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ORIGINAL PAPER

Performance of activated carbon-impregnated cellulose filters for indoor VOCs and dust control

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Abstract An activated carbon-impregnated cellulose filter was fabricated, and the capacity to remove dust and volatile organic compounds was evaluated in a laboratory. The adsorption capacities for benzene, toluene, ethyl benzene and *m*-xylene gases were compared by an adsorption isotherm test conducted as a preliminary test, showing that *m*-xylene and benzene were the most and least favorable for adsorption onto activated carbon, respectively. Cellulose filters were made with four levels of activated carbon contents, and dust removal was performed with all of the filters showing 99 % and higher efficiencies stable with a small variation during the experiment. Activated carbon content of 5 g in the unit filter area (125 g/m^2) was found optimum for benzene, toluene, ethylbenzene and *m*-xylene removal, as it appeared that higher than 5 g activated carbon content was unnecessary for the improvement of its capacity. With increasing benzene, toluene, ethylbenzene and *m*-xylene loading, the highest removal rates were determined as 0.33–0.37 mg/cm^2 s for as short as 0.0046 s of air filter residence time. The rapid removal was possible because of the high surface area of the activated carbon-impregnated cellulose filter provided by powdered activated carbon, which is distinguished from the granular form in conventional activated carbon towers. As fixed within a cellulose scaffolding structure, the powdered activated carbon performed excellent benzene, toluene, ethylbenzene, and *m*-xylene adsorption (98.9–100 %), and at the same time, particular matters were removed in average 99.7 % efficiency after being filtered through the cellulose filter sheet.

Keywords Activated carbon · Adsorption · Air filter residence time · Cellulose filter · Dust and volatile organic compounds

Introduction

Contaminants affecting indoor air quality can be classified into two large categories: particulate matter and gases. Particulate matter comprises tiny solids or liquid droplets that can be grouped simply by size, such as PM10 (particles between 2.5 and 10 μm) and PM2.5 (particles smaller than 2.5 μm). These particles differ not only in size but also in sources and health effects. It is understood that smaller PM2.5 has worse health effects because it travels deeper in human respiratory systems and is composed of more toxic heavy metals and cancer-causing compounds. Gaseous contaminants in air can be grouped roughly into three categories: (1) acid gases, (2) volatile organic compounds, and (3) other common gases, and each group includes (1) sulfur dioxide, nitrogen dioxide, nitric oxide, hydrogen sulfide and chloride; (2) benzene, toluene, ethylbenzene, xylene, acetaldehyde, 2-butanone, dichloromethane and isobutyl alcohol; and (3) formaldehyde, ozone and ammonia, respectively. The lists of gases are just some examples of the entire gas-phase contaminants.

Control of the indoor air quality should be addressed depending on the target contaminants, their physical and chemical properties, and the level of expected removal

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efficiency. Particulate matters are captured in air filters normally by four mechanisms: interception, straining, internal impaction, and Brownian diffusion (Vaughn and Ramachandran 2002; Devine et al. 2013), where each individual mechanism is responsible for the removal efficiency of particles in a certain size range. Typical air filters, made of glass fiber or synthetic polymers, are classified by their target particle sizes for separation, from coarse (≥10 μm) to fine (≥1 μm), with consideration of the pressure drop and the removal efficiency when they are operated. High-efficiency air filters such as HEPA (high-efficiency particulate air) and ULPA (ultra-low penetration air) filters are designed to trap even smaller (0.12–0.3 μm) particles with higher than 99.99 % efficiency under a minimal pressure drop and maximum airflow. Because of the high efficiency, HEPA and ULPA filters are applied in clean rooms and precision assembly areas, which require very clean air quality (Schroth 1996).

Unlike particulate matters, gas-phase contaminants should be controlled by means of adsorption, using chemical filters impregnated with any type of adsorbent, such as activated carbon, zeolite, and other polymeric substances. Activated carbon (AC) is most common economically beneficial adsorbent in removing a variety of gaseous contaminants because of the large surface area associated with the internal pore structure. From a pyrolysis of various base materials such as coal, wood, bark, and coconut shell, activated carbon can be manufactured in a high-temperature oxidation process. Not only is it used as an impregnated form in a filter, but it is also used in column-type filters as a medium and manufactured as carbon fiber cloths or felts for convenient applications. A number of studies using activated carbon filters showed that they are excellent volatile organic compounds (VOCs) adsorbents, having a long lifetime with a consistent VOCs removal efficiency with periodical regeneration (Das et al. 2004; Lorimier et al. 2005; Ramirez et al. 2005; Haghighat et al. 2008; Bastani et al. 2010; Ramos et al. 2010; Sidheswaran et al. 2012; Gupta et al. 2012; Jo and Chun 2014). Adsorption onto carbon is sensitive to temperature and humidity because the equilibrium time becomes shorter at high temperature and desorbing VOCs may occur when heated, as the molecules gain kinetic energy (Hwang and Lee 1994; King and Do 1996). As a result, at a given relative pressure, the adsorption amount decreases with increasing temperature, although some researchers also revealed the “activated entry effect” of some adsorbates, which showed temperature-dependent adsorption onto activated carbon. Chiang et al. (2001) explained the effect of using benzene adsorption increment at a high temperature because of the enhancement of interactions between benzene molecules and the activated carbon. At humid conditions, again, the adsorption of some gases may be affected because they compete with water molecules. High humidity results in the decrease in adsorption because the adsorption of water occurs faster than gases or even replaces the gases already adsorbed in the pores (Cal et al. 1996; Sidheswaran et al. 2012).

