TiO_2/AC

Fig. 4(a) shows the effect of the presence of BTEX on the photodegradation of NO using TiO_2 and TiO_2/AC at a humidity level of 2100 ppmv under different residence time. The conversion of NO or BTEX is calculated by:

$$\text{conversion (\%)} = \frac{\text{initial concentration} - \text{final concentration}}{\text{initial concentration}} \times 100\% \qquad (2)$$

where initial concentration is the inlet pollutant concentration and final concentration is the photo-steady-state concentration at an irradiation time of 120 min. The presence of BTEX inhibited the photodegradation of NO owing to the competition of adsorption sites on TiO_2 [16]. Similar effect was observed on TiO_2/AC. The conversion of NO decreased with decreasing residence time. At a lower residence time, the collision rate between NO and TiO_2 also decreased. For TiO_2/AC, the decrease in NO reduction is also contributed to the decrease in NO adsorbed on AC. Under a low humidity level where the competition effect between the pollutant and water vapor is not significant, the difference in NO conversion is not significant using TiO_2 and TiO_2/AC. Fig. 4(b) shows the generation of NO_2 from the photodegradation of NO with the same experimental conditions as shown in Fig. 4(a). The effects of using TiO_2/AC in reducing the NO_2 generation become more significant with decreasing residence time and the presence of BTEX. When the residence time decreased, the impact frequency between the pollutant and the TiO_2 surface also reduced. The use of AC caused the pollutant to be adsorbed and diffused to the TiO_2 for photodegradation. The adsorption of pollutants on AC is presumably less affected by the decrease in residence time compared to that of TiO_2 since the adsorption capacity of AC is much higher than TiO_2. In addition, owing to the large adsorption capacity of AC compared to TiO_2, the presence of BTEX did not significantly affected the generation of NO_2. Since no adsorption was found for NO and BTEX on TiO_2 filter, the photodegradation rate of NO_2 is manly depended on the collision rate between TiO_2 and NO_2. Thus, at a decreasing residence time, the generation of NO_2 using TiO_2 filter is more significant than using TiO_2/AC.

Table 1 shows the conversions of BTEX with and without the presence of NO using TiO_2 and TiO_2/AC at a humidity level of 2100 ppmv under different residence time. The conversions of BTEX decreased with decreasing residence time, which is similar to the photodegradation of NO. However, the decrease in conversions of BTEX using TiO_2/AC is significantly lower compared to that using TiO_2. In

