



저작자표시-비영리-변경금지 2.0 대한민국

이용자는 아래의 조건을 따르는 경우에 한하여 자유롭게

- 이 저작물을 복제, 배포, 전송, 전시, 공연 및 방송할 수 있습니다.

다음과 같은 조건을 따라야 합니다:



저작자표시. 귀하는 원저작자를 표시하여야 합니다.



비영리. 귀하는 이 저작물을 영리 목적으로 이용할 수 없습니다.



변경금지. 귀하는 이 저작물을 개작, 변형 또는 가공할 수 없습니다.

- 귀하는, 이 저작물의 재이용이나 배포의 경우, 이 저작물에 적용된 이용허락조건을 명확하게 나타내어야 합니다.
- 저작권자로부터 별도의 허가를 받으면 이러한 조건들은 적용되지 않습니다.

저작권법에 따른 이용자의 권리는 위의 내용에 의하여 영향을 받지 않습니다.

이것은 [이용허락규약\(Legal Code\)](#)을 이해하기 쉽게 요약한 것입니다.

[Disclaimer](#)

보건학석사 학위논문

**Removal Efficiency of Volatile Organic Compounds
using Different Types of Activated Charcoal
in the Fume Hood**

흡후드에서 활성탄 형태에 따른
휘발성 유기화합물 제거에 관한 연구

2015 년 8 월

서울대학교 보건대학원
환경보건학과 산업보건전공

이 상 아

ABSTRACT

Removal Efficiency of Volatile Organic Compounds using Different Types of Activated Charcoal in the Fume Hood

Sang ah Lee

Department of Environmental Health Sciences

Graduate School of Public Health

Seoul National University, Korea

Advisor Chungsik Yoon, Ph.D., CIH

Objective In laboratories, fume hoods are used to handle most chemicals, with the goal of protecting the health of workers and preventing the deterioration of indoor air quality. However, there is no obligation to install air purifiers in fume hood systems in Korea. As a result, harmful vapors and gases from fume hoods can be emitted directly into the atmosphere through the exhaust duct. This study compared the breakthrough time of three different types of activated charcoal adsorbent, and evaluated their capacity to adsorb volatile organic compounds (VOCs) within a local exhaust ventilation (LEV) system.

Methods Acetone was used as a surrogate for polar volatile organic compounds (VOCs) and toluene was used as a surrogate for non-polar VOCs. Both were tested against three different kinds of adsorbent: an activated carbon fiber (ACF), granular activated carbon (GAC), and an ACF + GAC mixture.

Approximately 10 and 50 ppm of the tested solvents were evaporated by a syringe pump in a hood, and the breakthrough time was determined by comparing the concentrations measured by a real-time monitor before and after adsorption. The adsorbents were installed 5 m from the hood as part of the LEV system.

Results The breakthrough time for toluene was on average two times longer (>1.1 - 2.8 times) than for acetone for all three adsorbents. When the 50 ppm concentration was used, the breakthrough time was 3.1 times shorter (>1.3 - 4.4) than when the 10 ppm concentration was used. The ACF + GAC mixture had the longest breakthrough time for both acetone and toluene regardless of the concentration used, followed by GAC and then ACF. The breakthrough time was reduced by 7.4 - 9.1 times when the length of the ACF + GAC was shortened from 14 to 7 cm. The adsorption efficiency for acetone and toluene was 75.6 and 80.7% of the total evaporated amount before breakthrough, respectively. The ACF + GAC mixture was proven to have a long breakthrough time and the adsorption rate was relatively stable until breakthrough.

Conclusions Among the three types of adsorbent the ACF + GAC mixture was found to have the longest breakthrough time for both toluene and acetone. An ACF + GAC mixture is therefore considered suitable for use within a laboratory LEV system to improve air quality.

Keywords: Fume hood, Activated carbon, adsorbent, VOCs

Student Number: 2013-21826

Contents

ABSTRACT	1
Contents	4
List of Tables	5
List of Figures	6
1. Introduction	7
2. Materials and method	9
2.1. Study design	9
2.2. Activated Carbon Adsorption	11
2.2.1. VOCs vaporization	13
2.3. Sampling method	15
2.4. Calculation and statistics	17
3. Results	18
3.1. Comparison of adsorbents	18
3.2. Comparison of adsorption length	23
3.3. Comparison of the breakthrough curve	25
3.3.1. Breakthrough curve for acetone	25
3.3.2. Breakthrough curve for toluene	27
3.4. Adsorption capacity	29
4. Discussion	33
5. Conclusions	36
6. References	37

List of Tables

Table 1. General Information of Adsorbent type	12
Table 2. Characteristics of the organic vapors used as adsorbates in this study	13
Table 3. Experimental conditions of the target organic compounds	14
Table 4. The condition of gas chromatography for analysis of acetone and toluene	16
Table 5. The capacity of activated charcoal adsorbent	30
Table 6. The percentage of adsorption amounts at each activated charcoal across times.	32

List of Figures

Figure 1. Outline of the sampling design	9
Figure 2. A schematic diagram of experimental LEV system.....	10
Figure 3. Real time monitoring by ppbRAE 3000 with (a) acetone 10 ppm, (b) toluene 10 ppm	20
Figure 4. Real time monitoring by ppbRAE 3000 with (a) acetone 50 ppm, (b) toluene 50 ppm	22
Figure 5 Change in breakthrough curves of ACF + GAC with packing lenth for acetone 50 ppm and toluene 50 ppm	24
Figure 6. Comparison of the breakthrough curve for 3 types adsorbent at acetone	26
Figure 7. Comparison of the breakthrough curve for 3 types adsorbent at toluene	28

1. Introduction

Laboratories are used for research and education in engineering and the natural, applied, and medical sciences. In laboratories, most chemicals are handled in fume hoods, which are installed as part of the local exhaust ventilation (LEV) system to protect the health of workers and to prevent the deterioration of indoor air quality. The LEV system vacuums air containing various hazardous chemicals in the laboratory and vents it into the atmosphere through rooftop exhaust stacks (Smith, 2004). Korean universities have an estimated 27,851 science and engineering laboratories (The Ministry of Education, Science, and Technology, 2009). In Korea, there is currently no obligation to install air purifiers in laboratory LEV systems. As a result, harmful agents from laboratory fume hoods may be emitted directly into the atmosphere through the exhaust duct. High VOC concentrations have been reported in laboratory buildings due to the high levels of chemical use and lack of purification systems in the local exhaust ventilation system (Park et al., 2014). It is necessary to install air purifiers in fume hood exhaust systems to protect the atmospheric environment from emissions that may reduce outdoor air quality (Park et al., 2014).

In most science and engineering laboratories, different amounts of various chemicals, including organic materials and acidic and basic materials, are used as solvents or solutes (Ashford and Miller., 1998). Volatile organic compounds (VOCs) produced by the use of organic solvents may have a detrimental effect on both human health and the environment. VOCs in the atmosphere can react with ultraviolet rays and contribute to tropospheric photochemical ozone formation over wide areas because of their slow rate of oxidation. They can also indirectly

influence the depletion of stratospheric ozone and contribute to global warming (John et al., 1999). These contaminants may also have significant effects on the eyes and nose, and long-term exposure may even cause cancer (Huang et al., 2002).

The effective control, removal, and emission reduction of VOCs are important for environmental protection. Several techniques have been developed and applied for VOC abatement: absorption, adsorption, condensation, and thermal or catalytic oxidation. Adsorption appears to be the most efficient method for the complete removal of VOCs. Various adsorbents have been used for VOC abatement, including activated carbons, zeolites, silica, and polymers. Of these materials, activated carbon has the most promise due to its low cost and versatility for different compounds (Guillaume B. Bour et al., 2015).

This study compared the breakthrough time of three different types of activated charcoal adsorbent, and evaluated their capacity to adsorb VOCs within an LEV system.

2. Materials and method

2.1. Study design

This study was conducted in a pilot local exhaust ventilation (LEV) system using three types of activated carbon adsorbents. The sampling design is shown in Figure 1.