In the present study, simultaneous removal of particulate and gaseous contaminants in an indoor environment was performed using cellulose filters impregnated with powdered activated carbon. The capacity of VOC adsorption was first evaluated using powdered AC and benzene, toluene, ethylbenzene and *m*-xylene (BTEX) gases, and the AC-impregnated cellulose filter (ACCF) was fabricated to be used for simultaneous dust and VOCs removal. The pristine cellulose filter was made of traditional paper material that has long been used in Korea but never been used for filtration purposes (Yoon et al. 2016), and the ACCF was made by mixing the cellulose and powdered activated carbon. After analysis of the physical properties, the filter was applied to continuous tests for dust and VOCs removal, and the capacity for BTEX gases adsorption was evaluated. The aim of this paper is to present results of the fabrication of ACCF and its use in environmental applications. The possibility of simultaneous control for particulate and gaseous matters with high efficiencies and removal rates for individual contaminants is discussed. This study was carried out from 2013 to 2015 in Gyeonggi-do, Republic of Korea.

Materials and methods

Adsorption isotherm test

Before the filter fabrication, the adsorption capacity of powdered activated carbon was evaluated with BTEX gases. Powdered AC was purchased from Hanil Tech Co. Gyeongnam, Korea, as made of coconut husk (97.5 %) in 325 mesh. The Brunauer, Emmett and Teller (BET) surface area of the AC was 1020 m^2/g, as determined by the nitrogen adsorption method at 77 K using an automatic high-end volumetric gas adsorption instrument (BELSORP-max, MicrotracBEL Corp, Osaka, Japan). For the adsorption isotherm, concentrate gases were prepared individually by injecting a known volume of pure liquid benzene into a fixed volume of the hydrocarbon-free air in a clean Tedlar bag (State of Calif. Air Resources Board 1986). Gradient amounts of AC, 1.0, 2.5, 5.0, 10, 20, and 50 mg, were placed in separate Tedlar bags, and the concentrate benzene gas (300 mg/m^3) was injected. After 24 h of shaking, the gas samples were collected, and the equilibrium concentrations were determined using a GC–MS system (Thermo DSQ II, Thermo Fisher Science Inc. TX. USA). The same procedure was applied with toluene, ethylbenzene, and *m*-xylene gases for individual adsorption isotherms.

Fabrication of the activated carbon-impregnated cellulose filter (ACCF)

The porous cellulose filter was prepared by the same procedure as illustrated in the previous study (Yoon et al. 2016). In addition to that, powdered AC was used this time in a mixed form with cellulose material. After spin dehydration of the raw pulp material to 75 % moisture content, the weighed pulp (2.5 g in dry weight) was mixed with 1.0, 2.5, and 5.0 g of activated carbon (AC) powder with 600 mL water in an electric mixer to make dilute pulp slurry. The slurry was then filtered slowly through a mesh covered by a fabric, treated with *t*-butyl alcohol (50 % w/w) spray, and freeze-dried. The *t*-butyl alcohol and freeze-drying steps were applied for optimum porous structure of the filter.

Pressure loss test

Gradient air flow rates were applied to the cellulose filters fabricated with activated carbon. Flow rates of 30, 60, 80, 100, 130, and 160 L/min (2.2, 4.4, 5.5, 7.4, 9.6, and 11.9 cm/s of air-to-cloth (A/C) ratios) were applied, and the pressure loss at each time was monitored by a manometer connected to the filtration system. Figure 1 shows the schematic diagram of the filtration system for dust and VOCs removal.

Continuous dust removal test

The filters with 0, 1.0, 2.5, and 5.0 g of AC contents were tested for continuous dust removal at the laboratory scale. Reagent grade JIS test powder (Test Powders 1, class 11) was used as a PM10 dust sample. The particle size of the powder was between 0.3 and 5 μm. The chemical composition of the powder included SiO_2 (34–40 %), Fe_2O_3 (17–23 %), Al_2O_3 (26–32 %), CaO (0–3 %), MgO (0–7 %) and TiO_2 (0–4 %). The filtration chamber was connected to a dust generator (fluidized bed dust generator, Model 3211, Kanomax Japan Inc. Osaka, Japan) and an air blower to control the dust concentration at a fixed flow rate. Dust counters were equipped in and out of the filtration chamber to monitor the number of dust particles at 1-min intervals (Dust monitor, model 3442, Kanomax).