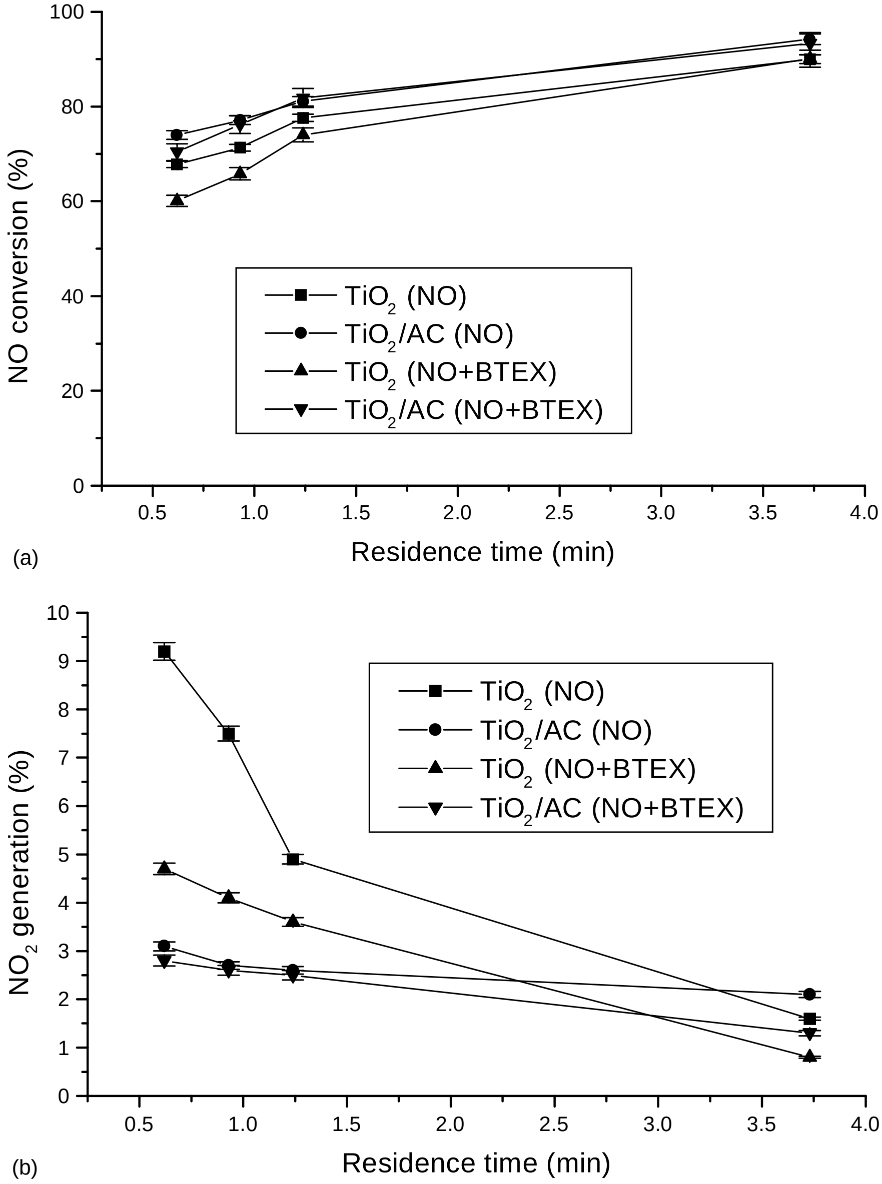


Fig. 4. (a) NO conversion using TiO_2 and TiO_2/AC with and without the presence of BTEX under different residence time. (■) TiO_2 (NO); (●) TiO_2/AC (NO); (▲) TiO_2 (NO + BTEX); (▼) TiO_2/AC (NO + BTEX). Experimental conditions: 200 ppb NO; 20 ppb BTEX; humidity level 2100 ppmv. (b) NO_2 generation using TiO_2 and TiO_2/AC with and without the presence of BTEX under different residence time. (■) TiO_2 (NO); (●) TiO_2/AC (NO); (▲) TiO_2 (NO + BTEX); (▼) TiO_2/AC (NO + BTEX). Experimental conditions: 200 ppb NO; 20 ppb BTEX; humidity level 2100 ppmv.

Table 1
BTEX conversions with and without the presence of NO using TiO_2 and TiO_2/AC under different residence time

Residence time (min)	TiO_2 (BTEX only)				TiO_2/AC (BTEX only)				TiO_2 (NO + BTEX)				TiO_2/AC (NO + BTEX)			
	B	T	E	X	B	T	E	X	B	T	E	X	B	T	E	X
3.7	76.5	84.1	84.2	87.7	84.6	87.8	87.1	93.7	87.8	89.4	83.7	87.7	88.7	89.8	85.2	86.9
1.2	57.5	69.9	68.9	72.5	74.3	76.2	72.3	85.7	69.1	78.2	77.2	78.0	76.2	83.5	81.0	83.3
0.9	39.9	46.2	52.7	53.3	62.7	63.8	61.4	70.8	48.5	58.6	60.8	62.1	68.9	70.2	67.9	75.4
0.6	17.2	37.3	47.8	45.4	53.2	60.6	58.6	58.3	28.4	46.3	58.4	57.0	57.8	64.7	63.3	64.2

Benzene (B); toluene (T); ethylbenzene (E); *o*-xylene (X). Experimental conditions: 200 ppb NO; 20 ppb BTEX; humidity level 2100 ppmv.

