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Performance of Air Cleaners for Removing Multiple Volatile Organic Compounds in Indoor Air

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ABSTRACT

Fifteen air cleaners, representing different technologies and types of devices, were tested with a mixture of 16 representative VOCs (17 VOCs in tests for products associated with ozone generation) in a full-scale stainless steel chamber by using a “pull-down” test method. Their initial performance was evaluated in terms of single-pass efficiency (η) and the clean air delivery rate (CADR). Technologies evaluated include sorption filtration, ultraviolet-photocatalytic oxidation (UV-PCO), ozone oxidation, air ionization (plasma decomposition), and botanical air cleaning. Based on test results, the relative effectiveness of the available technologies tested and the effect of product configuration and VOC properties on the VOC removal efficiencies are analyzed. The implication of test results on the development of a standard test method for performance evaluation of gas-phase air cleaners is also discussed briefly in this paper.

INTRODUCTION

Poor indoor air quality (IAQ) can significantly affect people’s health, comfort, satisfaction, and productivity. Air cleaning/purification devices, which can be an effective strategy for improving IAQ in conjunction with source control and ventilation, have held a substantial market for use in residences and offices for removing various contaminants (US EPA 1996). Volatile organic compounds (VOCs) represent a major class of indoor pollutants. Typical sources include new building materials and furnishings, consumer products, maintenance materials, tobacco smoke, and polluted outdoor air. VOC pollutants may cause offensive odors, skin and membrane irritations, allergic reactions, and chronic effects including cancer. In recent years, more and more air cleaning

devices are advertised in the market for removing chemical pollutants such as VOCs and for odor control. However, there is limited information available regarding their performance beyond the general claims of the manufacturers, and there are no standard methods for testing the removal of gaseous contaminants by air cleaning devices.

This paper briefly reviews the available technologies for removing indoor VOCs and presents test results for initial VOC removal efficiencies of 15 air cleaners (12 portable air cleaners and 3 in-duct devices for typical residential applications), representing different technologies. It discusses the relative effectiveness of the available technologies tested and the effect of product configuration and VOC properties on VOC removal efficiencies.

OVERVIEW OF TECHNOLOGIES FOR REMOVING INDOOR VOCs

Technologies for removing indoor VOC contaminants mainly include sorption filtration, ultraviolet-photocatalytic oxidation (UV-PCO), ozone oxidation, air ionization (plasma decomposition), and botanical air cleaning. Here, “removing” generally refers to the concentration decrease of target VOC pollutants in indoor air. They can either be physically removed from air by adherence to, and retention on, the solid sorbents (at least temporarily) or be chemically changed to other substances such as CO₂ and water as the desired final products. The former is a reversible process, while the latter is an irreversible one.

Sorption filtration removes gaseous contaminants from indoor air by adsorption on solid adsorbents. It is a traditional and most commonly used technology. Most off-the-shelf commercial products are based on this technology. The effec-

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tiveness of cleaners based on adsorption technology depends on the properties and amount of sorbents, the packing (or coating) density of the sorbent layer, the velocity and flow rate of air passing through the sorbent media, the properties of the VOCs, and environmental conditions such as relative humidity and temperature. Depending on specific application requirements, adsorbents such as activated carbon, zeolite, and activated alumina with various packing density can be used as filtration media. In some cases where specific contaminant(s) is targeted, the adsorbents can also be impregnated with selected chemicals that will react with target substances (chemisorption) (ASHRAE 1999). Activated carbon, especially granular activated carbon (GAC), is the most common media for general indoor gaseous pollutant removal purposes (Henschel 1998; VanOsdell and Sparks 1995). Due to the saturation effect of adsorbents after long-term use, the complete evaluation of a sorption type device should include evaluation of both the initial performance (e.g., by initial removal efficiencies) and the long-term performance (e.g., by breakthrough time). In addition, possible reemission of the adsorbed VOCs is a concern.