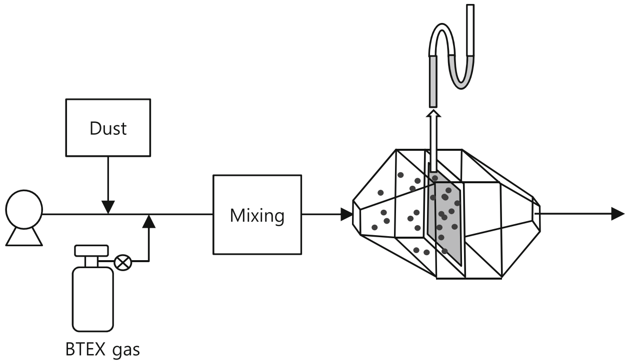

Fig. 1 Schematic of the ACCF filtration system for simultaneous dust and VOCs removal

BTEX removal through the ACCF with dust cake

As a preliminary test, filters impregnated with 0, 0.1, 1.0, 2.5, 5.0, and 8.0 g of activated carbon were prepared and used for BTEX removal. The incoming BTEX concentrations were 5 mg/m^3 each, and flow rate was controlled to be 90 L/min (6.7 cm/s). Once the removal efficiencies of each ACCF were determined, only one AC content was selected for the next experiment for BTEX removal with dust cake present.

Because of the technical limitation in the analysis of VOCs with dust present, a simultaneous dust and BTEX removal test was not conducted. Instead, VOCs monitoring in the presence of dust cake already in the filters' surface was tested individually at four different conditions, i.e., BTEX removal with a clean ACCF and with dust cake on the ACCFs at three levels, 9.7, 23.1, and 43.6 g/m^2. The filters with dust cake were prepared by 1, 3, and 6 h of operation for dust removal with clean ACCFs. At each dust level, four increasing linear velocities were applied at a fixed initial BTEX concentration of 5 mg/m^3. BTEX gases were purchased from Union Gas, Co, Goyang-si, Korea, as a pressed gas mixture in a 10-L cylinder, containing 50 mg/m^3 of benzene, toluene, ethylbenzene, and *m*-xylene.

Results and discussion

BTEX adsorption isotherm

Benzene, toluene, ethylbenzene, and xylene (BTEX) are chemicals frequently occurring in indoor and outdoor environments. They are used as solvents for paint and coating materials and constituents of petroleum products such as gasoline and diesel fuels. Generally, BTEX gases co-occur in air, water, and soil, and exposure to these gases may cause neurological impairment or cancers in human beings. The adsorption of BTEX gases on powdered activated carbon was tested at an initial concentration of 300 mg/m^3, and the equilibrium concentrations were identified. Table 1 summarizes the result of each individual BTEX adsorption test.

Table 1 Summary of the BTEX adsorption tests on activated carbon

AC dose (mg)	Initial conc. (mg/m^3)	Final conc. (mg/m^3)	Adsorbed conc. (mg/L)	Adsorbed mass (mg)	Adsorbed mass per unit adsorbent (mg/g)
Benzene					
1.0	284	237.15	0.0468	0.0422	42.2
2.5		171.52	0.1125	0.1012	40.5
5.0		112.04	0.1720	0.1548	31.0
10		27.95	0.2560	0.2304	23.0
20		8.15	0.2758	0.2483	12.4
50		6.91	0.2771	0.2494	5.0
Toluene					
1.0	300	229.97	0.0700	0.0630	63.0
2.5		158.92	0.1411	0.1270	50.8
5.0		63.68	0.2363	0.2127	42.5
10		3.44	0.2966	0.2669	26.7
20		1.00	0.2990	0.2691	13.5
50		0.91	0.2991	0.2692	5.4
Ethyl benzene					
1.0	300	230.2	0.0698	0.0628	62.8
2.5		159.0	0.1410	0.1269	50.8
5.0		66.10	0.2339	0.2105	42.1
10		14.72	0.2853	0.2568	25.7
20		5.44	0.2946	0.2651	13.3
50		1.49	0.2985	0.2687	5.4
m-Xylene					
1.0	300	232.38	0.0676	0.0609	60.9
2.5		157.96	0.1420	0.1278	51.1
5.0		65.87	0.2341	0.2107	42.1
10		8.49	0.2915	0.2624	26.2
20		5.32	0.2947	0.2652	13.3
50		2.91	0.2971	0.2674	5.3

The adsorption results were applied to Langmuir and Freundlich adsorption models (Table 2), and the adsorption isotherm parameters were identified. The Langmuir model is valid for the case of monolayer adsorption on the outer surface of adsorbate, and no further adsorption takes place. By the linear plot of $1/q_e$ versus $1/C_e$, the values of $1/Q_0$ and K_L are identified, and they show the maximum monolayer adsorption capacity and the Langmuir isotherm constant. The equilibrium parameter R_L is a dimensionless constant, referred to as a separation factor, that indicates the adsorption nature to be either unfavorable (>1), linear (=1), favorable (<1) or irreversible (=0). From this study, the maximum monolayer coverage capacities (Q_0) for BTEX gases were found to be 61.73, 67.11, 49.02, and 140.85 mg/g, respectively, and the values of K_L (Langmuir isotherm constant) were 16.2, 149, 102, and 14.2 (L/mg). The R_L values for each BTEX gases were 0.179, 0.0219, 0.0316, and 0.190, indicating that the adsorption of BTEX gases is favorable onto the activated carbon, and desorption is unfavorable in the order of toluene, ethylbenzene, benzene, and *m*-xylene (Table 3).

