

Utilization of Element-doping Titania-impregnated Granular Activated Carbon in a Plug-flow System for Removal of BTEX

Wan-Kuen Jo*, Seung-Ho Shin, Eun-Song Hwang and Sung-Bong Yang¹⁾

Department of Environmental Engineering, Kyungpook National University, Daegu 702-701, Korea

¹⁾Department of Chemistry, University of Ulsan, Ulsan 680-749, Korea

*Corresponding author. Tel: +82-53-950-6584, E-mail: wkjo@knu.ac.kr

ABSTRACT

The use of an activated carbon (AC) system alone has the limitation that the pollutants are not eliminated but only transferred to another phase with the consumed AC becoming hazardous waste itself. Therefore, the present study investigated the feasibility of using a combined system of granular AC (GAC) with S-doped visible-light-induced TiO₂ (GAC/S-doped TiO₂) to clean monocyclic aromatic hydrocarbons (MAHs) with concentrations at $\leq 3 \text{ mg m}^{-3}$, using a continuous air-flow reactor. This study conducted three different experiments: an adsorption test of pure GAC and GAC/S-doped TiO₂; a long-term adsorptional photocatalytic (AP) activity test of GAC/S-doped TiO₂; and an AP activity test of GAC/S-doped TiO₂ under different conditions. For the AP activity test, three parameters were evaluated: various weights of GAC/S-doped TiO₂ (0.9, 4.4, and 8.9 g); various flow rates (FRs) (0.5, 1 and 2 L min⁻¹); and various input concentrations (ICs) of the target MAHs (0.1, 1, 2 and 3 mg m⁻³). The adsorption efficiencies were similar for the pure GAC and GAC/S-doped TiO₂ reactors, suggesting that S-doped TiO₂ particles on GAC surfaces do not significantly interfere with the adsorption capacity of GAC. Benzene exhibited a clear AP activity, whereas no other target MAHs did. In most cases, the AP efficiencies for the target MAHs did not significantly vary with an increase in weight, thereby suggesting that, under the weight range tested in this study, the weights or FRs are not important parameters for AP efficiency. However, ICs did influence the AP efficiencies.

Key words: Photocatalytic activity, Visible-light irradiation, Element-doping, Granular activated carbon, Plug-flow system

1. INTRODUCTION

Monocyclic aromatic hydrocarbons (MAHs) such as benzene, toluene, ethyl benzene and xylene (BTEX) have been measured at high concentration levels in urban atmospheres, mainly as a result of human activities such as motor vehicle exhausts and other combustion processes utilizing fossil fuels, petroleum storage and distribution, solvent usage and other industrial processes (Brown *et al.*, 2007; Buzcu and Fraser, 2006). Several researchers have also reported that MAH levels in urban air were higher than those of pristine or suburban air (Hoshi *et al.*, 2008; Buzcu and Fraser, 2006). Atmospheric pollutants can penetrate indoors, thereby elevating the indoor concentration levels (Hänninen *et al.*, 2004). Furthermore, indoor MAH levels can be further elevated by various indoor sources such as consumer products, cigarette smoke, and/or building materials (Jia *et al.*, 2008; Kwon and Jo, 2007). Most MAHs are toxic (e.g. benzene) or potentially toxic to humans (e.g. toluene, ethyl benzene, and xylene) (IARC, 2004). These characteristics of MAHs warrant the development of controls to minimize the health risk from indoor as well as outdoor air exposure.

Activated carbon (AC) has been typically used as an adsorbent for the control of various air pollutants including MAHs because of its high pore volume and large exposed surface area to volume ratios (Sasaki *et al.*, 2008; Giraudet *et al.*, 2006; Lillo-Ródenas *et al.*, 2005). However, many previous AC studies have dealt primarily with concentrations at high levels (typically more than 100 mg m⁻³), which is more typical of the air at industrial workplaces or chemical process stream than that associated with indoor air quality (IAQ). Extrapolation of adsorption performance data collected at concentrations much higher than the intended application may not be valid. This assertion suggests the need of AC application studies for the

removal of MAHs at IAQ levels.

Additionally, the use of AC systems alone has the limitation that the pollutants are not eliminated but only transferred to another phase with the consumed AC becoming hazardous waste itself. As such, the regeneration of AC is subsequently necessary for reuse of the AC thereby reducing the disposal cost. To overcome this disadvantage, an adsorbent coupled with other control methods can be utilized to remove environmental pollutants. Photocatalytic oxidation (PCO) has been considered as an attractive AC regeneration technique (Kim *et al.*, 2006; Tao *et al.*, 2006; Shiraiishi *et al.*, 2003). PCO provides a reduction of absolute toxicity as the gaseous products from the complete PCO of toxic hydrocarbons are carbon dioxide and water (Hunger *et al.*, 2010; Boulinguez *et al.*, 2008; Han *et al.*, 2008; Fukahori *et al.*, 2007). Due to their modular characteristics and low pressure drop across the reactor, PCO reactors can easily be incorporated into existing AC systems. For example, Areerachakul *et al.* (2007) demonstrated that a granular AC adsorption-photocatalysis hybrid system resulted in higher removal efficiency of herbicides from water compared to just a photocatalysis system alone (without the pre-adsorption).

Moreover, in order to overcome the main drawback of TiO_2 which exhibits photocatalytic activity only in the near UV region, other researchers (Demeestere *et al.*, 2005; Ohno *et al.*, 2004) have employed S-doped TiO_2 to enhance light absorption and photocatalytic activity under visible-light irradiation. Besides several water pollution applications, the combined technique of granular AC (GAC) and visible light induced photocatalysis with S-doped photocatalysts of air pollutants

has rarely been reported (Areerachakul *et al.*, 2007). Consequently, the present study investigated the feasibility of applying the combined system of GAC with S-doped visible-light-induced TiO_2 (GAC/S-doped TiO_2) to clean gas-phase MAHs. This was done with concentrations at $\leq 3 \text{ mg m}^{-3}$, using a plug-flow reactor (annular-type reactor), which provides a well-characterized reactive catalyst surface along the length of the reactor body and allows for uniform light distribution (Mo *et al.*, 2005).