UV-PCO removes gaseous contaminants via chemical reactions on semiconductor catalyst surface under UV irradiation. More specifically, when a semiconductor material is irradiated by photons with energy that matches or exceeds the band gap energy (E_g) of the semiconductor, an electron is promoted from the valence band (VB) to the conduction band (CB), leaving a hole behind. These photogenerated holes and electrons diffuse to the surface and react with adsorbed water molecules. The resultant hydroxyl radicals are highly reactive species that can oxidize VOCs adsorbed on the catalyst surface (Hager and Bauer 1999; Jacoby et al. 1996). Hoffmann et al. (1995) reported that the application of illuminated semiconductors for the remediation of contaminants has been successfully used for a wide variety of compounds (alkanes, simple aromatics, etc.). However, there is lack of widespread commercialization of this technology, and only a few products are available in the US market. The effectiveness of cleaners based on UV-PCO technology depends on the photoactivity of the catalyst, the UV light intensity on the catalyst surface, contact time between the contaminated airflow and catalyst surface, the properties of VOCs, and environmental conditions such as relative humidity and temperature. The most widely used photocatalyst for air purification today is TiO_2 with $E_g = 3.2$ eV. Depending on the type and concentration level of the contaminants treated, generation of harmful intermediates and by-products may be a concern.

Ozone is a strong oxidizer. Theoretically, it can react with many VOCs found indoors. In today's market, some ozone-oxidation-based air purifiers are advertised for regular use in homes and offices for removing chemicals and odors. However, under low VOC and ozone concentration levels, the reaction rate might be too low to be effective for most indoor VOCs. In case of those VOCs that do react with ozone fast enough (e.g., a subset of VOCs with unsaturated carbon-

carbon bonds), reaction with ozone may produce other contaminants, e.g., aldehydes and organic aerosols (Weschler 2000). In addition, lack of adequate control on the ozone generation level can be a concern of safety because ozone itself is a potent lung irritant and is harmful to people at elevated levels.

Air ionizers create charged air molecules upon the application of an energy source (Daniels 2002). Theoretically, air ionization forms "nonthermal" plasmas—cluster ions (radicals)—which decompose VOCs by a complex series of oxidation reactions with eventual products of CO_2 and water. Destruction efficiency depends on ion density, treatment time, and chemical structures of VOCs (Yan et al. 1998). Two modes of ionization have often been employed: photon ionization and electronic ionization. However, since indoor air chemistry triggered by the ionization process mainly relies on the natural tendency of the ions and the chemicals that exist in the surrounding air, harmful intermediates and by-products may be generated during the process. In addition, many ionizers may produce ozone. Related fundamental studies are limited and experimental data are lacking for the demonstration of this technology for indoor environmental applications.

Botanical air cleaning refers to the removal of gaseous contaminants from indoor air by plants and their soils through biological processes. It is a relatively novel idea. There are no commercial products in the US market advertised for this technology, although significant reductions in formaldehyde and other VOCs were reported in several initial static chamber studies (Godish 2001).

DESCRIPTION OF AIR CLEANERS SELECTED FOR EVALUATION

For residential houses, two types of devices are readily available: stand-alone (portable) room air cleaners (including desktop units) and in-duct devices (filters). Portable air cleaners can be easily operated in a room with flexible time schedules but only clean the air in a limited area (e.g., up to several connected rooms without obstructions to airflow). In-duct devices (filters) work for the whole house but need to be installed in the air-handling system and function only when the air-handling system is operating. Table 1 presents descriptions of air cleaners tested in this study. In Table 1, the air cleaners are grouped based on the product type first, then the primary technology for VOC removal, and finally are sorted according to the purchase price within the same technology group.

EXPERIMENTAL METHODS

Test Facilities

All of the tests for characterizing the VOC removal efficiencies were carried out in a full-scale environmental chamber (Figure 1), which has an interior volume of 1920 ft^3 (16 ft by 12 ft by 10 ft). The chamber and all its components are made of stainless steel to minimize the adsorption/desorption of contaminants by the chamber itself. It has a dedicated