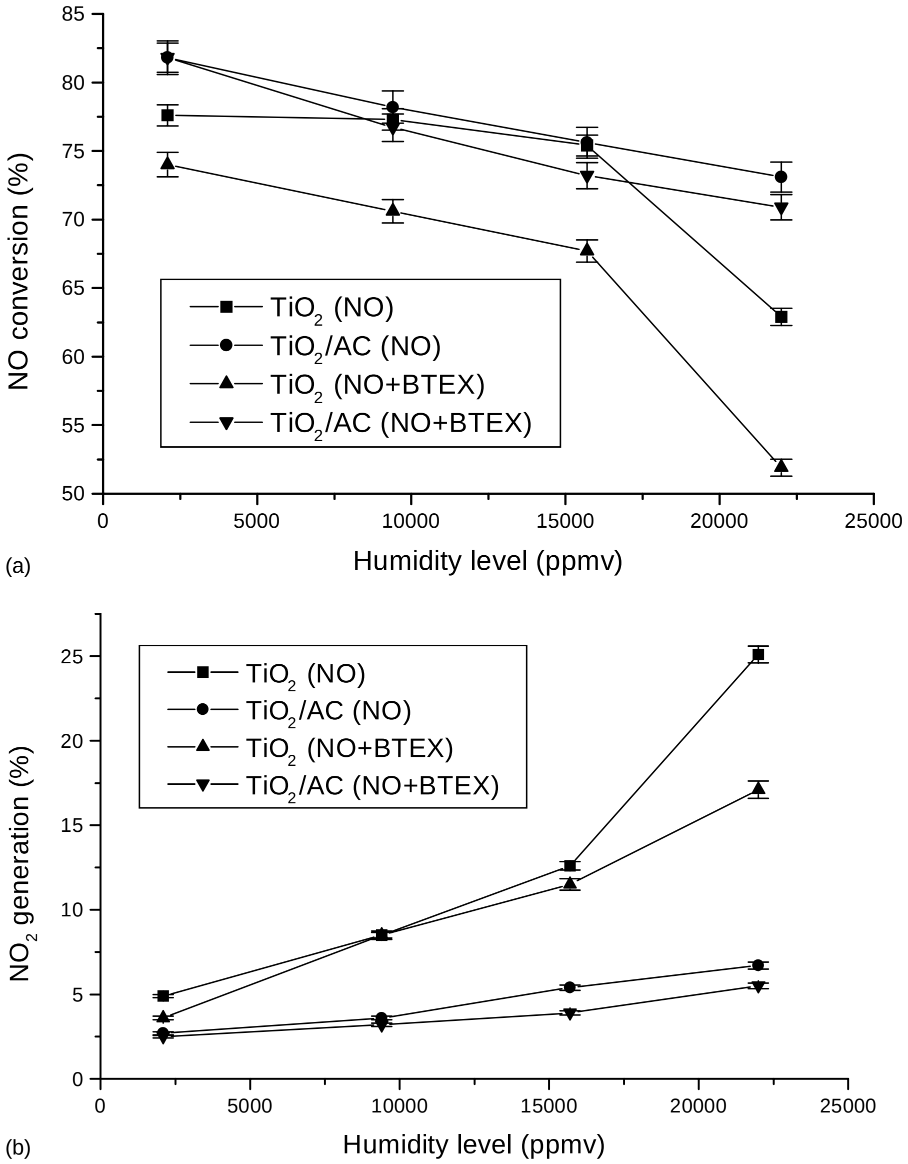


Fig. 5. (a) NO conversion using TiO_2 and TiO_2/AC with and without the presence of BTEX under different humidity levels. (■) TiO_2 (NO); (●) TiO_2/AC (NO); (▲) TiO_2 (NO + BTEX); (▼) TiO_2/AC (NO + BTEX). Experimental conditions: 200 ppb NO; 20 ppb BTEX; residence time 1.2 min. (b) NO_2 generation using TiO_2 and TiO_2/AC with and without the presence of BTEX under different humidity levels. (■) TiO_2 (NO); (●) TiO_2/AC (NO); (▲) TiO_2 (NO + BTEX); (▼) TiO_2/AC (NO + BTEX). Experimental conditions: 200 ppb NO; 20 ppb BTEX; residence time 1.2 min.

addition, the difference in BTEX conversions is higher than NO conversion using TiO_2/AC compared to TiO_2. This is probably owing to the high conversion of NO under low humidity levels which may hinder the effect of AC.