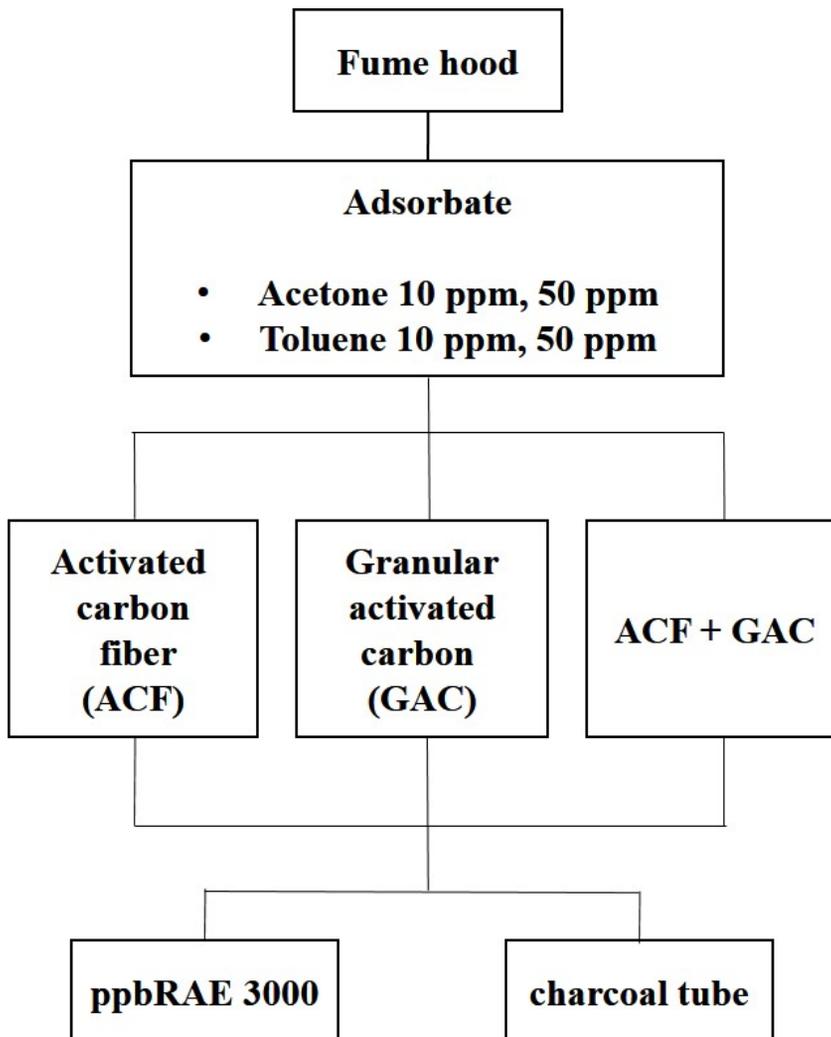


Figure 1. Outline of the sampling design.

A local exhaust ventilation (LEV) system was created for this study, consisting of a hood, duct, fan, and exhaust stack (Figure 2). The total length and height of the LEV system were 2 m and 7 m, respectively. The adsorbate enclosing hood had side-by-side doors with length, width and height of 500 mm, 1000 mm and 550 mm respectively. The system used an inverter motor that could adjust the flow rate using a fan.

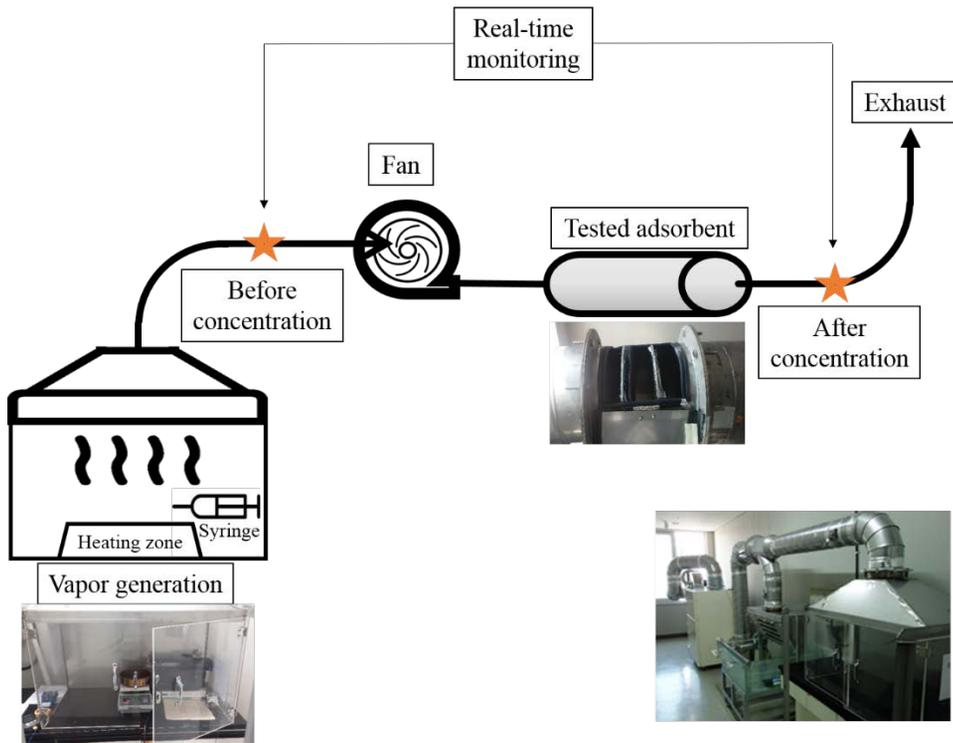


Figure 2. A schematic diagram of experimental LEV system.

Each photo was presented under the subunit diagram.

An adsorbing unit measuring 280 cm² in area with an adjustable length of 21 cm was installed near the exhaust. This area was installed 5 m from the hood so that the concentration of VOCs could be compared. Adsorbents can be inserted into this airtight device through a door on the upper surface.

2.2. Activated Carbon Adsorption

The activated carbon adsorbents used in this study included Activated Carbon Fiber (ACF), Granular Activated Carbon (GAC), and a combination of the two (ACF+ GAC). A 14-cm length of the adsorbents was separately tested in the device. Because ACF+GAC was efficient using 14-cm length test, an additional test using a 7-cm length was conducted. General details on different adsorbents used in this study can be found in Table 1.

Table 1. General Information of Adsorbent type

Absorbent	Type	Length (cm)	Cross section area (cm ²)	Total Volume (cm ³)	Weight (g)	Particle Size (mm)	Total surface Area ¹⁾ (m ²)
Activated Carbon Fiber (ACF)	Fiber	14	314	4396	261	0.01 ~ 0.03	443,700
Granular Activated Carbon (GAC)	Granular	14	314	4396	6700	4 ~ 8	6,700,000
ACF + GAC	ACF + GAC	14	314	4396	3495	X	3,646,500
ACF + GAC	ACF + GAC	7	314	2198	1780	X	1,798,250

¹⁾ Specific surface area of ACF, GAC was 1700 m²/g, 1000 m²/g, respectively (Yang et al., 2008). Total surface area of ACF+GAC was calculated using amount of each component and specific surface area.

2.2.1. VOCs vaporization

We chose the volatile organic compounds (VOCs) acetone and toluene as the adsorbates in this study. We used acetone as the polar substance and toluene as the non-polar substance VOC. Table 2 is a summary of the physical properties of the selected substances

Table 2. Characteristics of the organic vapors used as adsorbate in this study

VOCs	Formula	Exposure limit (ppm)*	Molecular weight (g/mol)	Boiling point (°C)	Density	Vapor pressure (mmHg at 20 °C)
Acetone	C ₃ H ₆ O	500	58.08	56.5	0.78	266
Toluene	C ₆ H ₅ CH ₃	50	92.13	110.8	0.87	22

*Korea Occupational Safety & Health Agency (KOSHA) TWA

We chose the concentration of the substances based on concentration measured in laboratory buildings (Part et al., 2014) that was 10 ppm as the low and selected 50 ppm as the high concentration. The evaporation rate of acetone and toluene was adjusted to generate constant concentrations in the LEV system. The total volume of substances generated is shown in Table 3.