The Freundlich adsorption model is commonly used to describe non-ideal and reversible adsorption characteristics for a heterogeneous surface. This equation is not restricted to the monolayer adsorption and can be used in multilayer adsorption (Foo and Hameed 2010). The slope ($1/n$) ranges from 0 to 1 and is a measure of the adsorption intensity or heterogeneity of the adsorbent surface, indicating high heterogeneity as it gets closer to zero. If the $1/n$ value is less than 1, it means normal adsorption. When $1/n$ is above 1, it indicates cooperative adsorption. Freundlich isotherm constants (K_F) of BTEX were 96.0, 105.6, 135.0, and 134.3 mg/g, respectively, indicating that adsorption onto the activated carbon was favorable in the order of ethylbenzene, *m*-xylene, toluene, and benzene. The slopes ($1/n$) of all BTEX gases were between 0.33 and 0.49

Table 2 Adsorption models

	Langmuir isotherm model	Freundlich isotherm model
Equation	$q_e = \frac{Q_0 K_L C_e}{1+K_L C_e}$	$Q_e = K_f C_e^{\frac{1}{n}}$
Linear form	$\frac{1}{q_e} = \frac{1}{Q_0} + \frac{1}{Q_0 K_L C_e}$	
	$\log Q_e = \log K_f + \frac{1}{n} \log C_e$	
	$R_L = \frac{1}{1+(1+K_L C_0)}$	
Where	C_e = the equilibrium concentration of the adsorbate (mg/L) q_e = the adsorbed amount per gram of the adsorbent at equilibrium (mg/g) Q_0 = maximum monolayer coverage capacity (mg/g) K_L = Langmuir isotherm constant (L/mg) C_o = initial concentration of adsorbate (mg/L) R_L = equilibrium parameter	K_f = Freundlich isotherm constant (mg/g) n = adsorption intensity C_e = the equilibrium concentration of the adsorbate (mg/L) Q_e = the adsorbed amount per gram of the adsorbent at equilibrium (mg/g)

Table 3 Langmuir and Freundlich adsorption isotherm parameters

	Benzene	Toluene	Ethylbenzene	*m*-Xylene
Langmuir adsorption parameters				
Q_0 (mg/g)	61.73	67.11	49.02	140.85
K_L (L/mg)	16.2	149	102	14.2
R_L	0.179	0.0219	0.0316	0.190
R^2	0.7864	0.7521	0.9940	0.9260
Freundlich adsorption parameters				
$1/n$	0.493	0.334	0.460	0.462
K_F (mg/g)	96.0	105.6	135.0	134.3
R^2	0.8580	0.8278	0.9615	0.8503

(Table 3), revealing that the adsorption of all four gases was normal and fit the Freundlich equation well. In both the Langmuir and Freundlich models, it was found that the adsorption of *m*-xylene onto AC was most favorable, whereas the adsorption of benzene was least favorable, although the difference in the adsorption capacities between the four individual gases was not great.

Fabrication and characterization of the ACCF

The activated carbon-impregnated cellulose filter (ACCF) was fabricated using moist cellulose material, with four different levels of activated carbon content. All filters were made by a filtering unit (20 × 20 cm; Yoon et al. 2016) using a consistent amount of cellulose (2.5 g in dry weight) with increasing AC contents, 0, 1.0, 2.5, and 5.0 g, as shown in Fig. 2. The physical properties of the filters are summarized in Table 4. With increasing AC content, the total mass of the filter increased, and the thickness and density of the filters also increased. Mixing the two different materials has caused dramatic increase in the pore size; compared to the cellulose filter without AC content, the ACCF made of 5.0 g AC showed around 30 times higher mean pore size (Table 4). The effect of pore size difference was mitigated by high areal and bulk densities, so the porosity levels of individual filter did not vary much and remained between 90 and 96 %.

Using the four different filters, a pressure loss test was conducted using clean air at increasing flow rates of 30, 60, 80, 100, 130, and 160 L/min (Fig. 3). Overall, the pressure changes for the increasing flow rate from 30 to 160 L/min were very small, and the highest pressure loss observed in 1 g ACCF was 0.022 atm. It was noticeable that the pressure drop in 0 g ACCF and 5 g ACCF showed the most similar curves with increasing flow rate, despite the relatively large difference in the filter thicknesses and pore sizes. It was expected that the large pore size of 5 g ACCF would lead to the least pressure loss, but it showed similar pressure changes with 0 g ACCF and 1.0 g ACCF. This was because the other physical properties, such as the thickness, density, and porosity, also had important roles in the pressure loss. Except for the pore size, all other properties of 5.0 g ACCF were unfavorable for receiving high flow rates compared to the other filters. The 2.5 g ACCF appeared to have the least pressure loss with increasing flow rate, indicating that the pressure drop of a filter was influenced by complex properties, not only the pore size or porosity but also the thickness and areal density. When comparing the 1 g ACCF and 2.5 g ACCF filters, it appeared that the pore size had the most important effect on the pressure changes, as all other physical properties were in similar ranges in this case.