In order to investigate the effect of BTEX on the photodegradation of NO in detail, a binary photodegradation of NO and BTEX was performed under different levels of humidity at a residence time of 1.2 min since humidity is a vital parameter for photodegradation of pollutant at ppb level [16]. As shown in Fig. 5(a), the photodegradation of NO decreased with increasing levels of humidity despite the presence of BTEX and the use of TiO_2 and TiO_2/AC. The decrease in photocatalytic activity is owing to the competition of adsorption sites on TiO_2 between pollutants and water vapor [16]. However, when TiO_2 was immobilized on AC, the decrease in NO conversion was significantly reduced. In addition, the inhibition effect of BTEX on the photodegradation of NO was also reduced using TiO_2/AC. This is probably due to the amount of NO adsorbed on AC (Fig. 2) despite the high levels of humidity and the presence of BTEX. The amount of NO adsorbed on AC was then diffused to the TiO_2 for photodegradation. Similar findings were obtained by Torimoto and others [20] using TiO_2 with AC to increase the photodegradation rate of dichloromethane. These authors showed that the amount of dichloromethane adsorbed predominantly on AC rather

Table 2
BTEX conversions using TiO_2 and TiO_2/AC with and without the presence of NO under different levels of humidity

Humidity (ppmv)	TiO_2 (BTEX only)				TiO_2/AC (BTEX only)				TiO_2 (NO + BTEX)				TiO_2/AC (NO + BTEX)			
	B	T	E	X	B	T	E	X	B	T	E	X	B	T	E	X
2100	57.5	69.9	68.9	72.5	74.3	76.2	72.3	85.7	69.1	78.2	77.2	78.0	76.2	83.5	81.0	83.3
9400	34.2	39.7	42.5	46.5	68.4	70.9	71.1	71.2	32.3	36.7	39.8	40.3	70.6	73.9	75.6	78.0
15700	17.8	20.1	23.1	20.0	63.2	65.8	67.1	66.8	14.2	17.3	21.0	17.3	68.8	67.2	72.2	74.3
22000	5.6	7.5	8.2	8.3	60.5	62.5	63.2	57.9	7.9	9.1	11.6	12.8	67.7	68.9	69.2	67.8

Benzene (B); toluene (T); ethylbenzene (E); *o*-xylene (X). Experimental conditions: 200 ppb NO; 20 ppb BTEX; residence time 1.2 min.