Table 3. Experimental conditions of the target organic compounds

VOC s	Concentration (ppm)	Injection Volume (ml/min)	G (m ³ /h)
Acetone	10	0.196	0.004
Acetone	50	0.980	0.019
Toluene	10	0.278	0.004
Toluene	50	1.390	0.019

As shown in Figure 2, substances were generated using a 30-mL syringe and syringe pump (Sage TM Pump model M365, USA) and a heated aluminum plate, which vaporized the acetone and toluene and allowed the VOCs to flow into the pilot local exhaust ventilation system.

The smoke tester and velocity meter (Veloci-CALC, TSI Inc., USA) was used to check air flow into the duct and no leakage outside through the LEV system. This study incorporated an analysis of computational fluid dynamic (CFD) modeling (ANSYS CFD 13.0, ANSYS, USA). The CFD simulation is included in the appendix.

2.3. Sampling method

To determine the breakthrough time, the concentration of VOCs at before and after of adsorbent was measured by a real time monitor (ppbRAE 3000, RAE systems Inc., USA). Real time samples were collected at 1 min intervals during the sampling period.

Prior to sampling, the ppbRAE 3000 monitor was calibrated by a calibration gas (isobutylene) with a known concentration of 10 ppm supplied by the manufacturer and zeroed with an adsorbent tube attachment. Simultaneous monitoring with real-time sampling and active sampling using adsorbent tube was performed to evaluate the accuracy of real time monitor.

We compared the results of active sampling considered as a standard method and real time sampling method. So at the same point with real time sampling, acetone and toluene were measured according to a standard NIOSH method using a charcoal tube (cat. no. 226-01, SKC Inc., USA) and a low-volume pump (LFS-114, Gillian, USA), with a constant flow rate of about 0.2 L/min (NIOSH method 1501, 2003). After sampling, all samples were sealed using aluminum foil to protect against light exposure and kept at a temperature of less than 4 °C until desorption.

Before active sampling analysis, each charcoal tube was broken and the front section and back section were transferred to different vials, respectively. The VOCs adsorbed charcoal tubes were extracted using 1ml of carbon disulfide for 30 minutes. After that, samples analyzed using gas chromatography (HP-6890N, Agilent Technologies, USA) with flame ionization detector and auto sampler (HP 18593B, Agilent Technologies, USA). Equity™ -1/fused silica capillary column

was used for analysis which has 30.0 m in length, 0.25 mm in inner diameter 1 μm in film thickness (28049-U, Supelco Inc., USA). GC was programmed to maintain the initial temperature at 45 °C for 3 minutes, and then 10 °C/min to 200 °C for 10minutes. GC-FID analysis conditions were showed Table 4.

Table 4. The condition of gas chromatography for analysis of acetone and toluene

The condition of analytical instrument	
Instrument	Gas chromatography Flame Ionization Detector (HP-6890N, Agilent Technologies, USA)
Column	Fused silica capillary column (30m x 0.25mm x 1.0 μm film thickness, Supelco, USA)
Injector Temperature	200 °C
Injection Volume	2 μl
Split ratio	Splitless
Carrier gas	Helium (99.99% purity)
Detector Temperature	250 °C
Oven condition	Initial 45 °C to 100 °C at 10°C/min to 200 °C at 10 °C/min

2.4. Calculation and statistics

The adsorbent life time was evaluated by C/C_0 analysis, where C_0 represents the inflow concentration of acetone and toluene in the fume hood, and C represents the discharge concentration. We defined breakthrough time as the time when the exhaust concentration was 50% of the before concentration. A correlation analysis was conducted to assess the relationship between the active sampling result and the real-time sampling result.

The total amount of acetone and toluene adsorbed before breakthrough time was calculated to evaluate the adsorption capacity of the three different types of activated charcoal using real-time monitoring data. Detailed equations are below.

$$TEA (g) = C_0 \times A \times V \times Bt \times 1000 \quad (1)$$

$$TDA (g) = C \times A \times V \times Bt \times 1000 \quad (2)$$

$$TAA (g) = TEA - TDA \quad (3)$$

$$\text{Adsorption Efficiency (\%)} = \frac{TDA}{TEA} \times 100 \quad (4)$$

Where, TEA: Total Evaporation Amount (g), TDA: Total Discharge Amount (g), TAA: Total Adsorption Amount (g), C_0 : inflow concentration (mg/m^3), A : Cross section area (0.0280 m^2), V : air velocity in duct ($0.1\text{m}/\text{sec}$), Bt : Breakthrough time (sec).

Statistical analyses were performed using the SAS 9.2 (SAS Institute Inc., USA). Correlation analysis was developed to identify associations between the real time sampling result and active sampling result. A graphical representation was generated using Sigma Plot 10.0 (Systat Software Inc., USA).

3. Results

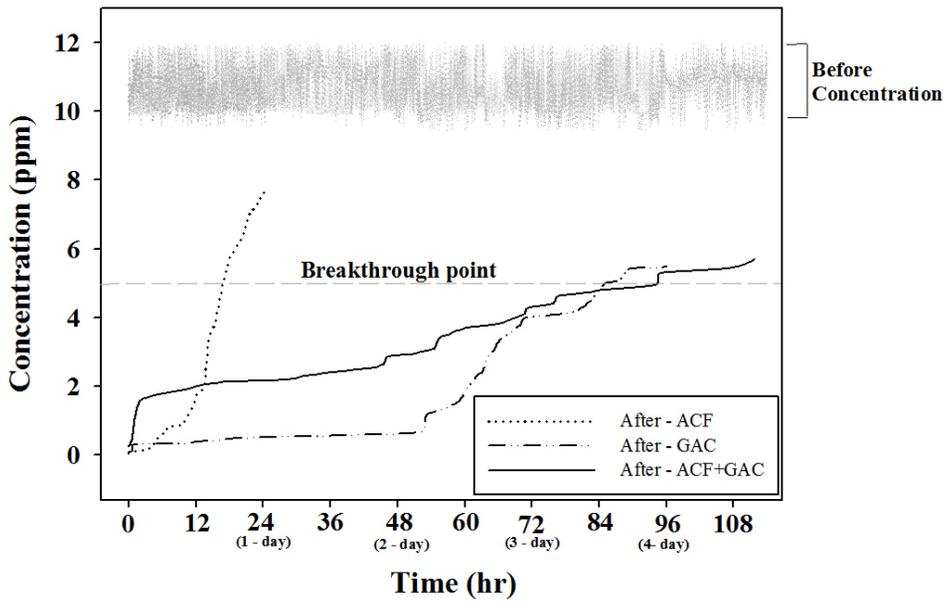
3.1. Comparison of adsorbents

The active and real-time sampling times using ACF showed correlations of 0.998 and 0.992 for acetone and toluene, respectively. Therefore, we determined that only real-time sampling was necessary to ensure reliable results.