Table 1. Summary of Tested Products

Product Type	Primary Technology for VOC Removal	Device No.	Purchase Price	Type of Air Cleaning Technologies (Stated by Manufacturer)	Flow Rate* (CFM)
Portable	Sorption filtration	P1	\$120	(1) Special high grade of activated carbon filter and (2) allergy relief filter	300
		P2	\$158	Activated carbon pre-filter and (2) HEPA filter	335
		P3	\$299	HEPA filter, (2) plasma deodorization unit, and (3) activated charcoal filter	240
		P4	\$300	Pre-filter, (2) cotton retaining filter, (3) 6.5 lbs. of carbon-zeolite mixture impregnated with potassium iodide, and (4) HEPA filter media	160
		P5	\$315	Aluminum mesh pre-filter, (2) HEPA filter, (3) polyester fiber filters treated with an anti-microbial solution, and (4) activated charcoal filter	250
		P6	\$360	Two layers of nonwoven, polyester filter media impregnated with activated carbon and (2) HEPA filter	200
		P7	\$470	Pre-filter, (2) electronic cell, and (3) activated carbon post-filter	320
	UV-PCO	P8	\$399	High-intensity UV lamp and photo-catalytic semi-conductor	110
	UV-PCO + Air ionization	P9	\$699	Photo-ionization module, including UV lamp and tri-metallic catalyst, and (2) electron generator	14
	Air ionization	P10	\$150	Needlepoint ionization – use 16 stainless steel, ion-producing electrodes to produce a high intensity of negative ions and generate ozone as a by-product	- [†]
	In-duct	Ozone oxidation	P11	\$200	Photoplasma/photochemistry
Botanical air cleaning		P12 [‡]	-	Biofiltration – plant and a proprietary lightweight soil	22 ^{**}
Sorption filtration		P13	\$33	Granular activated carbon and activated alumina impregnated with potassium permanganate	N/A ^{††}
	UV-PCO + Sorption filtration	P14	\$485	(1) High-intensity UV lamps and photo-catalytic semi-conductor and (2) pleated activated carbon filter	N/A
	UV-PCO	P15 [‡]	-	Two honeycomb monoliths coated with titanium dioxide catalyst and an array of 3 germicidal UV lamps in between	N/A

* Measurement methods can be found later in section of flow rate measurements. Results shown here are for maximum speed level for each air cleaner.

[†] Product P10 is an ionizer with no fan unit but generates tiny ionic breeze. Accurate measurement of the flow rate, although possible, was difficult using our current experimental setup and therefore was not conducted.

[‡] Product P12 and P15 are prototypes of innovative products.

^{**} Product P12 is an indoor plant system but has a small fan to deliver air movement through the soil and the plant root system.

^{††} “N/A” means “Not Applicable” because product P13, P14, and P15 are in-duct devices and their flow rates are controlled by the air-handling system. The measured pressure drop under test conditions was 0.022 in. w.g., 0.05 in. w.g., and < 0.01 in. w.g. for product P13, P14, and P15, respectively. The initial resistance from manufacturer is only available for product P13 and the given initial resistance is 0.18 in. w.g. at 300 ft/min.

HVAC system for the control of the airflow rates and environmental conditions in the chamber. A detailed description of this chamber facility and its performance evaluation can be found in Herrmann et al. (2003).

Test Procedures

ASHRAE has sponsored several research projects to investigate feasible test methods for determining the effectiveness and capacity of gas-phase air filtration equipment for indoor applications (Ostojic 1985; VanOsdell 1994). A draft standard (ASHRAE Standard 145.1P) has been proposed. It

mainly addresses the media performance and therefore cannot be used for rating the overall performance of an air cleaner. To our best knowledge, no standard test methods have been established for testing the effectiveness of gaseous portable or residential in-duct air cleaners. AHAM has developed an ANSI-approved standard (AHAM 2002) for testing the particulate removal efficiencies of portable air cleaners. Under this standard, the effectiveness of the room air cleaner is quantified by the clean air delivery rate (CADR). This concept has been applied to testing the initial gaseous contaminant removal effi-



Figure 1 Full-scale chamber.

ciencies of portable air cleaners by previous researchers (Daisey and Hodgson 1989; Niu et al. 1998).

Since most of the selected products were portable air cleaners, a “pull-down” test method, similar to that used by Daisey and Hodgson (1989) and Niu et al. (1998), was used in this study. It consisted of three test periods under full-recirculation condition: injection period (1 h), static period (1 h), and dynamic period (12 h) (Figure 2). The injection of a known amount of contaminants into the experimental system, followed by a static period, resulted in stable initial high concentration levels. The time when the air cleaner was turned on was defined as time zero, at which the dynamic period began. Using the measured concentration decay rate from the dynamic period, the clean air delivery rate (CADR) as well as the removal efficiency of the cleaner could then be calculated for each VOC tested. It should be noted that only *initial* performance of air cleaners was tested under this procedure.