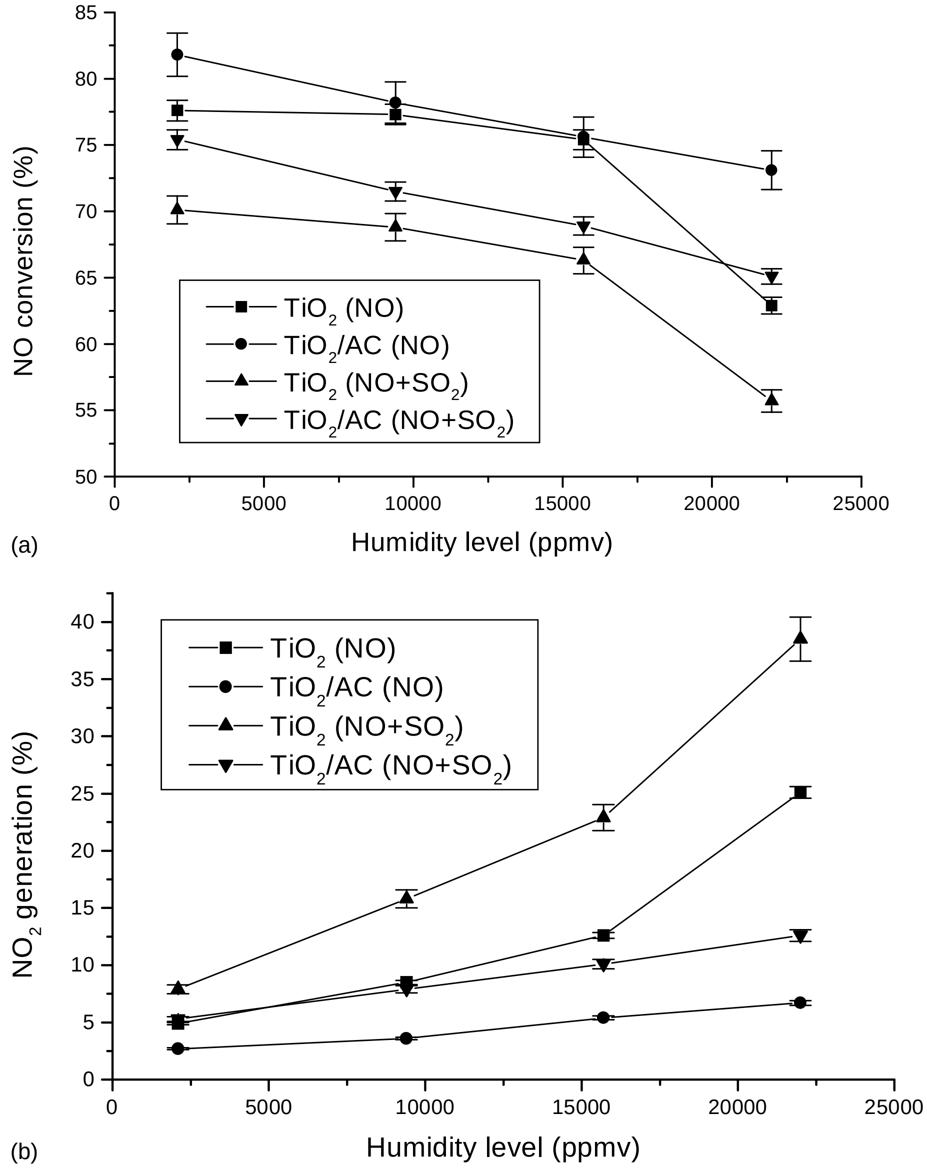


Fig. 6. (a) NO conversion using TiO_2 and TiO_2/AC with and without the presence of SO_2 under different humidity levels. (■) TiO_2 (NO); (●) TiO_2/AC (NO); (▲) TiO_2 (NO + SO_2); (▼) TiO_2/AC (NO + SO_2). Experimental conditions: 200 ppb NO; 200 ppb SO_2; residence time 1.2 min. (b) NO_2 generation using TiO_2 and TiO_2/AC with and without the presence of SO_2 under different humidity levels. (■) TiO_2 (NO); (●) TiO_2/AC (NO); (▲) TiO_2 (NO + SO_2); (▼) TiO_2/AC (NO + SO_2). Experimental conditions: 200 ppb NO; 200 ppb SO_2; residence time 1.2 min.

than on TiO_2. The adsorbed dichloromethane then diffused from AC to TiO_2 for photodegradation.

Fig. 5(b) shows the generation of NO_2 from the photodegradation of NO with the same experimental conditions as shown in Fig. 5(a). The generation of NO_2 was largely suppressed by the use of TiO_2/AC despite the presence of BTEX. For instance, nearly 25% of NO_2 was generated using TiO_2 whereas only less than 5% of NO_2 was generated using TiO_2/AC at a humidity level of 22,000 ppmv with the presence of BTEX. The immobilization of TiO_2 on AC not only reduced the target pollutant NO but also the intermediate NO_2. Study [19] also showed that the use of TiO_2 with activated carbon reduced the amount of intermediate from the photodegradation of propyzamide.

Table 2 shows the conversions of BTEX with and without the presence of NO using TiO_2 and TiO_2/AC at a residence time of 1.2 min under different levels of humidity. The effect of TiO_2/AC in BTEX conversions is even more significant compared to the effect of difference in residence time as shown in Table 1. Under high humidity levels, water vapor competed with the pollutants for adsorption sites. Although the amount of BTEX adsorbed on AC decreased with increasing humidity (Fig. 2b), the adsorbed BTEX on AC was still able to diffuse to the TiO_2 for photodegradation. Under high humidity level, the presence of NO did not affect the conversion of BTEX significantly.

3.4. Binary photodegradation of NO and SO_2 by TiO_2 and TiO_2/AC

Fig. 6(a) shows the binary photodegradation of NO with the presence of SO_2 using TiO_2 and TiO_2/AC under different humidity levels at a residence time of 1.2 min. Similar to the presence of BTEX, the presence of SO_2 inhibited the conversion of NO. Under the presence of SO_2, the conversion of NO decreased to 55.7% when using TiO_2, whereas 65.1% of NO conversion was achieved using TiO_2/AC. The inhibition effect of SO_2 is owing to the formation of sulfate ion on the TiO_2 and competed with NO for the adsorption sites [38]. SO_2 adsorbed on activated carbon and formed sulfuric acid [41,42]. With the presence of water vapor, the sulfuric acid disassociated into sulfate ion. This sulfate ion, similar to the pollutant diffusion from the activated carbon to the TiO_2, diffused to the TiO_2 surface and competed with the pollutants for adsorption sites on the TiO_2. Nevertheless, the activated carbon also concentrated the pollutant from the inlet stream to the TiO_2 for photodegradation. Another possible reason is that the amount of SO_2 removed by TiO_2 is higher than TiO_2/AC (see Fig. 3). Using TiO_2/AC, the conversion of NO is 10% higher than using TiO_2.