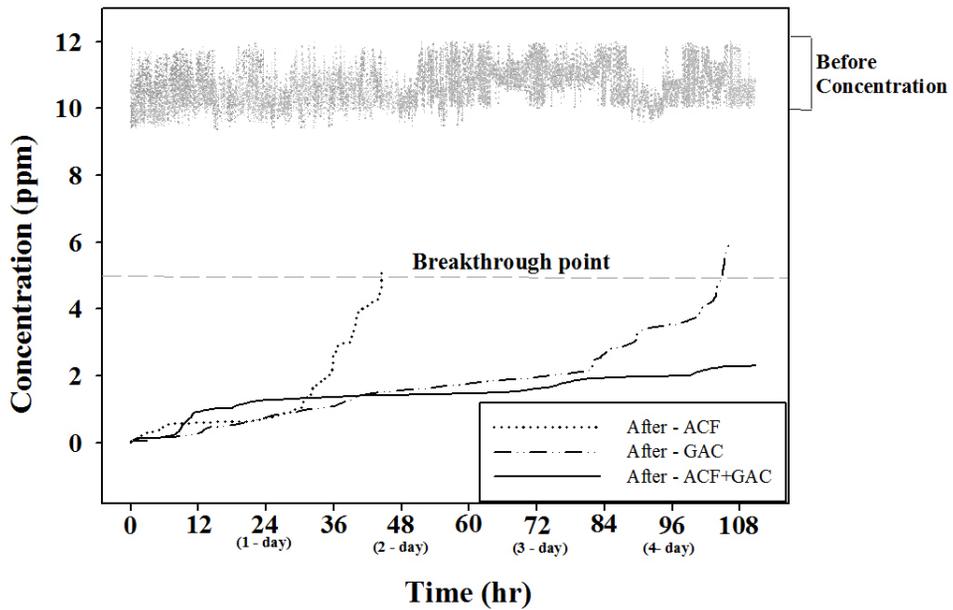
Figure 3 (a) shows the real-time monitoring of acetone (10 ppm) using ppbRAE 3000, where the “before concentration” represents acetone generation in the fume hood. Adsorption by ACF increased sharply at 14.1 hours and reached the breakthrough point at 16.6 hours. Adsorption by GAC increased sharply at 50.1 hours and reached the breakthrough point at 85.2 hours. In contrast to ACF, the GAC breakthrough curve of outlet concentration was consistently maintained at under 1 ppm until 50.1 hours, when there was an abrupt increase in the concentration adsorbed up until the breakthrough point. The concentration adsorbed by ACF+GAC increased steadily until the breakthrough point at 94.4 hours. ACF+GAC demonstrated a synergy of the trends seen for ACF and GAC alone, allowing for more constant adsorption over a longer period.

Figure 3 (b) shows the real-time monitoring for toluene (10 ppm) by ppbRAE 3000. The three adsorbents maintained similar adsorption patterns until 34.9 hours. The toluene concentration adsorbed by ACF increased sharply at 34.9 hours and reached the breakthrough point at 44.4 hours. The toluene concentration adsorbed by GAC increased sharply at 96.1 hours and reached the breakthrough point at 105.1 hours. The toluene concentration adsorbed by ACF+GAC did not reach the

breakthrough point within our experimental time (108 hours) and demonstrated stable adsorption over 108 hours.



(a)

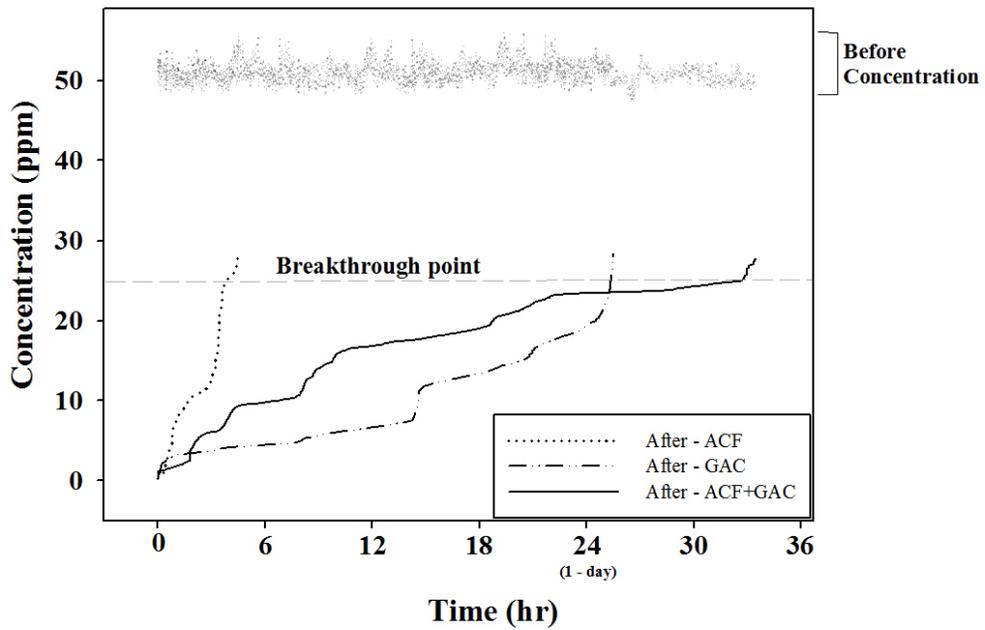


(b)

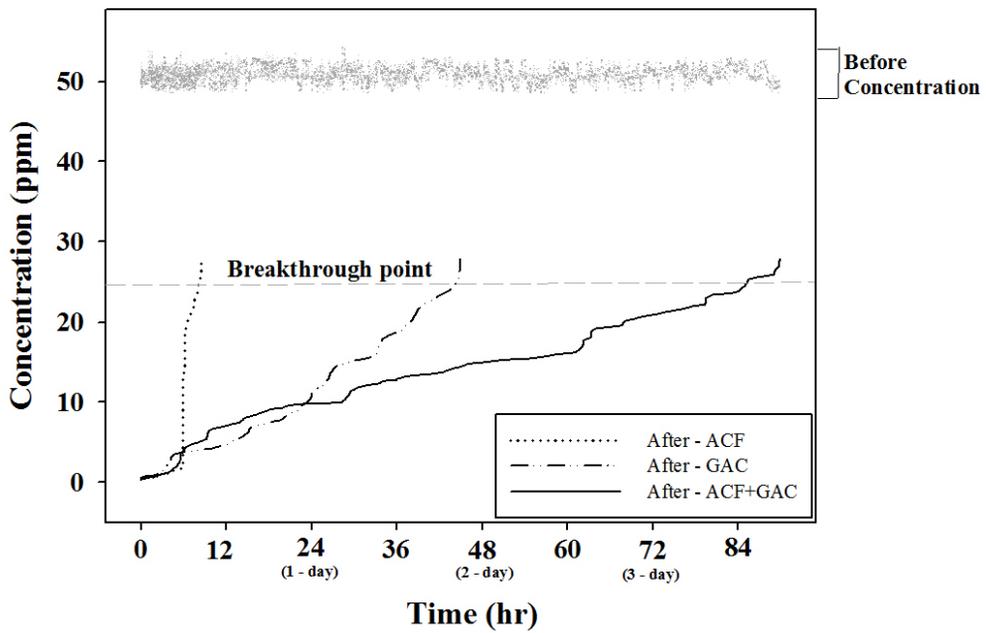
Figure 3. Real time monitoring by ppbRAE 3000 with (a) acetone 10 ppm, (b) toluene 10 ppm, where before concentration represents the acetone and toluene generation in the fume hood.

Figure 4 (a) shows the breakthrough curves for the three types of adsorbents using an acetone concentration of 50 ppm. We found that ACF+GAC required the longest time to reach the breakthrough point. ACF reached the breakthrough point at 3.8 hours. ACF showed a sharp increase in concentration over a short period. GAC reached the breakthrough point at 85.2 hours. In contrast to ACF, GAC showed stable adsorption until 25.3 hours, before an abrupt adsorption decline near the breakthrough point. ACF+GAC reached the breakthrough point at 32.7 hours.

Figure 4 (b) shows the real time monitoring by ppbRAE 3000 for toluene with a concentration of 50 ppm. The slope of the ACF breakthrough curve was steep, reaching the breakthrough point at 10.5 hours. The GAC breakthrough curve increased consistently, with a breakthrough point at 44.5 hours. For ACF+GAC, the concentration of toluene gradually increased and reached the breakthrough point at 85.3 hours.



(a)



(b)

Figure 4. Real time monitoring by ppbRAE 3000 with (a) acetone 50 ppm (b) toluene 50 ppm, where before concentration represents the acetone and toluene generation in the fume hood.

3.2. Comparison of adsorption length

To elucidate the effect of adsorbent length on the breakthrough point and adsorption capacity, the experiments were conducted using 7 and 14 cm lengths of the adsorption material ACF+GAC and 50 ppm concentrations of acetone and toluene. As shown in Figure 5, the breakthrough times for acetone using 7 and 14 cm lengths of adsorbent were at 4.4 and 32.7 hours, respectively. The breakthrough times for toluene using 7 and 14 cm lengths of adsorption material were at 9.4 and 85.3 hours, respectively. We observed that the breakthrough time changed depending on the length of the activated charcoal adsorbent. As adsorption length decreased from 14 cm to 7 cm, the breakthrough time decreased 7.4 - 9.1 times, and the breakthrough curve showed a steeper slope.