2. EXPERIMENTAL METHODS

2.1 Experimental Set-Up

The experimental set-up consisted of a pure dried air supply system, a humidification unit, a standard injection unit, and a plug-flow Pyrex reactor (Fig. 1). Dried air was supplied from a zero-grade air cylinder with a two-stage pressure regulator. This air was further cleaned for hydrocarbons by passing it through an activated carbon filter normally used for gas chromatograph (GC). The pure dried air was humidified by passing the zero-grade air through a humidification device in a water bath (Cole-Parmer HAAKE W26). The temperature of the water bath was fixed at 35°C . The relative humidity (RH) of the zero-grade air was measured, immediately prior to entering the inlet valve on the Pyrex reactor using a humidity meter (Thermo Recorder TR-72S, T & D Co.). Then, the humidified air was mixed with standard MAHs in a heated 500-mL bulb. The desired concentrations were achieved through the use of a syringe pump (KdScientific Model 210). Finally, the gas flowed through the annular region

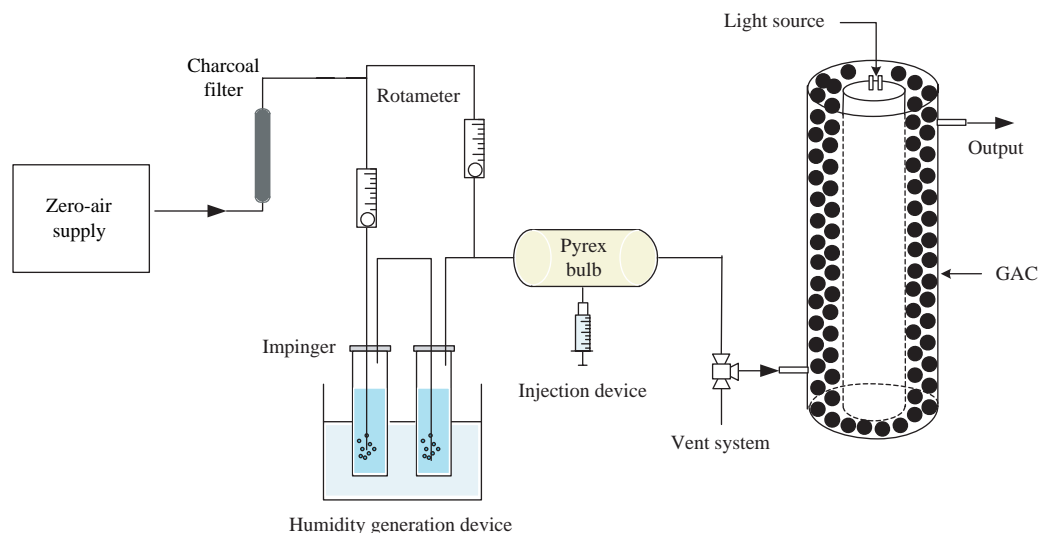


Fig. 1. Schematic diagram of experimental set-up.

of the Pyrex reactor. The flow rate (FR) was measured using identical rotameters ($0\text{--}10\text{ L minute}^{-1}$) calibrated against a dry test meter (URG 3000-020C).

The Pyrex reactor had annular geometry, and a cylindrical UV light source was inserted inside the glass tube and served as the inner surface of the annular reactor. The hydraulic diameter of the PCO reactor (defined as the inside diameter of the annular reactor tube minus the outside diameter of the lamp) was 5 mm. Visible radiation was supplied by an 8-W fluorescent daylight lamp (F8T5DL, Youngwha Lamp Co.). The spectrum of this lamp ranged from 400 to 720 nm. The visible radiation intensity measured at a distance from the visible-light lamp equal to half the hydraulic diameter of the reactor using a Digital Lux Meter (INS Model DX-100) was 1.8 mW cm^{-2} . The annular region of this reactor was filled with a commercially-available GAC prepared from a coconut shell (Samchully Activated Carbon, Korea) or GAC/S-doped TiO_2 . The surface area and average diameter of the AC were $1,100\text{ m}^2\text{ g}^{-1}$ and 4×8 mesh, respectively. The GAC/S-doped TiO_2 was prepared using a dip-desiccation method, which was previously used for GAC/ TiO_2 by other researchers (Liu *et al.*, 2007; Tao *et al.*, 2006). The sulfur element was impregnated into the TiO_2 photocatalysts (Degussa P-25) following a procedure previously described (Jo and Kim, 2008; Ohno *et al.*, 2004). GAC was washed with ultra-pure water and dried at 105°C for 3 h prior to use. It was immersed into water suspended with the prepared S-doped TiO_2 for 2 h with sonification and was then dried at 105°C for 3 h. The amount of coated S-doped TiO_2 was determined by the weight difference before and after the coating procedure.

2.2 Study Protocol

This study consisted of three different experiments: an adsorption test of pure GAC and GAC/S-doped TiO_2 ; a long-term adsorptional photocatalytic (AP) activity test of GAC/S-doped TiO_2 ; and an AP activity test of GAC/S-doped TiO_2 under different conditions. The adsorption or AP efficiency was calculated by comparing the concentrations measured at the inlet and outlet of each reactor. In the absence of visible-light, the adsorption test was performed for two different weights (0.9 and 4.4 g) of pure GAC and GAC/S-doped TiO_2 . Another adsorption test was done for 0.9 g of GAC/S-doped TiO_2 in order to investigate if the adsorption efficiency varies for the three different FRs (0.5 , 1 , and 2 L min^{-1}). The individual input concentration (IC) of the target MAHs (benzene, toluene, ethyl benzene, m,p-xylene, and o-xylene) was constant at 1 mg m^{-3} . RH was 50-55%, which is within the ASHRAE (arts and sciences of heating, ventilation,

air-conditioning and refrigeration) comfort range. The long-term test of GAC/S-doped TiO_2 was conducted in both the absence and presence of visible light. For this test, IC, RH, and FR were adjusted to 1 mg m^{-3} , 50-55% and 1 L min^{-1} , respectively. The weight of the GAC/S-doped TiO_2 used was 0.9 g. For the third AP activity test, three parameters were evaluated: the weights of the GAC/S-doped TiO_2 (0.9, 4.4, and 8.9 g); the FRs (0.5 , 1 and 2 L min^{-1}); and the ICs of the target MAHs (0.1 , 1 , 2 and 3 mg m^{-3}). TiO_2 weights for 0.9, 4.4, and 8.9 g of GAC/S-doped TiO_2 were 47, 246, and 521 mg g^{-1} , respectively.

2.3 Sampling and Analysis

A series of samples regarding the target MAHs were collected at both the inlet and outlet of the reactor in the absence and presence of visible-light, over specified experimental periods. Sampling was done by filling an evacuated 5 L Tedlar bag at a constant flow rate. Air was then drawn through a sorbent trap containing 0.2 grams of Tenax TA and 0.2 gram of carboxen 569, using a constant flow-sampling pump (A.P. Buck Inc. Model I.H). Sampling times varied from one to five minutes depending on the flow rate. All samples were collected at ambient room temperature ($19\text{--}25^\circ\text{C}$), and the FRs were recorded at between 0.1 and 1 L min^{-1} . The FR range and sampling volume did not have any breakthrough problems. The target compounds collected on the sorbent trap were analyzed by coupling a thermal desorption system (Donam SPIS TD-2) to a GC (Hewlett Packard 5890) in conjunction with a flame ionization detector (HP 5890II), by using a 0.32-mm -i.d. by 60-m -length fused silica column (Supelco Co. SPB-5).