Dust removal performance

A dust removal test was performed for the filters by supplying synthetic PM10 dust particles from a dust generator. The influent dust concentration was controlled to be within

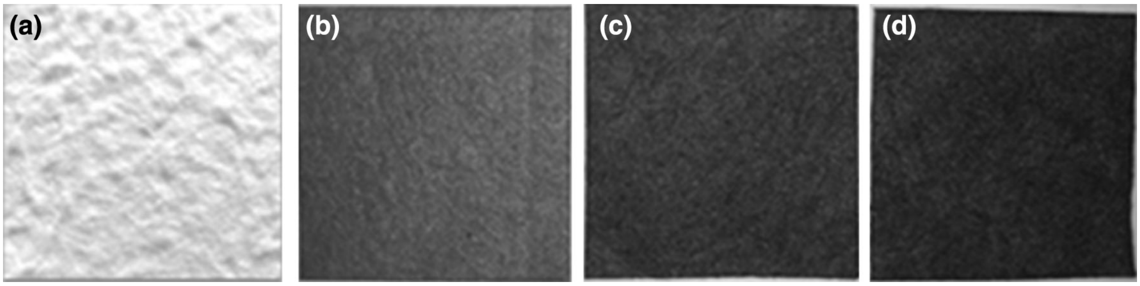

Fig. 2 Cellulose filters fabricated with 0 (**a**), 1.0 (**b**), 2.5 (**c**), and 5.0 g (**d**) of activated carbon

Table 4 Properties of the ACCFs

AC content	0 g	1.0 g	2.5 g	5.0 g
Thickness (mm)	0.50	0.60	0.80	0.95
Mean pore size (μm)	7.49 (±5.75)	8.33 (±6.05)	64.92 (±46.75)	241.98 (±130.59)
Areal density (mg/cm^2)	5.53	11.27	15.46	24.29
Bulk density (mg/cm^3)	110.6	187.9	193.3	255.7
Porosity (%)	95.8	92.9	92.7	90.4

Table 5 Summary of the dust removal performance

AC content	0 g (0 g/m^2)	1.0 g (25 g/m^2)	2.5 g (62.5 g/m^2)	5.0 g (125 g/m^2)
In (cpm)	4451 (±690)	5784 (±1915)	6578 (±1039)	5702 (±773)
Out (cpm)	4.4 (±10.8)	56 (±18)	22 (±13)	17 (±4)
Efficiency (%)	99.89 (±0.25)	98.97 (±0.39)	99.67 (±0.13)	99.69 (±0.07)

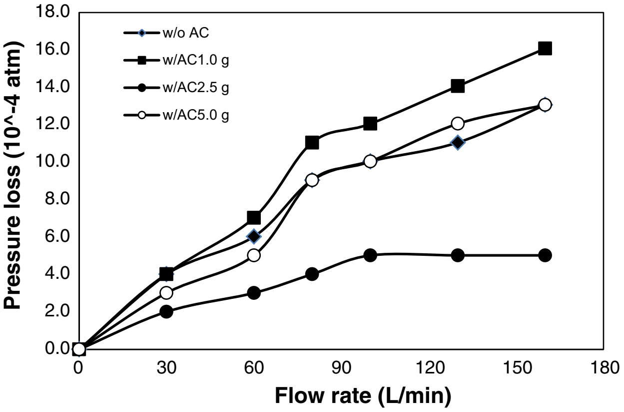

Fig. 3 Pressure loss of the four different filters as a function of the flow rate

the 4000–7000 cpm (count per minute) range. During the 4 h of the experiment, it was found that all the four kinds of filters treated influent dust successfully with higher than 98 % removal efficiencies. The effluent dust concentrations treated from the four different filters did not vary much and showed stable low levels with higher than 98 % removal efficiencies in all of the filters (Table 5). This was not exceptional with the filters of large pore size (5 g ACCF), which showed the second highest (99.7 %) dust removal efficiency among the filters. It is assumed that the excellent dust removal performance of 5 g ACCF was due to the proper porosity with a thickness that helps keep dust particles safely within the filter structure. Figure 4 illustrates SEM photographs of the filter surface: the cellulose filter w/o AC, the AC-impregnated filter, and the ACCF after dust removal (from left).

BTEX removal with increasing linear velocity

Figure 5 shows the result of BTEX removal efficiencies using the filters impregnated with six levels of AC content. When AC was not added, the filter performed 10–15 % removals for toluene, ethylbenzene, and *m*-xylene, but benzene was not removed in this case. With 0.1 g AC content, benzene showed approximately 40 % removal efficiency and other gases were removed between 92 and 97 %. To obtain higher than 95 % removal efficiencies for all BTEX gases, it was found that AC content of 1.0 g was the minimum requirement, and the efficiency was not improved further at higher than 5.0 g AC content. Based on this result and also from the pressure drop and dust removal tests, the filter containing 5.0 g of activated carbon was selected as an optimal content and applied for the subsequent BTEX removal test.

Five grams of ACCF was used to evaluate the BTEX removal performance under linear velocity changes. Four different flow rates were applied to the ACCF, and they can be expressed as linear velocity values, such as 6.7, 11.9, 15.6, and 20.7 cm/s. Individual BTEX removal efficiencies under different velocity conditions were determined, as illustrated in Fig. 6. The linear velocity was inversely proportional to the gas removal performance, and this effect was obvious during benzene removal and also shown by the ethylbenzene and *m*-xylene test results. However,