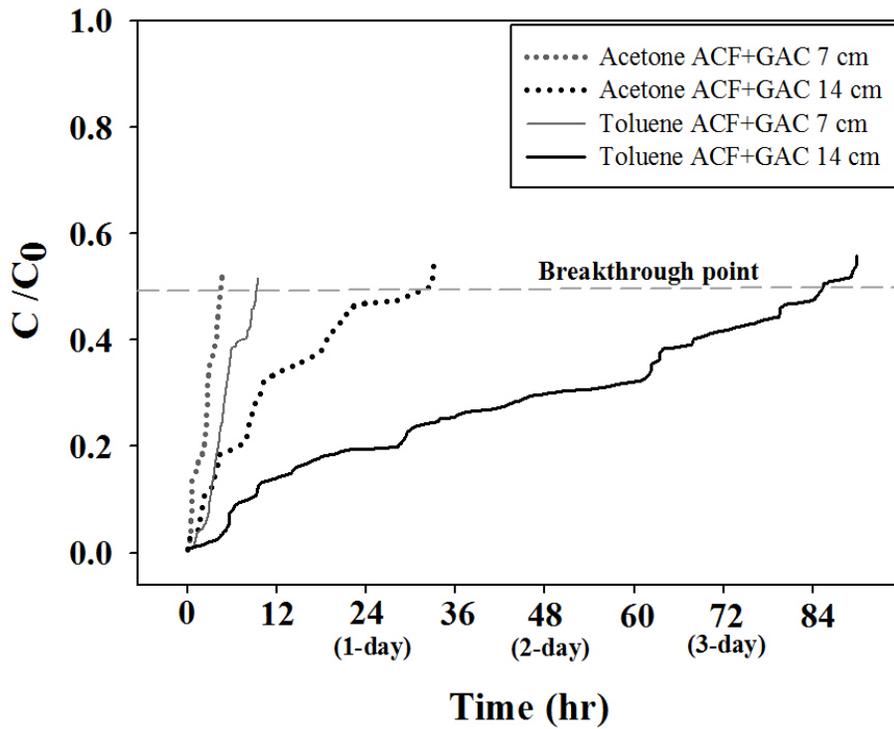


Figure 5. Change in breakthrough curves of ACF+GAC with packing length for acetone 50 ppm and toluene 50 ppm, where C is the outlet concentration, and C_0 is the before concentration.

3.3. Comparison of the breakthrough curve

We calculated the adsorption capacities of the different types of adsorbent using C/C_0 . For a given concentration, a longer breakthrough time indicated greater adsorption capacity.

3.3.1. Breakthrough curve for acetone

The breakthrough curves for the adsorption of acetone concentrations of 10 ppm and 50 ppm by the different adsorbents are shown in Figure 6. The breakthrough time over ACF was 16.6 hours for acetone at a concentration of 10 ppm and 3.6 hours at a concentration of 50 ppm. The ACF breakthrough curve was the steepest of all three adsorbents. The GAC breakthrough time was 85.2 hours at an acetone concentration of 10 ppm and 25.3 hours at a concentration of 50 ppm.

The ACF+GAC breakthrough time was 96.3 hours at an acetone concentration of 10 ppm and 32.6 hours at a concentration of 50 ppm. ACF+GAC had the longest breakthrough time of the three materials at both high and low concentrations of acetone. In general, it was clear that the breakthrough time decreased as the before concentration increased for all adsorbents. Moreover, the breakthrough curves became steeper as the before concentrations increased.

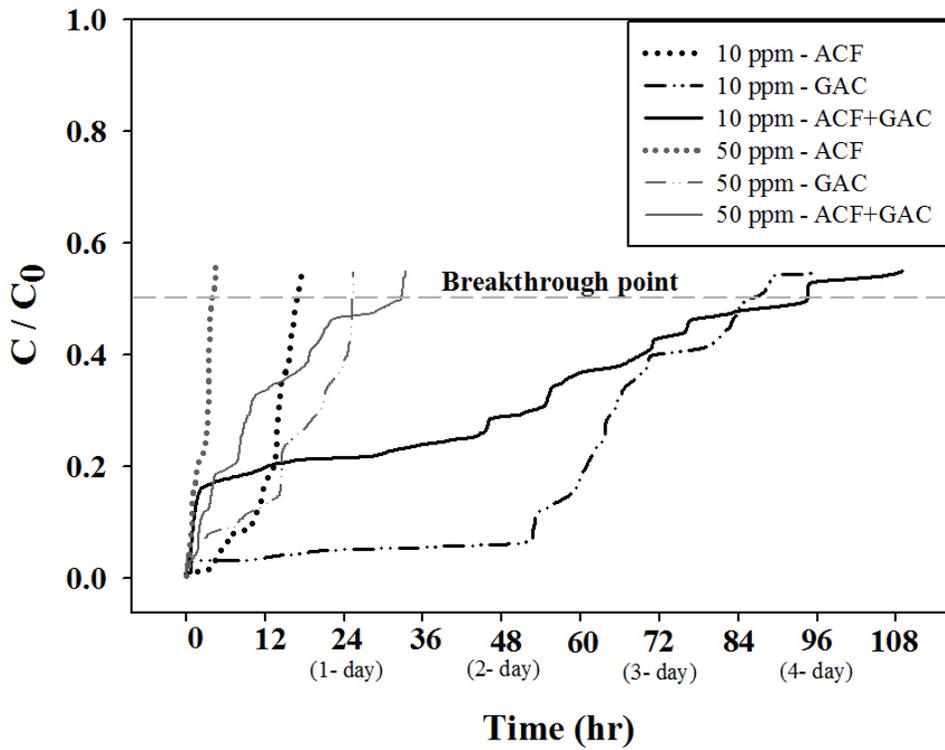


Figure 6. Comparison of the breakthrough curve for three types of adsorbent for acetone, where C is the outlet concentration, and C_0 is the before concentration.

3.3.2. Breakthrough curve for toluene

Figure 7 shows the adsorption breakthrough curves for the three adsorbents with high and low toluene concentrations. The breakthrough curve for ACF increased steeply for both toluene concentrations. The breakthrough times were 44.6 hours and 10.5 hours at toluene concentrations of 10 ppm and 50 ppm, respectively. For GAC, as the before concentration of toluene increased from 10 ppm to 50 ppm, the breakthrough time decreased from 96.1 hours to 44.5 hours. For ACF+GAC, the breakthrough point was not reached during the experimental time (108 hours) when the before concentration of toluene was 10 ppm, whereas it was reached at 85.3 hours with a before concentration of 50 ppm. As shown in Figure 7, a higher before concentration resulted in a shorter breakthrough time and a steeper breakthrough curve slope.