The quality assurance/quality control program regarding the measurement of the target MAHs included laboratory blank traps and spiked samples. At the beginning of the day, a laboratory blank trap was analyzed to monitor any trap contamination. An external standard, prepared by following the same procedures according to the calibration standards, was analyzed daily in order to monitor the quantitative response. When the daily quantitative response differed by more than $\pm 15\%$ from that predicted by the specified calibration equation, a new calibration equation was determined. The method detection limits ranged from 0.3 to $2.6\text{ }\mu\text{g m}^{-3}$ depending on the target MAHs.

3. RESULTS AND DISCUSSION

3.1 Adsorption Efficiencies of Pure GAC and GAC/S-Doped TiO_2

In the absence of visible-light, the adsorption effici-

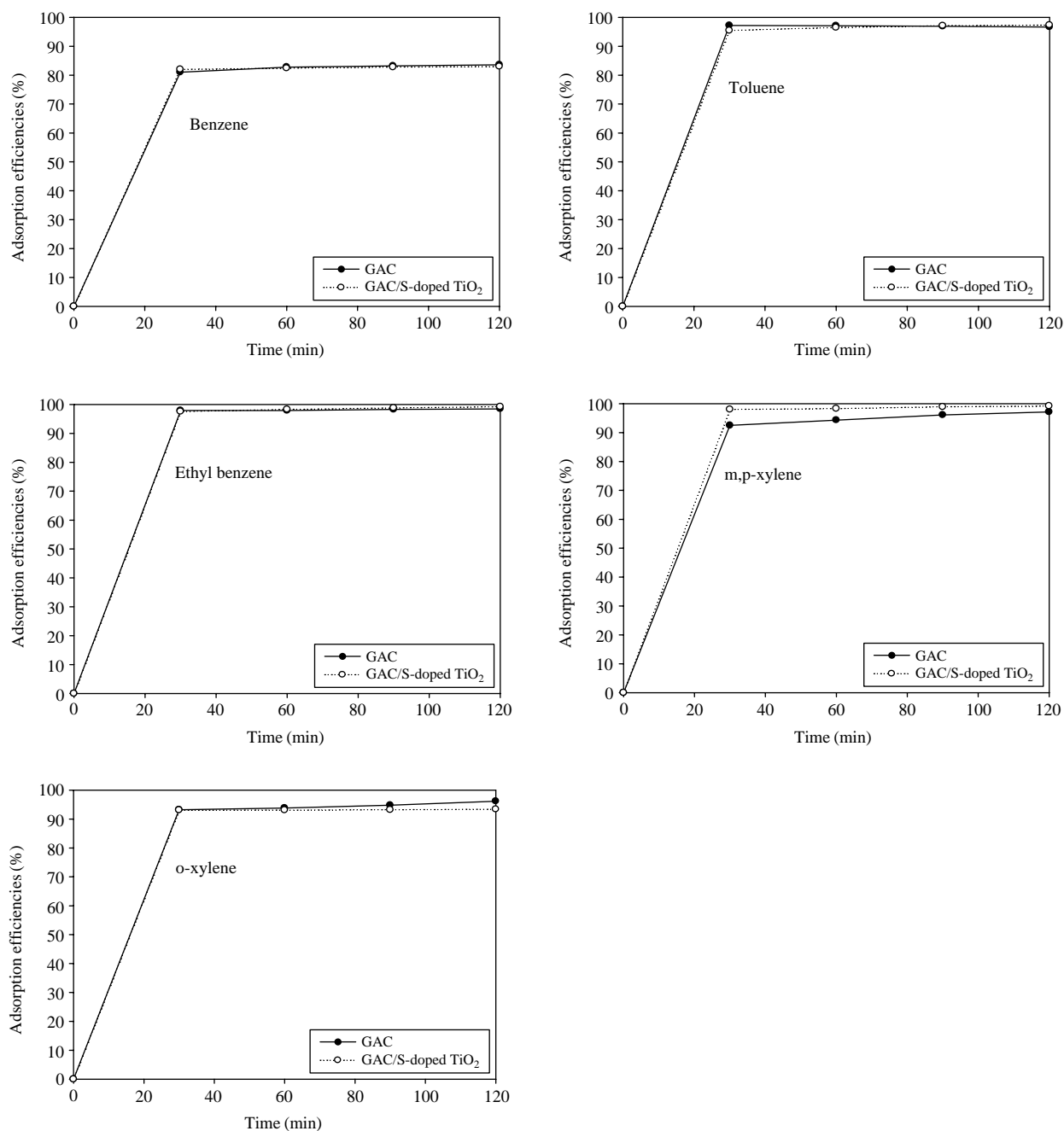


Fig. 2. Adsorption efficiencies (%) of target MAHs (benzene, toluene, ethyl benzene, m,p-xylene, and o-xylene) by pure granular activated carbon (GAC) and GAC with S-doped visible-light-induced TiO₂ (GAC/S-doped TiO₂) reactors filled with 0.9 g in each reactor.

encies of both the pure GAC and GAC/S-doped TiO₂ for the target MAHs were investigated. Fig. 2 exhibits the adsorption efficiencies of the target MAHs determined via both the pure GAC and GAC/S-doped TiO₂ reactors filled with 0.9 g in each reactor. The adsorption efficiencies for the two reactors were similar with

around 80% and between 90 and 100% adsorption for benzene and the other target MAHs, respectively. In addition, for 4.4 g of GAC or GAC/S-doped TiO₂, the adsorption efficiencies were also similar for the two reactors, although they were slightly higher for m,p-xylene and o-xylene compared to the low weight of