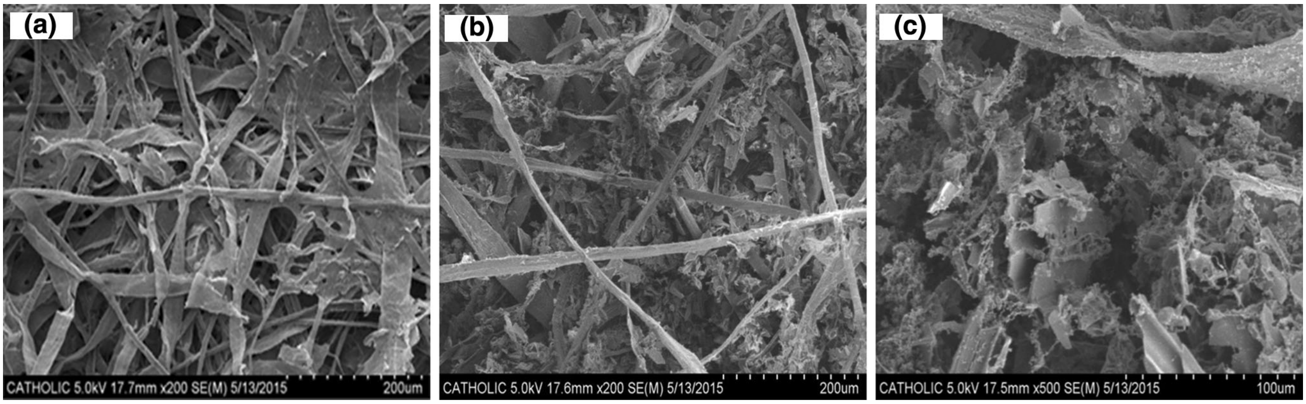

Fig. 4 SEM photographs of **a** cellulose filter, **b** 5 g ACCF, and **c** 5 g ACCF after dust removal

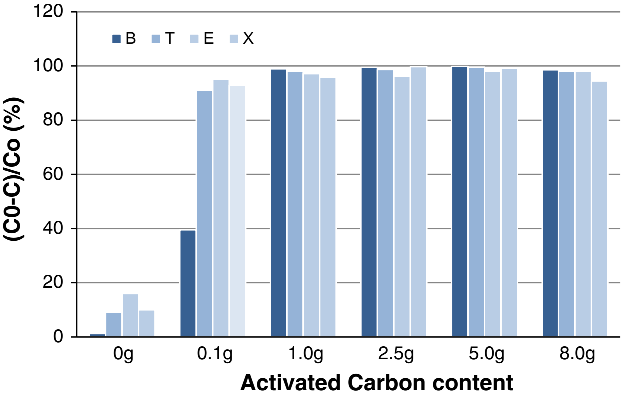

Fig. 5 BTEX removal efficiencies of the filters with various AC contents

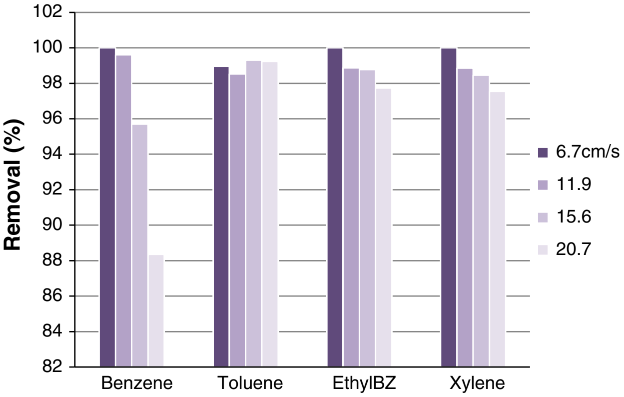

Fig. 6 BTEX removal at increasing linear velocity conditions

toluene removal was not affected by the linear velocity changes. At a low linear velocity (6.7 cm/s) condition, benzene, ethylbenzene, and *m*-xylene removal was close to 100 %, whereas toluene removal efficiency was slightly low (99 %). On the other hand, at a high linear velocity (20.7 cm/s) condition, toluene removal efficiency became even better, whereas all other efficiencies became worse. This result indicates that the rate of toluene adsorption onto the activated carbon was the highest among the four gases, so its adsorption was not affected from increasing flow rate. Additionally, desorption from the AC is unfavorable in the case of toluene, as already mentioned by the R_L from the Langmuir isotherm model (Table 3).

In Fig. 7, the correlation between BTEX loading and the adsorption rate in the filter is computed and shown as linear plot. Before the experiment, it was expected that BTEX adsorption would become slow, and the efficiency would decrease with increasing BTEX loading rate. However, the correlation appeared to be directly proportional, with all R^2 values close to 1. Compared to other gases, the slope of benzene was slightly low, indicating that the adsorption rate becomes slower with increasing benzene loading. This can be due to the molecular size, partial polarity or vapor pressure of this VOC so that benzene is relatively less beneficial to be adsorbed in AC, but it cannot be confirmed from this result. The removal rates of BTEX at highest loading were 0.33, 0.37, 0.36, and 0.36 mg/cm^2 s, respectively. At this loading rate, the residence time of the incoming gas in the ACCF sheet was only 0.0046 s. It is understood that this surprisingly high BTEX removal rate was due to the following features in this study: (1) making powdered AC fixed in a filter sheet could provide large surface area for incoming VOC gases with AC pores and at the same time allow a low pressure loss, and (2) the diffusion coefficient of BTEX gases is high enough for the gases to be adsorbed in the ACCF within the short residence time.