For all of the tests, air temperature in the chamber was maintained at $73.4 \pm 1^\circ\text{F}$, and relative humidity was maintained at $50 \pm 5\%$. Tracer gas (CO_2 or SF_6) was injected and monitored during the tests to account for any mass loss due to the chamber leakage and air sampling.

For portable air cleaners, the flow rate through the device was controlled by its own operation level setting. A 160 CFM (5 ACH) air recirculation rate was provided through a square type diffuser by the HVAC system to achieve good air mixing in the chamber (i.e., mixing level $> 94\%$). For in-duct air cleaners, airflow through the device was controlled by the flow rate of the chamber’s HVAC system. While it is desirable to have a flow rate that results in a face velocity of 300–600 ft/min as in real applications, the current chamber HVAC could only provide a maximum of 800 CFM recirculation flow, which was used and resulted in a 200 ft/min face velocity for the 2 ft by 2 ft cross section of the air cleaning devices tested.

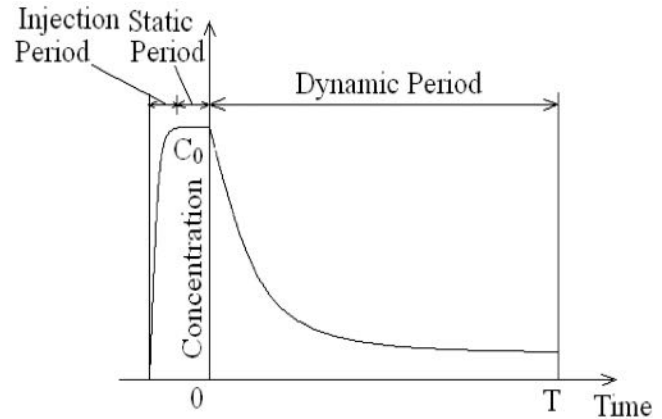


Figure 2 Schematic of “pull-down” test method.

Test VOCs

Over 300 VOCs have been found indoors, and all of these compounds may not be of equal importance in a single environment. A mixture of 16 VOCs (Table 2) was chosen in this study, covering major chemical categories and a wide range of molecular weight and boiling points. For air cleaning devices associated with ozone generation, d-Limonene was added because it belongs to the subset of VOCs that contains unsaturated carbon-carbon bond(s) and can react with ozone much faster according to theory (Weschler 2000). Choice of the initial concentrations for testing also proved to be a problem. The initial concentration levels should be reasonable for indoor applications and yet still high enough so that the concentration decay curve can be accurately measured before it goes below the instrument’s detection limit. In this research, initial concentrations of 1 mg m^{-3} were targeted for all VOCs except for formaldehyde and acetaldehyde that had a target initial concentration of 2 mg m^{-3} . Formaldehyde was generated by directly heating solid paraformaldehyde inside the chamber, and other VOCs were introduced into the chamber by vaporizing a known amount of VOC liquid mixture during the injection period.

Test Specimen

The portable air cleaners were tested as received without modification. Each air cleaner was positioned at the same place inside the chamber (3 ft away from the corner) and operated at its maximum speed setting except for P11, which was run at “low” operation level according to the product’s user guide due to the concern on the ozone emission.

For the in-duct devices, necessary modifications were made so that the device can be installed and sealed reasonably well in the test box on the return duct of the chamber’s HVAC system. These modifications did not alter any VOC removal component(s) of the devices.