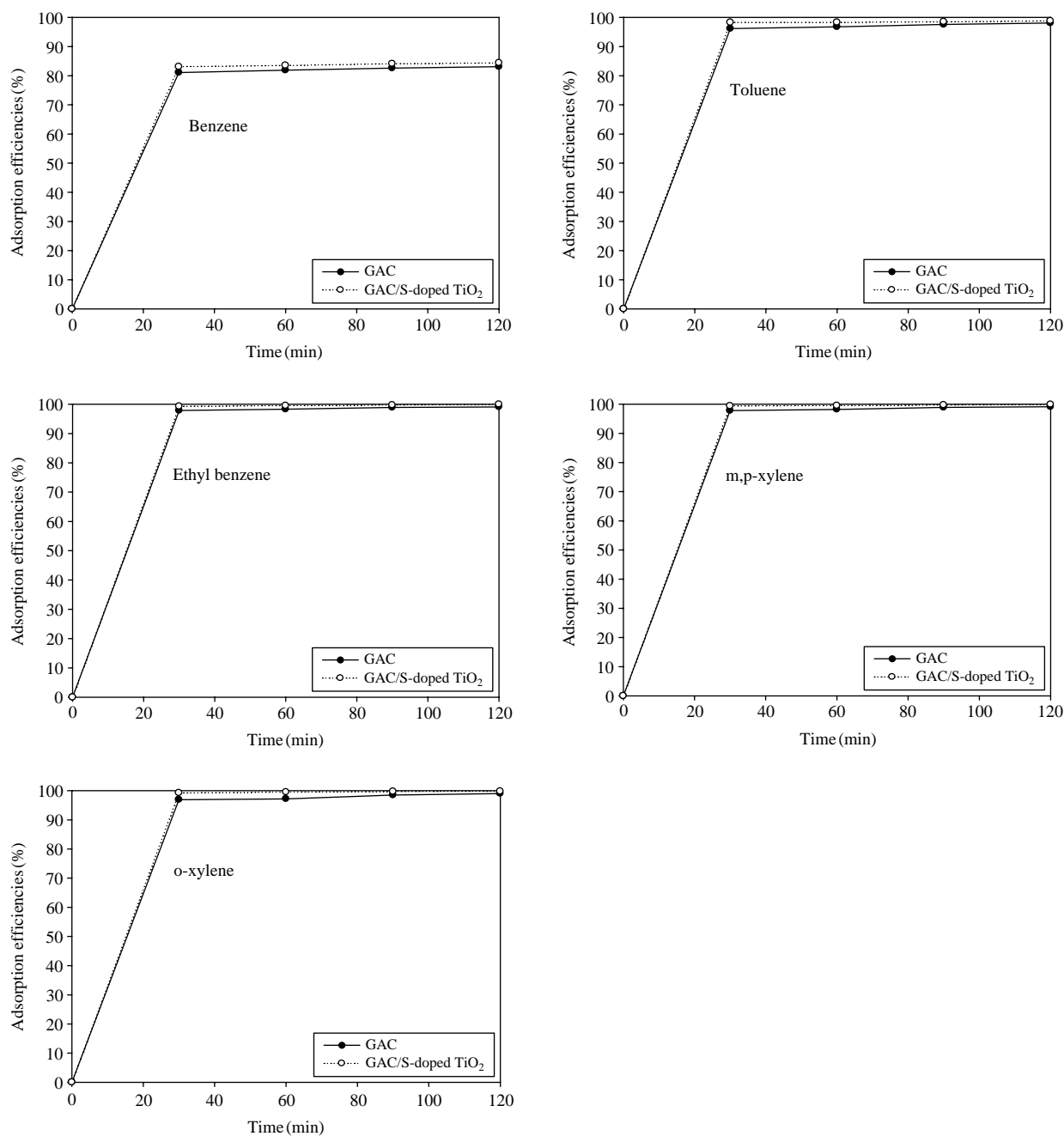


Fig. 3. Adsorption efficiencies (%) of target MAHs (benzene, toluene, ethyl benzene, m,p-xylene, and o-xylene) by pure granular activated carbon (GAC) and GAC with S-doped visible-light-induced TiO₂ (GAC/S-doped TiO₂) reactors filled with 4.4 g in each reactor.

GAC or GAC/S-doped TiO₂ (Fig. 3). The similarity in adsorption efficiencies for the two reactors suggests that the TiO₂ particles on the GAC surfaces do not significantly interfere with the adsorption capacity of GAC. Previous studies (Tao *et al.*, 2006; Ao and Lee, 2003) also reported that the adsorption capacity of the

GAC unit was almost identical to that of the GAC/ pure TiO₂ reactor for the removal of BTEX and methanol.

It is noteworthy that the adsorption efficiency of benzene was lower than those of the other target compounds. This result can be explained by the decrease in solubility and increase in molecular weight (Dai-

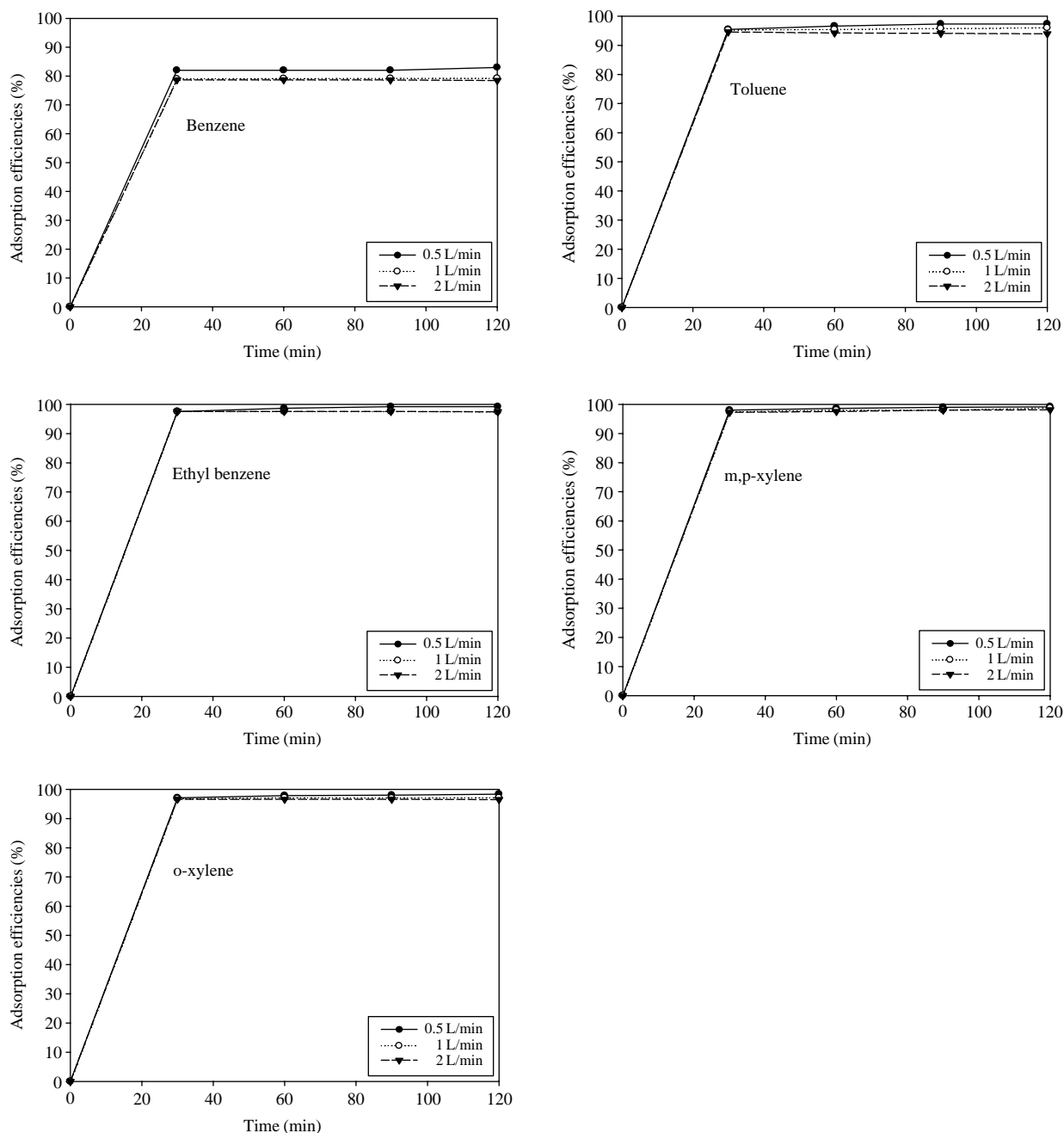


Fig. 4. Adsorption efficiencies (%) of target MAHs (benzene, toluene, ethyl benzene, m,p-xylene, and o-xylene) by GAC with S-doped visible-light-induced TiO_2 , according to flow rates.

fullah and Girgis, 2003). Meanwhile, the adsorption efficiencies of the GAC/S-doped TiO_2 did not significantly varied with the variation of the FRs (Fig. 4). This suggests that, under the experimental conditions of this study, FR is not an important parameter for the adsorption process of GAC/S-doped TiO_2 .