Conventional AC towers utilize granular or pelletized forms of activated carbon filled in a fixed bed for lowered pressure loss but must scarify high surface area because of the large particle size of absorbent. In this study, powdered activated carbon was used in ACCF fabrication to maximize surface areas for VOCs adsorption as well as provide high enough porosity by the porous cellulose structure. This made it possible for the rapid adsorption of BTEX

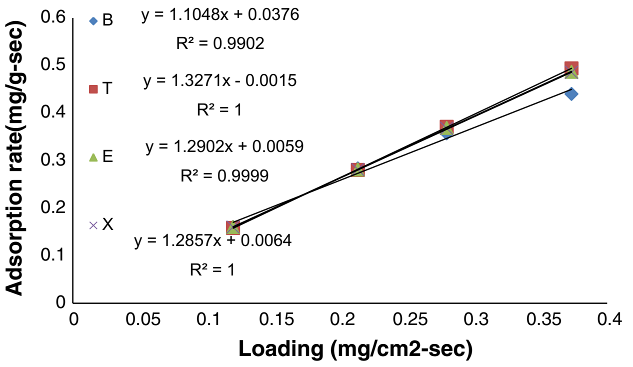

Fig. 7 Relation between BTEX loading and adsorption in the ACCF

gases when filtered through the ACCF sheet. Considering the BTEX diffusion coefficients ranged from 0.68 to 0.93 × 10^5 m^2/s at 25 °C (Yaws 1995), the residence time 0.0046 s was sufficient for the adsorption of BTEX in the filters.

The effect of dust cake on BTEX removal was evaluated using filters after receiving dust for 1, 3, and 6 h to simulate simultaneous dust and BTEX removal conditions. The filters were weighed to determine the mass of dust cake per unit filter area before the BTEX removal test. A clean filter was also used in the same manner as a control. Generally, dust cake appeared to help improve the removal efficiency of all BTEX gases (Fig. 8), especially at a high flow rate. Above all, the effect was clear in the case of benzene (Fig. 8a), which showed high removal efficiency consistently with the increasing mass of dust cake. At higher dust cake, effect of linear velocity changes even disappeared.

Similar results were obtained with the other gases, and the efficiency levels at four different dust cake conditions were all in the similar ranges at the lowest linear velocity. With the clean filter, the removal efficiency became lowered with increasing linear velocities, except for toluene. It is obvious that BTEX removal with the highest dust cake condition showed best removal efficiencies regardless of linear velocity changes. This may be because the dust itself played a role as an BTEX absorbent, and more likely dust particles hindered air flow rate at the filter surface, so that gave more chance of contact between BTEX gases and AC powder during the filtration process. The adsorption of

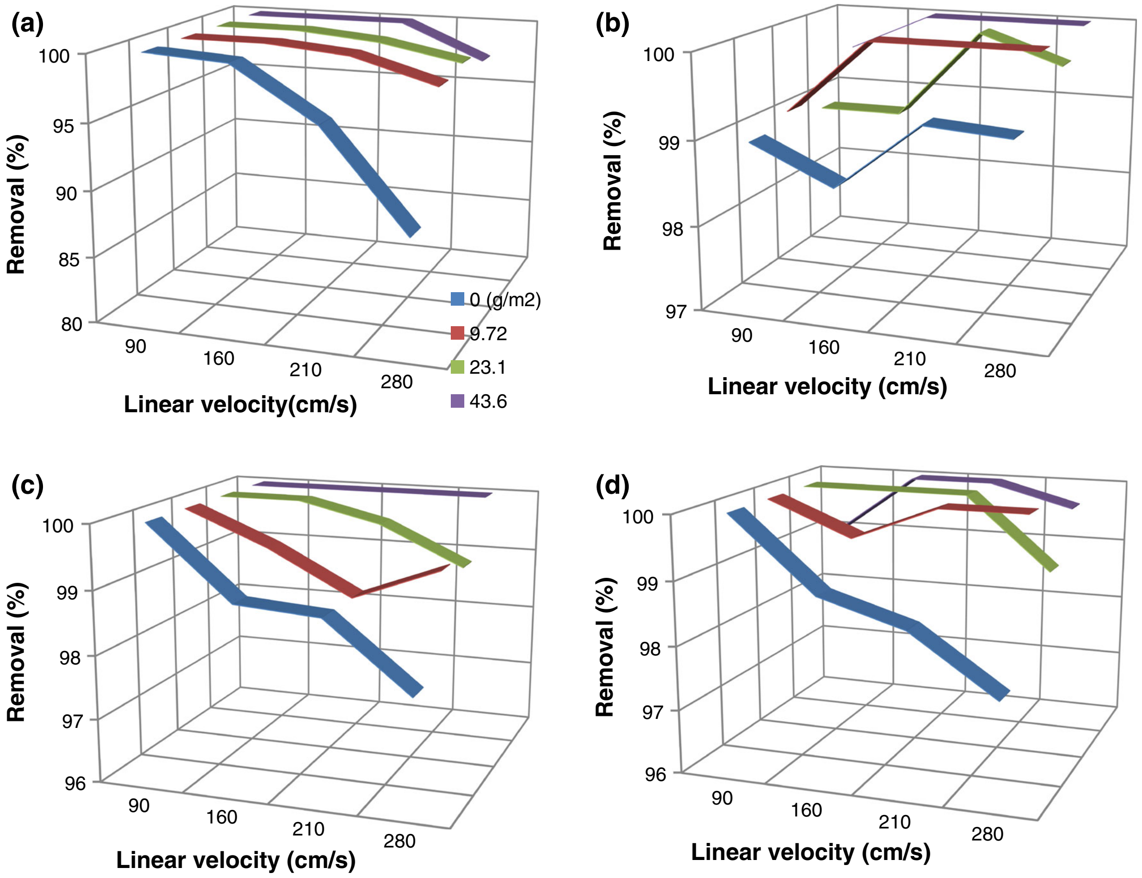

Fig. 8 BTEX removal in the presence of dust cake on ACCFs: **a** benzene, **b** toluene, **c** ethylbenzene, and **d** *m*-xylene