Table 2. Components of Challenge VOC Mixture and Their Properties

Chemical Category	Chemical Name	Molecular Formula	MW	BP (°C)	VP at 23°C (mm Hg)	ASHRAE Std 145.1P*
Alkane	n-Hexane	C ₆ H ₁₄	86.2	69	139.88	X
	n-Octane	C ₈ H ₁₈	114.2	126	12.56	
	n-Decane	C ₁₀ H ₂₂	142.3	174	1.25	
	n-Undecane	C ₁₁ H ₂₄	156.3	196	0.35	
	n-Dodecane	C ₁₂ H ₂₆	170.3	216	0.12	
Aromatic	Toluene	C ₇ H ₈	92.1	111	25.64	X
	Ethylbenzene	C ₈ H ₁₀	106.2	136	8.58	
Chlorocarbon	Dichloromethane	CH ₂ Cl ₂	84.9	40	399.27	X
	Tetrachloroethylene	C ₂ Cl ₄	165.8	121	16.66	X
	1,2-Dichlorobezene	C ₆ H ₄ Cl ₂	147.0	180	1.19	
Aldehyde	Formaldehyde	CH ₂ O	30.0	-19	3652.58	X
	Acetaldehyde	C ₂ H ₄ O	44.1	20	835.7	X
	n-Hexanal	C ₆ H ₁₂ O	100.2	128	10.00	
Ketone	2-Butanone	C ₄ H ₈ O	72.1	80	86.95	X
	Cyclohexanone	C ₆ H ₁₀ O	98.2	156	3.82	
Alcohol	2-Butanol	C ₄ H ₁₀ O	74.1	100	16.01	
Terpene HC	d-Limonene* [†]	C ₁₀ H ₁₆	136.2	177	1.74	

* Compounds included in VOC challenge group of ASHRAE Standard 145.1P were included (indicated by "X").

[†] Compound with "*" was used only in tests for products P9, P10, and P11.

Instrumentation for Sampling and Analysis

A precalibrated photoacoustic multi-gas monitor was used for real-time measurements of the concentration of total hydrocarbon as toluene equivalent (TVOC_{toluene}), the concentration of total formaldehyde and acetaldehyde as formaldehyde equivalent (C_{formal+acetal}), and the concentration of tracer gas (CO₂ or SF₆). For TVOC_{toluene} and C_{formal+acetal}, since the sensitivity and response factor of the instrument for different compounds are different, the readings from the gas monitor were only used as semi-quantitative measures to characterize the change of TVOC concentrations over time and how they differ for different air cleaning devices. For quantitation of individual VOC, air samples were collected on the return duct of the chamber using sorbent tubes (Tenax TA, 0.2 mg). At least eight samples were taken during the 12 h dynamic period for each test. The tube sampling periods varied from 0.7 L to 5 L, depending on the expected highest concentration level of individual VOC. These sample tubes were then analyzed by an ATD-GC/MS (automated thermal desorber-gas chromatograph/mass spectrometer) system to determine the concentration of each individual compound, excluding formaldehyde and acetaldehyde. The detection limit was estimated to be 0.004 mg m⁻³ for a 0.75 L sample. For formaldehyde and acetaldehyde, DNPH-Silica cartridges were used to collect samples and then analyzed by an HPLC system. The detection limit was estimated to be 0.025 mg m⁻³ for a 10 L sample. The

measurement uncertainty for individual VOC was estimated to be ±15% based on the 95% confidence interval. A chemiluminescence ozone analyzer was used to measure ozone concentration, which has a precision of 0.5% of reading and a detection limit of 0.6 ppb.

Flow Rate Measurement for Portable Air Cleaners

Airflow rate measurements were made at each speed setting for each portable air cleaner. Since flow rates of tested devices varied from a few CFM to hundreds of CFM, two different experimental setups were used. For flow rates above 50 CFM, a flow hood system was used to directly measure the flow rate. For flow rates below 50 CFM, the velocities and cross-sectional area at air intake (or outlet) were measured and the flow rate was then calculated. The measurement uncertainty was estimated to be within ±15%.

Empty Chamber Characterization

An empty chamber test was performed first to investigate the possible effects of chamber characteristics (mainly sink effect) on test results for the air cleaners. Figure 3a shows the measured results of TVOC_{toluene}, C_{formal+acetal}, and tracer gas SF₆ from the gas monitor. Figure 3b shows the measured results for several individual VOCs. Normalized concentrations (i.e., concentration divided by the initial concentration at time $t = 0$) were used to facilitate the comparison.