3.2 Long-Term AP Efficiencies by GAC/S-Doped TiO_2

The AP efficiencies of the GAC/S-doped TiO_2 reactor over a long-term period (185 h) were determined for the target MAHs in both the absence and presence of visible-light in order to identify if the GAC/S-doped TiO_2 reactor has any AP activities. Regardless of the

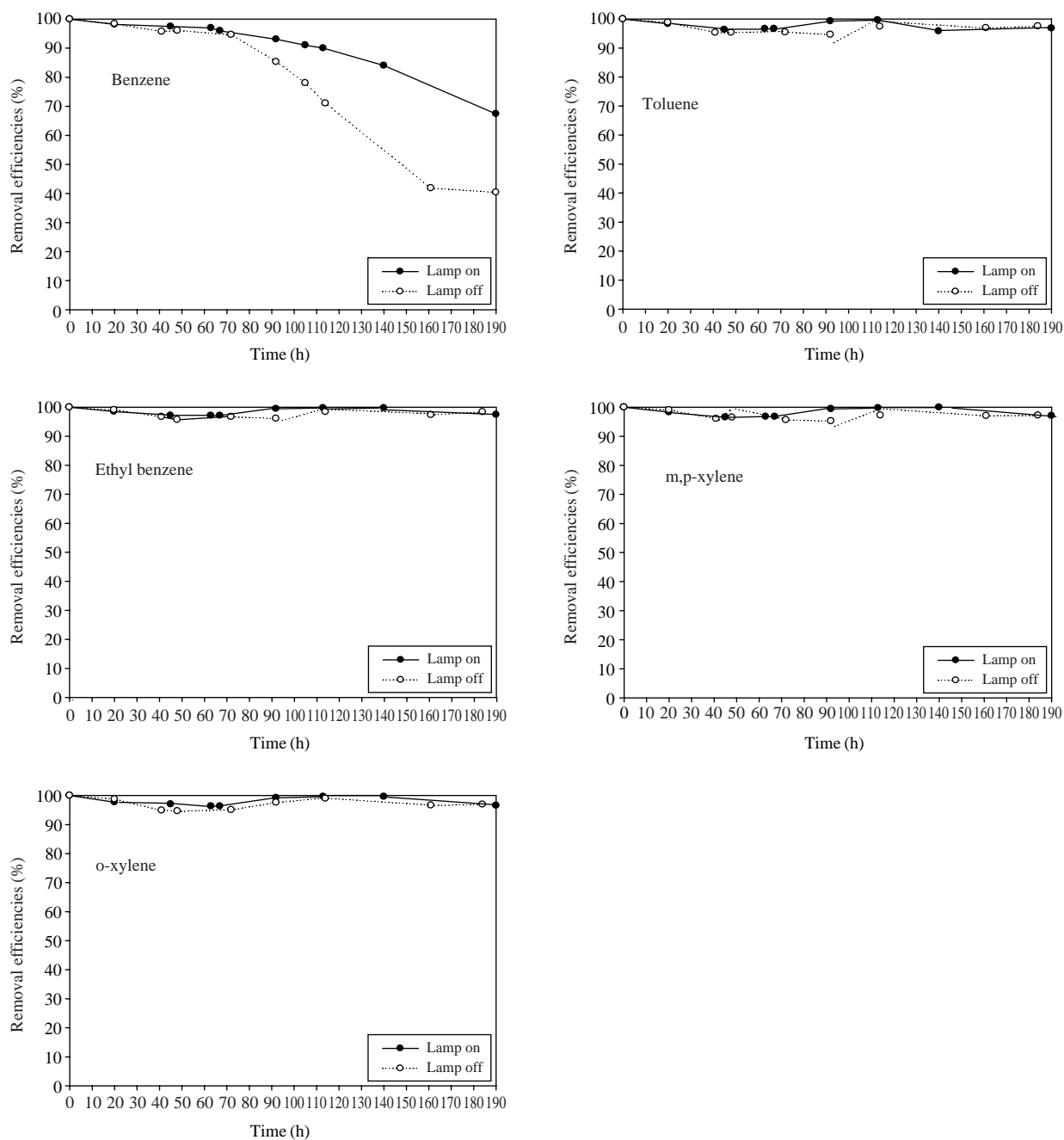


Fig. 5. Long-term AP efficiencies via GAC with S-doped visible-light-induced TiO_2 in the absence and presence of visible-light.

availability of visible-light, the removal efficiencies for toluene, ethyl benzene, m,p-xylene, and o-xylene were all well above 90% over the 185-h time period (Fig. 5), suggesting that there was no significant AP activity for the GAC/S-doped TiO_2 reactor. For benzene, however, the removal efficiency of the GAC/S-doped TiO_2 reactor in the presence of visible-light was 70%, whereas it was 40% for those with the abs-

ence of visible-light. Therefore, for benzene, the removal capability of the GAC/S-doped TiO_2 reactor in the presence of visible-light was superior to that with the absence of visible-light. A possible explanation for this difference is that the S-doped TiO_2 embedded into GAC could photo-catalytically destroy benzene in the presence of visible light and thus at least, partially regenerate the GAC *in situ*. Similarly, other studies