Table 6 Summary of selective carbon filters performance

Filter type	Contaminant	Inlet conc.	Flow rate (linear velocity)	Adsorption temp (°C)	Performance	BET (m^2/g)	References
Granular AC (packed bed)	Xylene	2400–6200 ppm	50 ml/min	40	250–317 min (breakthrough time)	500	Gupta et al. (2012)
Activated carbon cloth	Benzene	0–94,000 ppmv	Gravimetric method (101 kPa)	20–60	–	1604	Ramirez et al. (2005)
Lyocell-based ACC (H_3PO_4 activation)	Benzene Toluene	0–112,000 0–33,000 ppmv	gravimetric	25	–	1705–1229	Ramos et al. (2010)
Activated carbon fiber	VOC	2,000–10,000 ppm	0.2–1.0 slpm	35–100	70–40 min (breakthrough time)	1000–1700	Das et al. (2004)
Activated carbon filter	Benzene, Toluene	0.1–2.0 ppm	1–7 L/min	–	120–1320 min (breakthrough time)	–	Jo and Chun (2014)
AC fiber cloths or felts	Toluene	21–18,161 mg/m^3	37 cm/s	–	>120 mg/g (adsorption capacity)	–	Lorimier et al. (2005)
Activated carbon filter	Toluene, benzene, *o*-xylene, 1-butanol,	20–30 ppb	~0.5 m/s	29 (30 % Relative humidity)	90 mgVOC/gACF (adsorption capacity) 60–80 % removal	–	Sidheswaran et al. (2012)
Activated carbon cellulose filter	Benzene, Toluene, Ethylbenzene, *m*-xylene	5 ppm	90 L/min (6.7 cm/s)	~20	98.9–100 % removal (VOCs) 99.7 % removal (PM10 dust)	–	This study

BTEX gases onto the AC was quick enough to overcome the highest linear velocity, 280 cm/s. In Table 6, performance results from selective carbon filters are summarized. Although the types of filters are varied from the fabrication, they are used for the same purpose of VOCs removal including benzene and toluene gases. Among the selective filters, only this study was applied for both the VOCs and dust removal with minimal pressure loss, and showed higher than 99 % removal efficiencies for both VOCs and dust. The result proved that the filter system could be applied for the purpose of simultaneous dust and VOCs removal, and the growth of the dust cake could give a positive effect on the VOCs removal, especially when the system is operated at a high flow rate.

Conclusion

Activated carbon-impregnated cellulose filter (ACCF) was fabricated, and the capacity was evaluated for simultaneous dust and VOCs removal. As a preliminary test, an adsorption isotherm test was conducted, and the isotherm parameters were determined using activated carbon powder for BTEX gases. Comparison of BTEX gases using Langmuir and Freundlich models revealed that the adsorption of *m*-xylene onto AC was most favorable, whereas benzene was least favorable. However, the difference in adsorption capacities between the four gases was not great. Filters made with four different AC contents were used in the dust removal test and BTEX removal with and without dust cake present. In every test, four increasing linear velocity levels were applied, and the removal efficiencies were determined. All filters showed a higher than 98.97 % average dust removal performance during 4 h of the experimental period, regardless of the pore size or porosity. Filters having large pore size performed as high as 99.7 % dust removal because of the higher filter density and thickness, which kept dust particles safely within the pore structure. A high linear velocity was observed to negatively affect the benzene adsorption, but the effect was small or not observed in toluene, ethylbenzene, and *m*-xylene gases, indicating that benzene adsorption was relatively slow compared to other gases. The result was in good agreement with the adsorption isotherm parameters. The BTEX removal rates were calculated by the loading rates and removal efficiencies, which were as high as 0.33–0.37 mg/cm^2 s, at 0.0046 s of residence time between the flowing gas and the filter sheet. Rapid BTEX adsorption was allowed by the filters when fabricated with powdered AC, which provided a large surface area so that BTEX gases had enough chance and time to be adsorbed onto the AC pores. This is distinguished from conventional AC towers filled with granular AC, which is beneficial for pressure loss but provides less surface area than powdered

AC. Dust cake on the filter surface appeared to help improve BTEX removal efficiency, likely because of the interruption to the gas flow passing through the filter pores. At a high flow rate, the positive effect of the dust cake became clear with increasing mass of the dust. Overall, the ACCF showed average 99.7 % dust removal efficiency and at the same time performed 98.9–100 % BTEX removal at the 6.7 m/s linear velocity condition. The result promises excellent simultaneous dust and VOCs removal, with the filters to be used for a wide range of air quality control purposes.

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