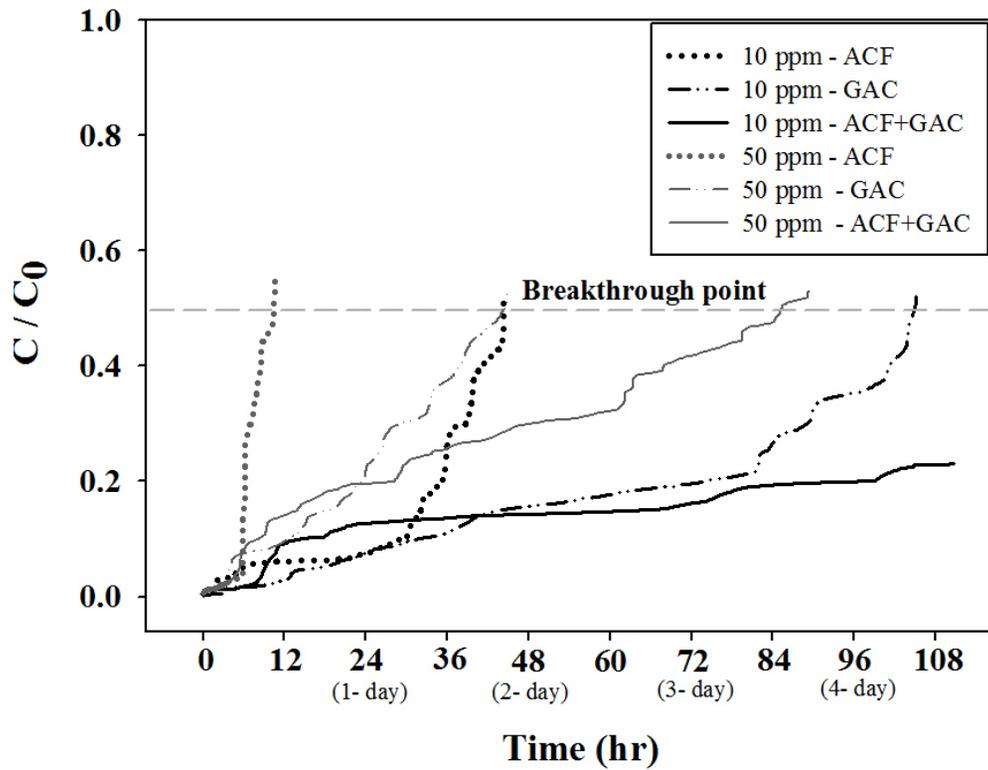


Figure 7. Comparison of the breakthrough curve for three types of adsorbent for toluene, where C is the outlet concentration, and C_0 is the before concentration.

3.4. Adsorption capacity

Table 5 gives the ACF, GAC, and ACF+GAC adsorption capacities up to the breakthrough time. We calculated the total evaporation, total discharge, and total adsorption amounts, and adsorption efficiency, defined as the total evaporation amount divided by the total adsorption amount, using equations (1) - (4). As shown in Table 5, both breakthrough time and adsorption efficiency decreased with increasing inlet concentration for all adsorbent materials. The adsorption efficiency was $8.6 \pm 4.34\%$ lower at an inlet concentration of 50 ppm than at 10 ppm. The adsorption efficiencies of acetone and toluene were $75.6 \pm 9.4\%$ and $80.7 \pm 5.3\%$, respectively, without statistical significance ($p = 0.33$).

Table 5. The capacity of activated charcoal adsorbent

Adsorbent	Length (cm)	Substance	Concentration (ppm)	Breakthrough time (h)	Total Evaporation Amount (g)	Total Discharge Amount (g)	Total Adsorption Amount (g)	Adsorption efficiency (%)
ACF	14	Acetone	10	16.6	740.65	95.98	644.67	87.04
			50	3.8	852.31	173.86	678.44	79.60
		Toluene	10	44.4	3139.11	415.22	2723.89	86.77
			50	10.5	3714.58	650.68	3063.90	82.48
GAC	14	Acetone	10	85.2	3805.23	578.47	3226.76	84.80
			50	25.3	5657.23	1080.01	4577.22	80.91
		Toluene	10	105.1	7436.23	1267.31	6168.92	82.96
			50	44.5	15742.72	3496.66	12246.06	77.79
ACF+GAC	14	Acetone	10	96.3	4216.87	1312.97	2903.90	68.86
			50	32.7	3236.35	1276.38	1959.97	60.56
		Toluene	10	> 108	> 7083.63	> 983.24	> 6100.39	> 86.12
			50	85.3	30182.39	8216.01	21966.39	72.78
ACF+GAC	7	Acetone	50	4.4	1058.2	227.63	780.57	74
	7	Toluene	50	9.4	3333.5	790.28	2543.22	76

Percentage adsorption values (defined as adsorption amount divided by evaporation amount) per 12 hours interval were calculated based on lifetime curves with modification of equations (1) - (4) and are listed in Table 6. For all adsorbates, percentage adsorption values decreased with time, and were greater for toluene than for acetone. We found that ACF+GAC had the greatest percentage adsorption for a toluene concentration of 10 ppm, followed by GAC at 10 ppm toluene. In general, the non-polar substance toluene resulted in a higher adsorption percentage at a given time than the polar substance acetone, regardless of the type of activated charcoal adsorbent.

Table 6. The percentage of adsorption amounts at each activated charcoal across times

Adsorbent	Adsorbate	Concentration (ppm)	The percentage of adsorption amounts (%) at a given time (hours)									
			1 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr	108 hr
ACF	Acetone	10	99	93	48	23				< 23		
		50	94	52	44	< 44						
	Toluene	10	99	95	94	87	59	49			< 49	
		50	99	71	44				< 44			
GAC	Acetone	10	97	97	95	95	94	89	69	58	47	
		50	95	90	73	45						
	Toluene	10	100	98	95	91	86	83	81	79	68	56
		50	99	94	85	70	53	44		< 44		
ACF+GAC	Acetone	10	95	82	79	77	74	68	61	54	51	
		50	97	79	60	52						
	Toluene	10	99	97	89	87	86	85	85	82	80	78
		50	99	92	82	78	72	69	62	55	51	

4. Discussion

We assessed the breakthrough time of three types of activated carbons including, ACF, GAC, and ACF+GAC. Carbon products are widely used in the absorptive industry today because of carbon's many useful qualities, including its sponge-like quality, light weight, high strength, and temperature tolerance, as well as the adjustable thermal and electrical conductivity (Chong et al., 2006).

This study suggests that it is possible to reduce the concentration of exhaust VOCs simply by attaching an activated carbon adsorbent to the outlet of the fume hood. Among the adsorbents used in the study, ACF+GAC had the longest breakthrough time, and this material also had high adsorption efficiency. As shown in Table 6, the non-polar material toluene showed a longer breakthrough time and better absorption capacity than did the polar material acetone. These results are similar to those reported in a previous study (Lee et al., 2008). These results may be related to differences in the molecular weights of the materials, as the higher molecular weight of toluene may have resulted in slower diffusion into the adsorbent pores and therefore slower breakthrough times (Son et al., 2006). The adsorption characteristics of toluene have been well studied. Toluene is non-polar and has larger molecules that adsorb better than polar and smaller molecules do. Additionally, toluene is an aromatic compound that has high affinity with carbon and is therefore highly adsorbed to the activated carbon (Son et al., 2006). As the before concentration of acetone and toluene increased, the breakthrough time decreased and the slopes of the breakthrough curves became steeper (Figure 6 and 7).

Many types of GAC are activated by different carbon particle sizes. In this study, we used the 4*8 mesh that is commonly used in atmospheric studies. In a previous study, it was found that adsorption differences decreased relative to the activated carbon particle size and that the total adsorption amount was not proportional to the size of the adsorptive surface area (G. McKay et al., 1985). Smaller particle sizes are associated with a larger pressure load, which should be considered when choosing GACs.

The slope of the breakthrough curve for GAC was more gradual than that for ACF. It has been suggested that ACF have a greater and quicker adsorption capacity relative to GAC because it consists of micro pores (Kim et al., 1993).

Within our novel LEV system, adsorbent concentrations fluctuated within the 9- to 12-ppm and 47- to 54-ppm ranges. This relatively stable before concentration was acquired by using syringe pump as a mass flow controller and constant air flow into the LEV (Noh et al., 2008).

Adsorbent length increased the breakthrough time. It has been suggested that as the before concentration was increased, MTZ (mass transfer zone) was increased. Adsorption capacity, MTZ, and LUB (length of unused bed) are important factors related to adsorption ability that can be obtained from breakthrough curves. Therefore, as the LUB becomes greater, the efficiency of the adsorption bed is decreased (Lee et al., 2008). This result may be explained by the fact that as the before concentration increased, the partial pressure also increased, resulting in faster pore diffusion in the activated charcoal (Baek et al., 2011).