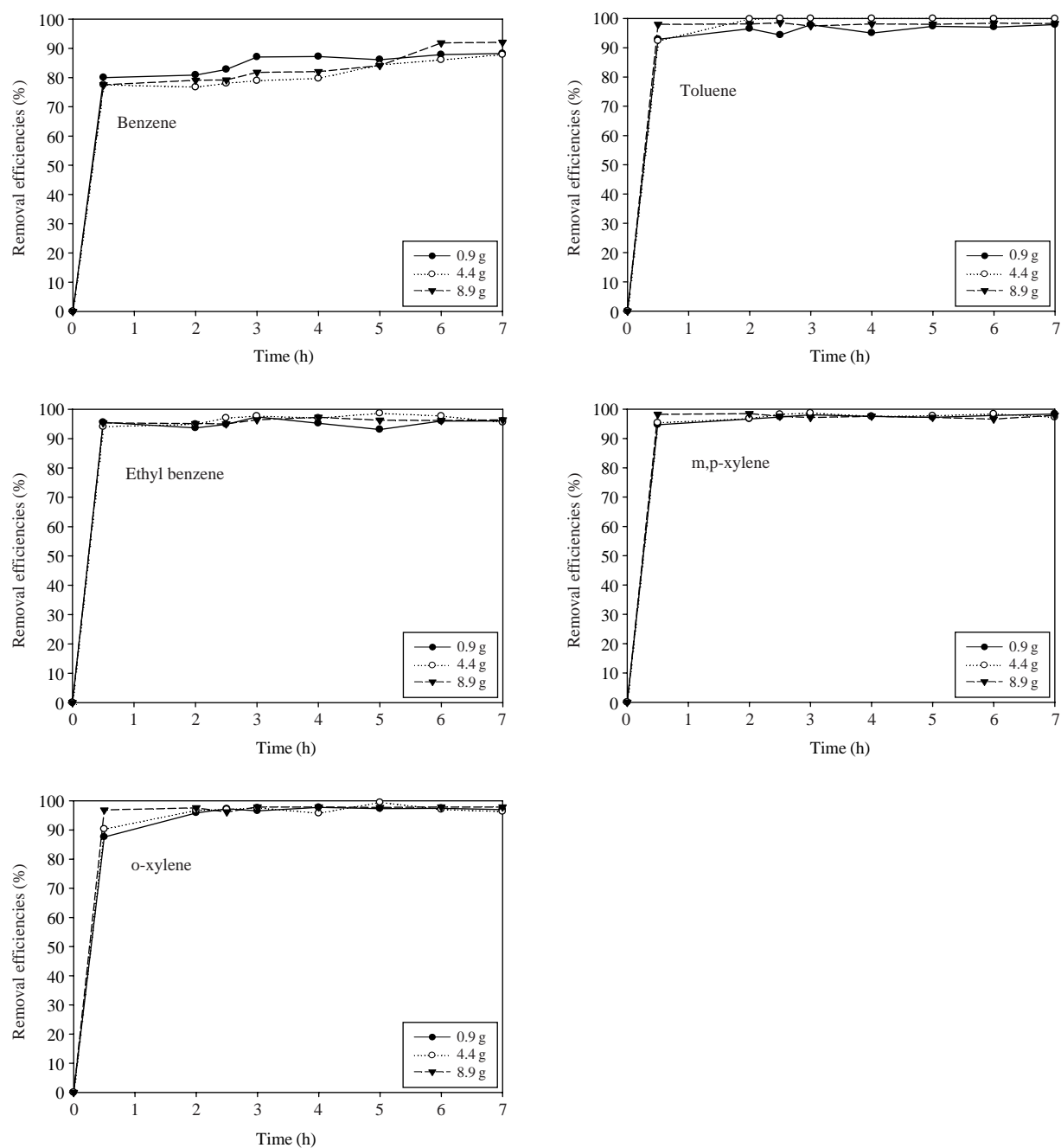


Fig. 6. AP efficiencies (%) of target MAHs (benzene, toluene, ethyl benzene, m,p-xylene, and o-xylene) by GAC with S-doped visible-light-induced TiO₂, according to the amounts filled into Pyrex reactor.

(Tao *et al.*, 2006; Ao and Lee, 2003) found that pure TiO₂ embedded into GAC in the presence of UV-light could enhance the removal efficiencies of BTEX and methanol compared to GAC alone or a GAC/TiO₂ unit in the absence of UV light. However, it was noted that, unlike the other target compounds, benzene concentrations decreased gradually after 70 to 80 h, even

when the light source was activated. This result is supported by d'Hennezel and Ollis (1997), who reported that the photocatalytic oxidation rate of benzene was lower compared to the other compounds. Consequently, the present study performed further experiments to evaluate the AP of the other target MAHs as well as benzene with the GAC/S-doped TiO₂ reactor

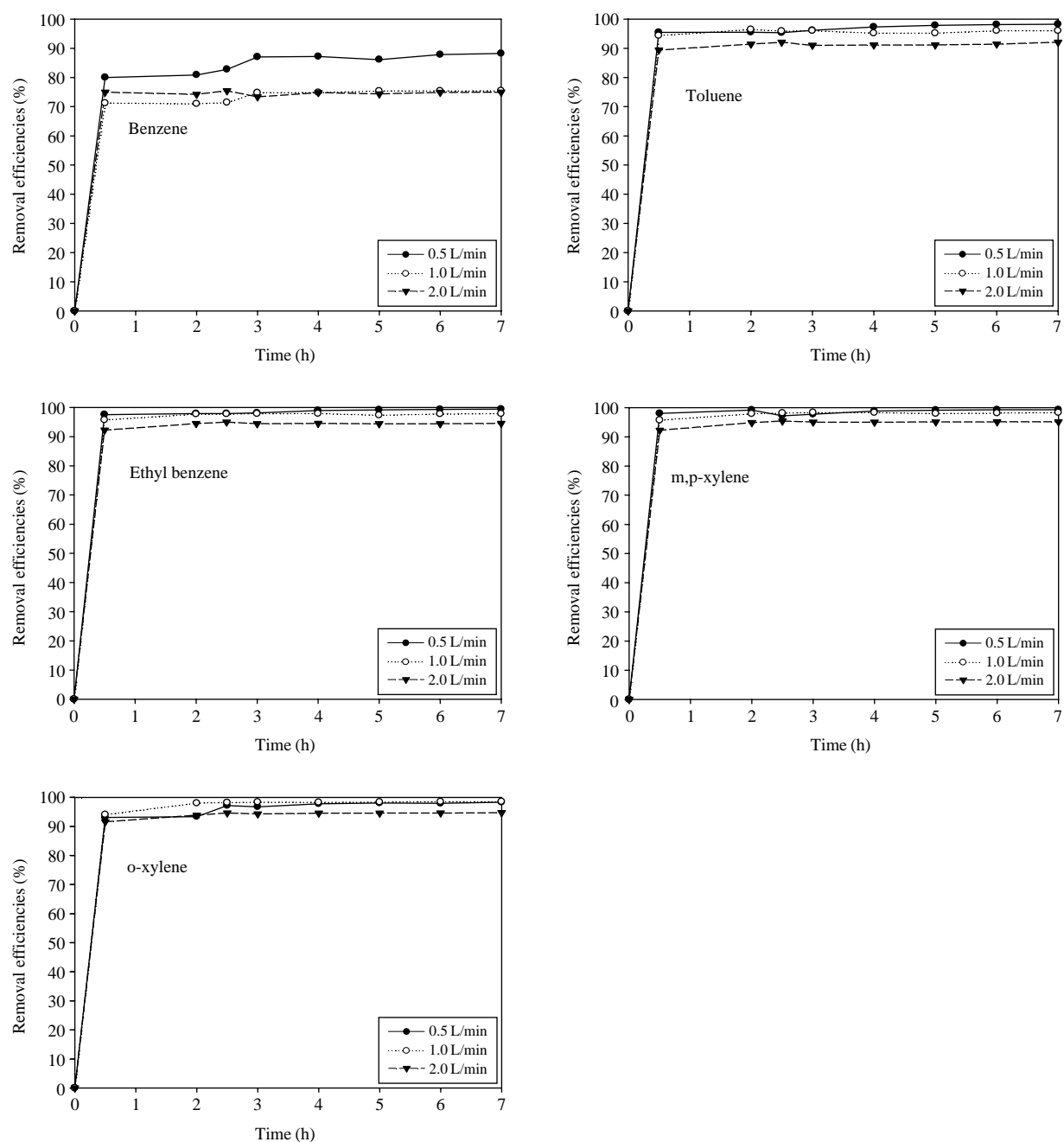


Fig. 7. AP efficiencies (%) of target MAHs (benzene, toluene, ethyl benzene, m,p-xylene, and o-xylene) by GAC with S-doped visible-light-induced TiO_2 , according to flow rates.

under different operational conditions.