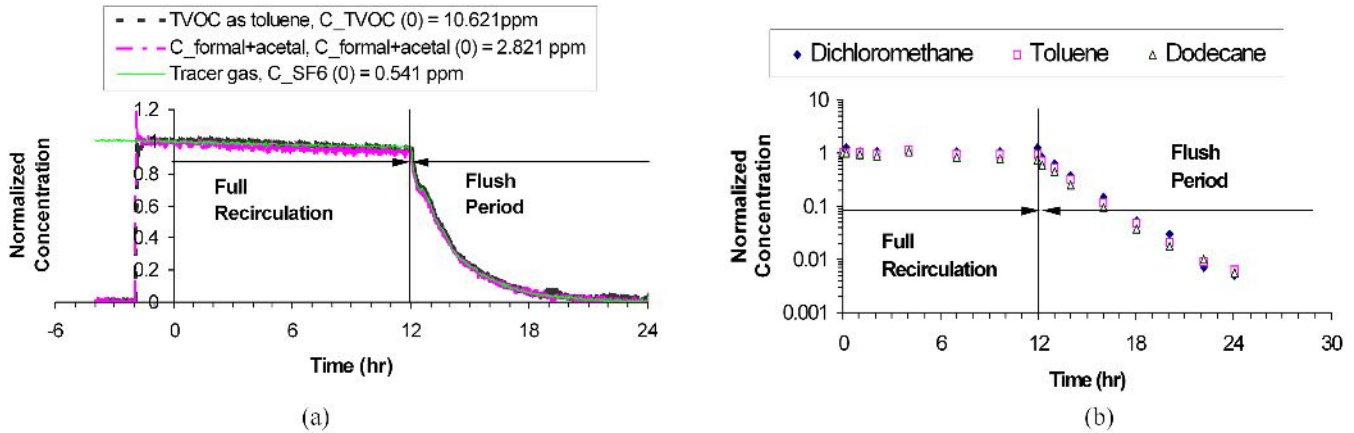


Figure 3 Measurement results of TVOC_{toluene}, C_{formal+acetal} and tracer gas (a) and some selected individual VOCs (b) for empty chamber test.

Results indicate that the decay rate of SF₆ was very small (0.003 ACH) under full-recirculation mode, which was negligible and indicated good airtightness of the chamber. As for the chamber sink effect, the decays of TVOC_{toluene} and C_{formal+acetal} under full-recirculation mode (5 ACH recirculating flow rate) were 0.005 ACH, which was only a little higher than the decay rate of SF₆ and indicated a small sink effect. Individual VOC analysis results show that the decay rate varied from compound to compound and the maximum decay rate was 0.023 ACH for dodecane (the heaviest compound in the test VOC mixture). In addition, during the flush period (0.5 ACH clean makeup air) following the full recirculation period, the VOC concentration decayed at almost the same rates as SF₆ until the concentrations reached the detection limit of the measurement instrument, which further verifies that the reversible sink effect of chamber was small under the experimental conditions. As a result, the maximum error caused in estimating N_{cl} is less than 0.023 ACH if the chamber sink effect is neglected. Since the CADR correspondent to 0.023 ACH is only 0.74 CFM, we neglect the chamber sink effect in this research and regard the effectiveness of air cleaner with N_{cl} ≤ 0.03 ACH (CADR ≤ 1 CFM) as insignificant. The initial VOC concentrations did not exactly match the expected values, which were possibly caused by the irreversible sink effect, the injection method uncertainty, and concentration measurement uncertainty. However, this did not affect the performance evaluation tests because the effectiveness of an air cleaner was measured by the concentration decay from its initial measured value.

Data Analysis Procedure

For each air cleaner tested, the single-pass efficiency (η) and the clean air delivery rate (CADR) were calculated for each VOC, respectively.

Single-pass efficiency (η) represents the fraction of pollutants removed from the airstream as it passes through the air cleaner. It is defined as

$$\eta = \frac{Q_{cl}(C_{in} - C_{out})}{Q_{cl}C_{in}} = \frac{C_{in} - C_{out}}{C_{in}}, \quad (1)$$

where

C_{in} = contaminant concentration at the inlet of air cleaner, mg m⁻³,

C_{out} = contaminant concentration at the outlet of air cleaner, mg m⁻³, and

Q_{cl} = airflow rate through the air cleaner, m³ h⁻¹ (CFM).

CADR reflects the “overall” effectiveness of the air cleaner. It is defined as

$$CADR = \eta \cdot Q_{cl} \cdot E_d, \quad (2)$$

where

E_d = short-circuiting factor of the air cleaner, $E_d = C_{in} / C$, where C is the average VOC concentration in the test chamber ($E_d = 1$ under well-mixed condition).