This study had several limitations that should be addressed in future research. First, this study did not consider the effect of temperature, humidity and air velocity in a LEV. This study was conducted at 28 ± 4 °C and at $32 \pm 4\%$ humidity. When the temperature of the adsorbent is increased, the breakthrough times are faster because the diffusion coefficient also increases (Baek, 2011). Furthermore, at higher humidity, shorter breakthrough times occur because water molecules and VOC molecules may compete to be adsorbed to the adsorbent (Noh. et al., 2008). It was reported that breakthrough times increase as the flow rate increases. The mass transfer coefficient and pore diffusion also increase with increased flow rate, resulting in a short MTZ (Baek et al., 2011). These results can be applied to developing designs for an adsorbent attachment in fume hood outlets that can assist with air purification.

As the exhaust stacks of most fume hoods are installed on laboratory building rooftops or windows, it is possible that hazardous substance emissions released in local environment could re-enter the building and effect indoor air quality. This study examined the usefulness of different types of activated carbon in removing VOCs. Thus, the results of this study could inform air quality improvement protocols with regard to the types of activated carbon that should be attached to the exhaust duct of fume hoods.

5. Conclusions

This study examined the adsorption of VOCs on activated carbon adsorbents placed in front of the exhaust of a fume hood. We used ACF, GAC, and ACF+GAC activated carbon as adsorbents. Acetone as was selected as the polar VOC, and toluene as the non-polar VOC. Both VOCs were tested using concentrations of 10 and 50 ppm in the fume hood.

- The breakthrough time was determined when the outlet concentration reached 50% of the before concentration. We calculated the adsorption efficiency and percentage of adsorption amount per each twelve hours interval.
- The breakthrough time with the ACF+GAC material was longest for both acetone and toluene at the test concentrations (10 and 50 ppm).
- The adsorption efficiency for both acetone and toluene was highest with the ACF+GAC material.
- The breakthrough times were longer and adsorption efficiency were higher for toluene than for acetone when adsorbed to each of the materials.

Overall, among the three types of adsorbent tested, the ACF+GAC was found to be the best adsorbent for both toluene and acetone. Therefore, to reduce the VOC emission from laboratory fume hood, the ACF+GAC could be used.

6. References

Ashford N. A., Miller C. S., Low-Level Chemical Exposures: A Challenge for Science and Policy. *Environmental Science and Technology* 1998, 32 (21), 508A-509A.

Baek, G.H., Kim J.S., Jang H.T., Cha W.S., Adsorption/desorption Properties of ACF in Toluene and MEK with Operation condition. *Journal of the Korea Academia-Industrial cooperation society* 2011, 12(6), 2898-2903.

Chen C., Kennel E. B., Stiller A. H., Stansberry, P. G., Zondlo, J. W., Carbon foam derived from various precursors. *Carbon* 2006, 44(8), 1535-1543.

Constable J. V. H., Guenther A. B., Schimel D. S., Monson R. K. Modelling changes in VOC emission in response to climate change in the continental United States. *Global Change Biology* 1999, 5, 791-806.

G. McKay, M. J. Bino, A.R altamemi. The adsorption of various pollutants from aqueous solutions on to activated carbon. *Water Research* 1985, 19(4), 491-495.

Guillaume B. B., Oliver B. Jonathan S., Igor Y., Lioubov K.M. Activated carbon fibers for efficient VOC removal from diluted streams: the role of surface functionalities. *Springer Science&Business Media New York* 2015, 21:255-264.

Huang Z. H, Kang F., Zheng Y. P, Yang J. B, Liang K. M. Adsorption vapor on viscose rayon-based activated carbon fibers. *Carbon* 2002, 40(8), 1363-1367.

Jamie P. MacDonald. Strategic sustainable development using the ISO 14001 Standard. *Journal of Cleaner Production* 2005, 13(6), 631-643.

Jo Anne G. Balanay, Alfred A. Bartolucci, & Claudiu T. Lungu., Adsorption Characteristics of Activated Carbon Fibers (ACFs) for Toluene: Application in Respiratory Protection., *Journal of Occupational and Environmental Hygiene* 2015, 11(3), 133-143.

Kim H.S., Park S.H., Adsorption Characteristics of Activated Carbon Fiber. *Journal of Taejon National University of Technology* 1993, 10(2), 283-291.

Kim S.G., Chang Y.R., Adsorption Characteristics of Toluene in the Adsorption Bed Packed with Activated Carbon Fiber. *Journal of Korean Society for Atmospheric Environment* 2008, 24(2), 220-228.

Lee D.G., Kim J.H., Lee C.H., Adsorption and thermal regeneration of acetone and toluene vapors in dealuminated Y-zeolite bed, *Separation and Purification Technology* 2011, 77(3), 312-324.

Lee N.R., Yi G.Y., Park D.Y., Research on the Adsorption Capacity for Benzene, Toluene, Acetone and N-hexane of Activated Carbon Acquired from the Domestic Market., *Journal of Korean society of Occupational and Environmental Hygiene* 2014, 24(2), 193-200.

Lee S.W., Park H.J., Lee S.H., Lee M.G., Comparison of adsorption characteristics according to polarity difference of acetone vapor and toluene vapor on silica–alumina fixed-bed reactor. *Journal of Industrial and Engineering Chemistry* 2008, 14(1), 10-17.

Lee S.W., Cheon J.K., Park H.J., Lee M.G., Adsorption characteristics of binary vapors among acetone, MEK, benzene, and toluene., *Korean Journal of Chemical Engineering*. 2008, 25(5), 1154-1159.

Ministry of Education, Science and Technology, Korea, Pilot study for building a laboratory safety and health center 2009.

Mohana N., Kannana G. K., Upendraa S., Subhab R. Breakthrough of toluene vapors in granular activated carbon filled packed bed reactor. *Journal of Hazardous Materials* 2009, 168, 777-781.

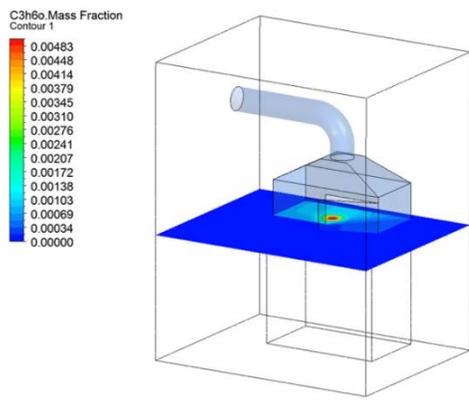
National Institute for Occupational Safety and Health. NIOSH method No.1300. 2003. Available from: URL:<http://www.cdc.gov/NIOSH/nmam/pdfs/>[accessed 30 January 2015].

National Institute for Occupational Safety and Health. NIOSH method No. 1501. 2003. Available from: URL:<http://www.cdc.gov/NIOSH/nmam/pdfs/>[accessed 30 January 2015].

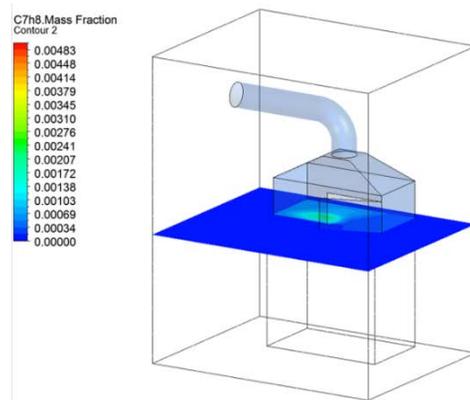
- Noh S.Y., Kim K.H., Choi J.H., Han S.D., Kil I.S., Kim D.H., Rhee Y.W.
Adsorption Characteristics of VOCs in Activated Carbon Beds. *Journal of Korean Society for Atmospheric Environment* 2008, 24(4), 455-469.
- Nunes C.A., Guerreiro M.C. Estimation of surface area and pore volume of activated carbons by methylene blue and iodine numbers. *Quimica Nova*. 2011, 34 (3), 472-476.
- Park J.H., Lee L.K., Byun H.J., Ham S.H., Lee I.K., Park J.I., et al., A study of the volatile organic compound emissions at the stacks of laboratory fume hoods in a university campus. *Journal of Cleaner Production* 2014, 66 (2014) 10-18.
- Son M.S., Kim S.D., Woo K.J., Park H.J., Seo M.C., Lee S.H., Ryu S.K.,
Adsorption Characteristics of Three components Volatile Organic Compounds on Activated carbonaceous Adsorbents. *Korean Chemical Engineering Research* 2006, 44(6), 669-675.
- Yang H.N., Liu L.F., Yang F.L., Yu J.C., Fibrous TiO₂ prepared by chemical vapor deposition using activated carbon fibers as template via adsorption, hydrolysis and calcinations. *Journal of Zhejiang University Science A* 2008, 9(7), 981-987.
- Zhou J., You Y., Bai Z., Health risk assessment of personal inhalation exposure to volatile organic compounds in Tianjin, China. *Science of the Total Environment* 2011, 409(3), 452-459.