3.3 Adsorptional Photocatalytic (AP) Activity of GAC/S-Doped TiO_2

The potential AP activities of GAC/S-doped TiO_2 for the target MAHs were further evaluated under different operational conditions. The operational param-

eters tested in this study included various weights of GAC/S-doped TiO_2 , FRs, and ICs. Three different weights (0.9, 4.9, and 8.9 g) were evaluated for MAH AP efficiencies under visible-light irradiation. The time-series AP efficiencies over a 7-h period are represented, according to weight, in Fig. 6. The AP efficiency for benzene increased slightly as the weight

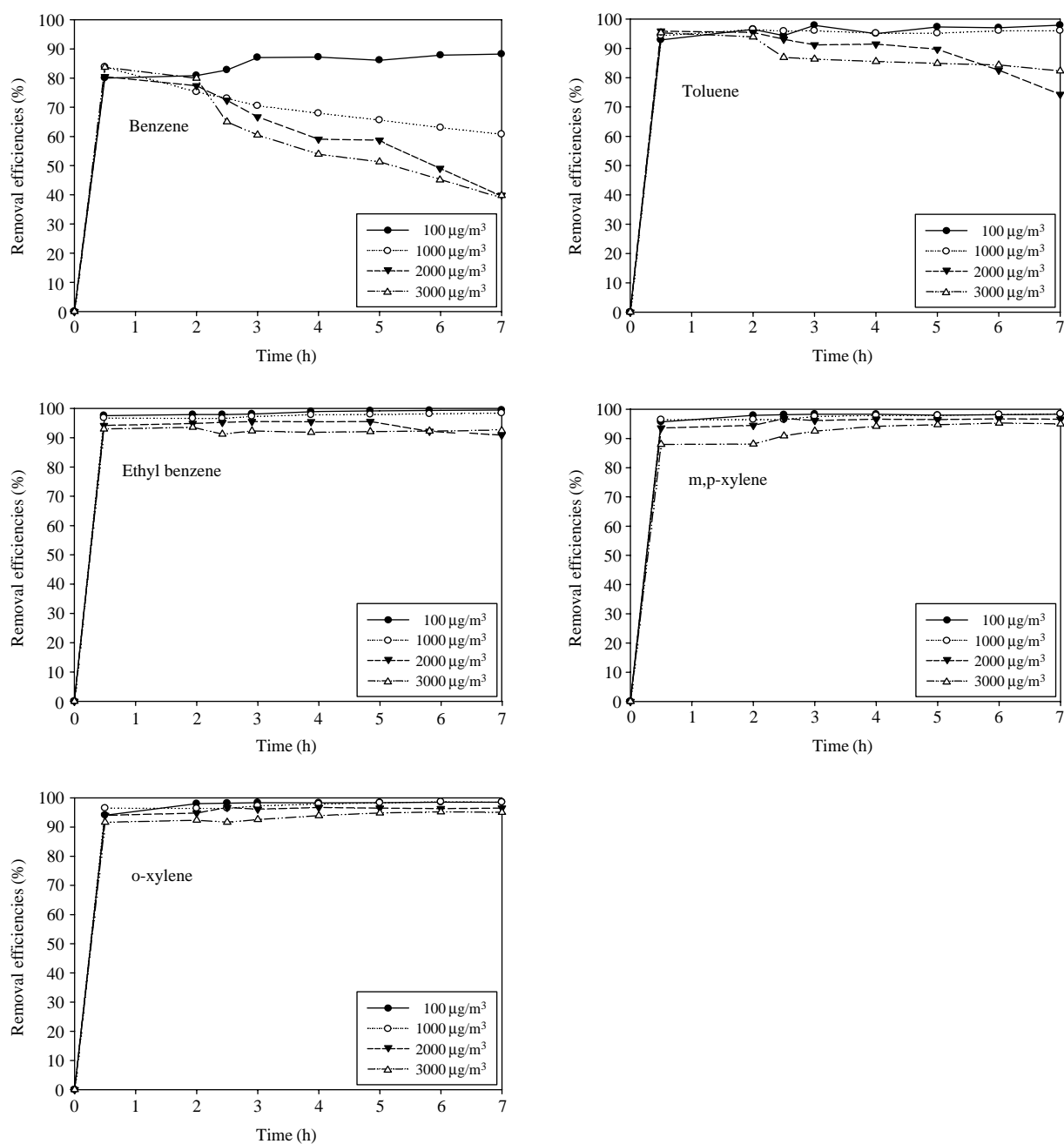


Fig. 8. AP efficiencies (%) of target MAHs (benzene, toluene, ethyl benzene, m,p-xylene, and o-xylene) by GAC with S-doped visible-light-induced TiO_2 , according to input concentrations.

increased from 0.9 to 4.4 g. Generally, however, the AP efficiencies for the target MAHs did not significantly vary with an increase in weight, thereby suggesting that, under the weight range tested in this study, the weights are not an important parameter for the AP efficiency.

Fig. 7 shows the AP efficiencies of the target MAHs determined by GAC/S-doped TiO_2 for visible-light

irradiation, according to the flow rates. Although for benzene the AP efficiency for the lowest FR (0.5 L min^{-1}) was higher than that for the two other higher FRs, FR dependency was not a significant. In addition, the other target compounds exhibited a similar pattern to that of benzene or an increasing pattern as FR increased. This suggests that, under the FR range of this study, FR is not an important parameter for AP

processes.

The AP efficiencies of the target MAHs determined by GAC/S-doped TiO₂ at four different ICs (0.1, 1, 2, and 3 mg m⁻³) under visible-light irradiation are presented in Fig. 8. Generally, the AP efficiencies of the target MAHs decreased as IC increased. This IC dependency is likely due to the increased competition between pollutant molecules for the adsorption sites of AC under a high concentration input condition. This result is supported by a previous study (Giraudet *et al.*, 2006) in that the adsorption capacity of the AC decreased with increasing IC of several volatile organic compounds.