Fig. 6(b) shows the NO_2 generation with the same experimental conditions as shown in Fig. 6(a). The effect of TiO_2 immobilized on activated carbon is significant in suppressing the generation of NO_2. With the presence of SO_2, over 35% and only around 10% of NO_2 was generated using TiO_2 and TiO_2/AC, respectively. It is worth noting that at a low humidity level (2100 ppmv), the effect in reducing NO_2 generation using TiO_2 and TiO_2/AC is not significant. Under low humidity levels, the competition effect between the pollutants and the water vapor is not significant. Using TiO_2 merely with the presence of SO_2, only 7.9% of NO_2 was generated, whereas 5.3% of NO_2 was generated using TiO_2/AC. When the humidity level increased to 22,000 ppmv, the adsorption sites on the TiO_2 were blocked by the water vapor and the sulfate ion formed from the adsorption of SO_2. The NO_2 generated from the photodegradation of NO leaving to the outlet stream without further photodegradated to HNO_3 owing to the adsorption site occupied by the water vapor and sulfate ion. Using activated carbon, the NO_2 generated adsorbed on it and thereby diffused to TiO_2 for photodegradation.

4. Conclusions

The use of TiO_2 immobilized on activated carbon filter significantly improved the conversion of NO and the suppression of NO_2 generated from the photodegradation of NO. The presence of BTEX and SO_2 reduced the amount of NO adsorbed on activated carbon. However, this amount of NO adsorbed was still able to diffuse to TiO_2 for photodegradation. Although the presence of SO_2 and BTEX reduced the conversion of NO, the use of TiO_2/AC provided a substantial improvement in NO conversion. The inhibition effect of SO_2 being more significant than BTEX is probably owing to the fact that SO_2 removal by TiO_2 is higher than TiO_2/AC. Using TiO_2/AC compared to TiO_2 under the presence of SO_2, the conversion of NO increased by 10% and the generation of NO_2 decreased by more than 20%. Under high humidity levels, the presence of NO did not significantly affected the conversions of BTEX compared to the effect of water vapor. The effect of TiO_2/AC is more significant with decreasing residence time and increasing levels of humidity. In essence, the effect of immobilizing TiO_2 on AC in improving the pollutant conversions is mainly due to reducing the competition effect between the pollutant and the water vapor rather than reducing the competition effect among pollutants. Under high humidity levels, the inhibition effect of water vapor is more significant compared to the presence of other pollutants. Using TiO_2 with the addition of adsorbent such as activated carbon, it is practically feasible to removal indoor air multiple pollutants at ppb level under high levels of humidity.