Appendix

The CFD programmed consisted of numerous differential equations that represented the airflow. The generating substance were not exposure to outside exhausted easily to duct through the CFD simulations.



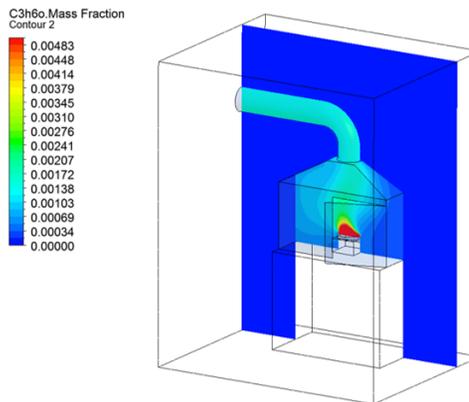
(a)



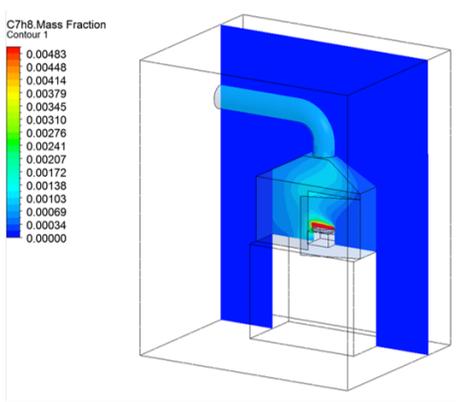
(b)

Horizontality section distribution of material concentration

(a) Acetone, (b) Toluene



(a)



(b)

Vertical section distribution of material concentration

(a) Acetone, (b) Toluene

The governing equation and numerical scheme for CFD simulation

Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = S_m \quad (1)$$

The mass added to the continuous phase from the dispersed second phase (e.g., vaporization of liquid droplets).

Momentum equation

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i \quad (2)$$

Gravitational body force and external body forces (e.g., that arise from interaction with the dispersed phase).

Energy equation

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_j}(u_j(\rho E + p)) = \frac{\partial}{\partial x_i}(k_{eff} \frac{\partial T}{\partial x_i}) - \sum_{j'} h_{j'} J_{j'} + u_j(\tau_{ij})_{eff} + S_h \quad (3)$$

Heat of chemical reaction, and any other volumetric heat sources.

Turbulence model: Realizable k-ε Model

The air turbulence is modelled by the standard two equation k-ε model which consists of the transport equations for turbulent kinetic energy k.

$$\frac{\partial}{\partial x_k}(\rho u_k k) = \frac{\partial}{\partial x_k} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_k} \right] + P - \rho \varepsilon \quad (4)$$

and dissipation rate ε

$$\frac{\partial}{\partial x_k}(\rho u_k \varepsilon) = \frac{\partial}{\partial x_k} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_k} \right] + C_1 \frac{\varepsilon}{k} P - C_2 \frac{\rho \varepsilon^2}{k} \quad (5)$$

$$\frac{\partial}{\partial x_i}(\epsilon \bar{u}_i) = \frac{\partial}{\partial x_i} \left[\left(\nu + \frac{\nu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_i} \right] + C_{1\epsilon} G_k \frac{\epsilon}{k} - C_{2\epsilon} \frac{\epsilon^2}{k}$$

Where P is the production of k due to mechanical shear.

$$G = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \quad (6)$$

The coefficients $C_{\epsilon 1}=1.44$ and $C_{\epsilon 2}=1.92$ are model constants. The turbulent

Prandtl numbers are $\sigma_k=1.0$ and $\sigma_\epsilon=1.3$ for k and ϵ , respectively. These values are ad hoc model constants that are determined empirically.

CFD analyzing condition

Nomenclature	
G	turbulence production
H	Numerical diameter
I	turbulence intensity
X	Space Coordinate
I, j, k	Unit vector
p	pressure
u	X-axis velocity
v	Y-axis velocity
w	Z-axis velocity
k	Turbulent kinetic energy
ε	Turbulent kinetic energy dissipation rate
ρ	Fluid density
τ_{ij}	Shearing stress
μ	dynamic viscosity
μ_t	turbulent viscosity
μ_{eff}	effective viscosity
ν	kinetic viscosity

국문초록

흡후드에서 활성탄 형태에 따른 휘발성 유기화합물 제거에 관한 연구

서울대학교 보건대학원

환경보건학과 산업보건전공

이 상 아

지도교수 윤충식

연구목적 실험실 환기시설은 화학물질 취급자의 건강보호와 실내 공기 질 저하에 기인하는 화학물질 증기의 확산 방지를 최소화하기 위해 운영되고 있다. 그러나 국내법에는 실험실에서 배출되는 물질에 대한 규제와 실험실 환기시설에 공기정화장치를 설치 할 의무가 없다. 그래서 환기시설의 배출구를 통해 유해한 증기 및 가스가 대기환경으로 배출되고 있다. 따라서 본 연구에서는 실험실의 대표적 환기시설인 흡후드를 선정하여 배출구에 간이 공기정화장치를 설치하고, 활성탄 형태에 따른 휘발성유기화합물의 제거를 비교하고자 하였다.

연구방법 실험실에서 주로 발생하는 휘발성 유기화합물을 극성과 비극성으로 분류하여 각각의 대표물질로 극성인 아세톤과 비극성인 톨루엔을 선정하였다. 그리고 파일럿 국소배기장치의 배출구 전단에 Activated carbon fiber (ACF), Granular activated carbon (GAC) 및 ACF + GAC 의 3 가지 형태 흡착제를 부착하여 흡착제 전과 후에서 실시간 농도변화를 비교하였다. 농도분석은 기기 (ppbRAE 3000)를 이용하여 휘발성유기화합물의 실시간 농도 변화를 관측하였으며, 활성탄관으로 간헐적 시료를 채취하여 불꽃 이온화 검출기가 장착된 가스 크로마토그래피로 분석하였다.

연구결과 파과 시간은 톨루엔이 아세톤보다 ACF, GAC 그리고 ACF+GAC 에서 모두 약 1.1 - 2.8 배 길었다. 물질을 50 ppm 발생시켰을 때 흡착제의 파과 시간은 10 ppm 을 발생시켰을 때 보다 1.3 - 4.4 배 짧아졌다. ACF+GAC 는 아세톤과 톨루엔을 발생시켰을 때 농도와 상관없이 ACF 와 GAC 보다 파과 시간이 길었다. 그리고 ACF+GAC 의 길이가 14 cm 에서 절반인 7cm 로 줄어들었을 때 파과 시간은 7.4 - 9.1 배 짧아졌다. ACF+GAC 의 흡착효율은 파과 되기 전까지 아세톤에서 75.6%, 톨루엔에서 80.7%를 나타냈고, 가장 긴 파과 시간과 안정적인 흡착을 보여주었다.

결론 ACF, GAC 그리고 ACF+GAC 3 가지 종류의 흡착제 중에서 ACF+GAC 가 아세톤과 톨루엔에서 모두 가장 긴 파과 시간을 가졌다.

그러므로 청정한 대기환경 조성을 위하여 실험실의 국소배기장치에
ACF+GAC의 사용이 요구된다.

주요어: 흡후드, 휘발성 유기화합물, 활성탄, 흡착제

학 번: 2013 - 21826