4. CONCLUSIONS

The present study investigated the feasibility of applying a combined system of GAC/S-doped TiO₂ to clean gas-phase MAHs with concentration at low levels (≤ 3 mg m⁻³). An adsorption test suggested that S-doped TiO₂ particles on GAC surfaces do not significantly influence the adsorption capacity of GAC. In addition, the long-term AP test indicated that the S-doped TiO₂ embedded into GAC can photo-catalytically destroy benzene in the presence of visible light and thus at least partially, regenerate the GAC *in situ*. An activity test of GAC/S-doped TiO₂, which was performed under various conditions, exhibited that the ICs are important parameters for AP processes, whereas the FRs or the weights of GAC/S-doped TiO₂ are not.

REFERENCES

- Ao, C.H., Lee, S.C. (2003) Enhancement effect of TiO₂ immobilized on activated carbon filter for the photodegradation of pollutants at typical indoor air level. *Applied Catalysis B: Environment* 44, 191-205.
- Areerachakul, N., Vigneswaran, S., Ngo, H.H., Kandasamy, J. (2007) Granular activated carbon (GAC) adsorption-photocatalysis hybrid system in the removal of herbicide from water. *Separation and Purification Technology* 55, 206-211.
- Boulinguez, B., Bouzaza, A., Merabet, S., Wolbert, D. (2008) Photocatalytic degradation of ammonia and butyric acid in plug-flow reactor: Degradation kinetic modeling with contribution of mass transfer. *Journal of Photochemistry and Photobiology A: Chemistry* 200, 254-261.
- Brown, S.G., Frankel, A., Hafner, H.R. (2007) Source apportionment of VOCs in the Los Angeles area using positive matrix factorization. *Atmospheric Environment* 41, 227-237.
- Buzcu, B., Fraser, M.P. (2006) Source identification and apportionment of volatile organic compounds in Houston, Tx. *Atmospheric Environment* 40, 2385-2400.
- Daifullah, A.A.M., Girgis, B.S. (2003) Impact of surface characteristics of activated carbon on adsorption of BTEX. *Colloids and Surfaces A- Physicochemical and Engineering Aspect* 214, 181-193.
- Demeestere, K., Dewulf, J., Ohno, T., Salgado, P.H., Langenhove, H.V. (2005) Visible light mediated photocatalytic degradation of gaseous trichloroethylene and dimethyl sulfide on modified titanium dioxide. *Applied Catalysis B: Environment* 61, 140-149.
- d'Hennezel, O., Ollis, D.F. (1997) Trichloroethylene-promoted photocatalytic oxidation of air contaminants. *Journal of Catalysis* 167, 118-126.
- Fukahori, S., Iguchi, Y., Ichiura, H., Kitaoka, T., Tanaka, H., Wariishi, H. (2007) Effect of void structure of photocatalyst paper on VOC decomposition. *Chemosphere* 66, 2136-2144.
- Giraudet, S., Pré, P., Tezel, H., Le Cloirec, P. (2006) Estimation of adsorption energies using the physical characteristics of activated carbons and the molecular properties of volatile organic compounds. *Carbon* 44, 2413-2421.
- Han, S.W., Lee, J.H., Kim, J.S., Oh, S.H., Park, Y.K., Kim, H. (2008) Gaseous by-products from the TiO₂ photocatalytic oxidation of benzene. *Environmental Engineering Research* 13, 14-18.
- Hänninen, O.O., Lebet, E., Ilacqua, V., Katsouyanni, K., Künzli, N., Srám, N., Jantunen, M. (2004) Infiltration of ambient PM_{2.5} and levels of indoor generated non-ETS in residences of four European cities. *Atmospheric Environment* 38, 6411-6423.
- Hoshi, J., Amano, S., Sasaki, Y., Korenaga, T. (2008) Investigation and estimation of emission sources of 54 volatile organic compounds in ambient air in Tokyo. *Atmospheric Environment* 42, 2383-2393.
- Hunger, M., Husken, G., Brouwers, H.J.H. (2010) Photocatalytic degradation of air pollutants-From modeling to large scale application. *Cement Concrete Research* 40, 313-320.
- IARC (International Agency for Research on Cancer) (2004) Monographs on the evaluation of the carcinogenic risks of chemicals to man, WHO, Geneva.
- Jia, C., Batterman, S., Godwin, C. (2008) VOCs in industrial, urban, and suburban neighborhoods, Part 1: indoor and outdoor concentrations, variation, and risk drivers. *Atmospheric Environment* 42, 2083-2100.
- Jo, W.K., Kim, J.T. (2008) Photocatalysis of low concentration of gaseous-pgase benzene using visible-light irradiated N-doped and S-doped titanium dioxide. *Environment Engineering Research* 13, 171-176.
- Kim, K.J., Kang, C.S., You, Y.J., Chung, M.C., Woo, M.W., Jeong, W.J., Park, N.C., Ahn, H.J. (2006) Adsorption-desorption characteristics of VOCs over impregnated activated carbon. *Catalysis Today* 111, 223-228.
- Kwon, K.D., Jo, W.K. (2007) Indoor emission characteristics of liquid household products using purge- and trap method. *Environmental Engineering Research* 12, 203-210.

- Lillo-Ródenas, M.A., Cazorla-Amorós, D., Linares-Solano, A. (2005) Behavior of activated carbons with different pore size distributions and surface oxygen groups for benzene and toluene adsorption at low concentrations. *Carbon* 43, 1758-1767.
- Liu, Y., Yang, S., Hong, J., Sun, C. (2007) Low-temperature preparation and microwave photocatalytic activity study of TiO₂-mounted activated carbon. *Journal of Hazardous Materials* 142, 208-215.
- Mo, J.H., Zhang, Y.P., Yang, R. (2005) Novel insight into VOC removal performance of photocatalytic oxidation reactors. *Indoor Air* 15, 291-300.
- Ohno, T., Akiyoshi, M., Umebayashi, T., Asai, K., Mitsui, T., Matsumura, M. (2004) Preparation of S-doped TiO₂ photocatalysts and their photocatalytic activities under visible light. *Applied Catalysis A: General* 265, 115-121.
- Sasaki, T., Matsumoto, A., Yamashita, Y. (2008) The effect of the pore size and volume of activated carbon on adsorption efficiency of vapor phase compounds in cigarette smoke. *Colloids and Surfaces A-Physicochemical and Engineering Aspect* 325, 166-172.
- Shiraishi, S., Yamaguchi, Y., Ohbuchi, A. (2003) Rapid treatment of formaldehyde in a highly tight room using a photocatalytic reactor combined with a continuous adsorption and desorption apparatus. *Chemical Engineering Science* 58, 929-934.
- Tao, Y., Wu, C.-Y., Mazyck, D.W. (2006) Removal of methanol from pulp and paper mills using combined activated carbon adsorption and photocatalytic regeneration. *Chemosphere* 65, 35-42.

(Received 2 September 2010, accepted 9 November 2010)