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References

[1] A.P. Jones, Atmos. Environ. 33 (1999) 4535.
[2] S.C. Lee, N.H. Kwok, H. Guo, W.T. Hung, Sci. Total Environ. 302 (2003) 75.
[3] S.O. Baek, Y.S. Kim, R. Perry, Atmos. Environ. 31 (1997) 529.
[4] H. Schleibinger, H. Ruden, Atmos. Environ. 33 (1999) 4571.
[5] X.Z. Li, F.B. Li, Environ. Sci. Technol. 35 (2001) 2381.
[6] J.C. Yu, J.G. Yu, W. Ho, L.Z. Zhang, Chem. Commun. (2001) 1942.
[7] C. Hu, Y.C. Tang, J.C. Yu, P.K. Wong, Appl. Catal. B Environ. 40 (2003) 131.
[8] A. Fujishima, T.N. Rao, D.A. Tryk, J. Photochem. Photobiol. C 1 (2000) 1.
[9] A.L. Linsebigler, G.Q. Lu, J.T. Yates, Chem. Rev. 95 (1995) 735.
[10] H. Einage, S. Futamura, T. Ibusuki, Phys. Chem. Chem. Phys. 1 (1999) 4903.
[11] X. Fu, W.A. Zeltner, M.A. Anderson, Appl. Catal. B Environ. 6 (1995) 209.
[12] O. d'Hennezel, P. Pichat, D.F. Ollis, J. Photochem. Photobiol. 118 (1998) 197.
[13] J. Peral, D.F. Ollis, J. Mol. Catal. A Chem. 115 (1997) 347.
[14] P. Pichat, J. Disdier, C. Hoang-Van, D. Mas, G. Goutailler, C. Gaysse, Catal. Today 63 (2000) 363.
[15] J.H. Xu, F. Shiraishi, J. Chem. Technol. Biotechnol. 74 (1999) 1096.
[16] C.H. Ao, S.C. Lee, C.L. Mak, L.Y. Chan, Appl. Catal. B Environ. 42 (2003) 119.
[17] C.H. Ao, S.C. Lee, J.C. Yu, J. Photochem. Photobiol. A 156 (2003) 171.
[18] T. Ibusuki, K. Takeuchi, J. Mol. Catal. 88 (1994) 93.
[19] T. Torimoto, S. Ito, S. Kuwabata, H. Yoneyama, Environ. Sci. Technol. 30 (1996) 1275.
[20] T. Torimoto, Y. Okawa, N. Takeda, H. Yoneyama, J. Photochem. Photobiol. A 103 (1997) 153.
[21] H. Yoneyama, T. Torimoto, Catal. Today 58 (2000) 133.
[22] N. Takeda, N. Iwata, T. Torimoto, H. Yoneyama, J. Catal. 177 (1998) 240.
[23] K. Hashimoto, K. Wasada, M. Osaki, E. Shono, K. Adachi, N. Toukai, H. Kominami, Y. Kera, Appl. Catal. B Environ. 30 (2001) 429.
[24] N. Takeda, M. Ohtani, T. Torimoto, S. Kuwabata, H. Yoneyama, J. Phys. Chem. B 101 (1997) 2644.
[25] C.H. Ao, S.C. Lee, Appl. Catal. B Environ., in press.
[26] G.O. Wood, Carbon 40 (2002) 685.
[27] J.H. Yun, K.Y. Hwang, D.K. Choi, J. Chem. Eng. Data 43 (1998) 843.
[28] M.L. Sauer, M.A. Hale, D.F. Ollis, J. Photochem. Photobiol. A 88 (1995) 169.
[29] Y. Luo, D.F. Ollis, J. Catal. 163 (1996) 1.
[30] Urban Air Pollution Control in China, China Science and Technology Press, China, 2001.
[31] C.J. Weschler, H.C. Shields, Environ. Sci. Technol. 28 (1994) 2120.
[32] C.Y. Chao, G.Y. Chan, Atmos. Environ. 35 (2001) 5895.
[33] S.C. Lee, W.M. Li, C.H. Ao, Atmos. Environ. 36 (2002) 225.
[34] S.C. Lee, H. Guo, W.M. Li, L.Y. Chan, Atmos. Environ. 36 (2002) 1929.
[35] P.N. Cheremisinoff, F. Ellerbusch (Eds.), Carbon Adsorption Handbook, Science Publishers, Ann Arbor, Michigan, 1980, pp. 331–387.
[36] K. Urano, S. Omorl, E. Yamamoto, Environ. Sci. Technol. 16 (1982) 10.
[37] F.I. Khan, A.K. Ghoshal, J. Loss Prev. Process. Ind. 13 (2000) 527.
[38] C.H. Ao, S.C. Lee, S.C. Zou, C.L. Mak, J. Catal., in press.
[39] E. Richter, R. Kleinschmidt, E. Pilarczyk, K. Knoblauch, H. Jontgen, Thermochim. Acta 85 (1985) 311.
[40] M.P. Cal, M.J. Rood, S.M. Larson, Gas Sep. Purif. 10 (1996) 117.
[41] A.A. Lizzio, J.A. DeBarr, Energy Fuels 11 (1997) 284.
[42] E. Raymundo-Pinero, D. Cazorla-Amoros, A. Linares-Solano, Carbon 39 (2001) 231.