The data analysis procedure was similar to that used by Daisey and Hodgson (1989) and Niu et al. (1998), which was based on the well-mixed single-zone model. Assuming perfect mixing in the chamber and neglecting sink effect, the mass balance for a test VOC under full-recirculation mode during the dynamic period can be written as

$$V \frac{dC}{dt} = -(Q_{leak} + CADR) \cdot C(t) \quad (C = C_0 \text{ at } t = 0) \quad (3a)$$

or

$$\frac{dC}{dt} = -(N_{leak} + N_{cl}) \cdot C(t) \quad (C = C_0 \text{ at } t = 0), \quad (3b)$$

where

- V = volume of chamber system, m^3 (ft^3);
 Q_{leak} = leakage flow rate of chamber system, $m^3 h^{-1}$ (CFM);
 t = time from beginning of dynamic period, h;
 N_{leak} = air change rate due to leakage ($N_{leak} = Q_{leak} / V$); and
 N_{cl} = equivalent clean air change rate of the air cleaner ($N_{cl} = CADR / V$).

If CADR does not change (i.e., η is constant) during the test period, an analytical solution can be obtained from Equation 3a as

$$C(t) = C_0 \cdot e^{-(N_{leak} + N_{cl}) \cdot t} \quad (t \geq 0). \quad (4)$$

N_{cl} can be determined by linear regression of $\ln(C/C_0)$ versus t from measured concentration decay curve. The CADR and η can then be estimated.

However, the obvious decrease of CADR was observed during the later part of the 12 h dynamic period for some sorption-based air cleaners. In addition, for devices using air cleaning technologies other than sorption filtration (e.g., P15), the concentration decay of some test VOCs was faster during the later part than the initial part of dynamic period. These made the direct fitting of all experimental data to Equation 4 inappropriate. To account for these effects, the $CADR_{1h}$ and $CADR_{12h}$ were defined, respectively, for the purpose of comparing different air cleaners and calculated as follows:

1. Calculate a 12-h average equivalent clean air change rate (N_{cl-12h}) based on the time-averaged VOC concentration during the test period

$$\frac{\int_0^T C dt}{T} = \frac{\int_0^T C_0 \cdot e^{-(N_{leak} + N_{cl-12h}) \cdot t} dt}{T}, \quad (5)$$

where, T is the length of the dynamic test period ($T = 12$ h).

Then obtain $CADR_{12h}$ by $CADR_{12h} = N_{cl-12h} \cdot V$ and calculate the removal efficiency η_{12h} according to Equation 2. N_{cl-12h} reflects the average effect of the air cleaner during the entire test period.

2. For sorption type devices, calculate N_{cl-1h} by fitting the first hour experimental data to Equation 4. Obtain $CADR_{1h}$ by $CADR_{1h} = N_{cl-1h} \cdot V$ and calculate the removal efficiency η_{1h} according to Equation 2. If $N_{cl-12h} \leq 0.03ACH$, the effectiveness of the air cleaner is considered “insignificant” for the given compound, and $CADR_{1h}$ is not reported.

It can be easily proved that $CADR_{1h}$ is equal to $CADR_{12h}$ if CADR remains constant during the test period.

TEST RESULTS

TVOC_{toluene} and C_{formal+acetal} from Gas Monitor Measurement

Figure 4 and Figure 5 present the TVOC_{toluene} and C_{formal+acetal} measured by gas monitor for all the air cleaners

tested, respectively. Normalized concentrations were used to facilitate the comparison. For product P14, the test was extended to 24 h since it consists of both a “UV-PCO” component and a pleated media filter. During the first 12 h, only the UV-PCO component was installed (P14[A]). During the second 12 h, both the UV-PCO component and the pleated media filter were installed (P14[B]).

A significant decrease of TVOC level was observed during the test for all sorption-related products except for P6. However, the performance varied a lot from product to product. For example, product P1 and P14(B) worked best. They reduced TVOC level most quickly and followed the single exponential decay well. However, for product P7, the decrease of TVOC level was significant and approximately followed the single exponential decay initially but became very slow during the latter part of test period, suggesting the decrease of removal efficiency. For product P6, the ATD-GC/MS analysis of tube samples showed the presence of a significant amount of a new compound. This new compound was tentatively identified as (S)-(+)-3-Bromo-2-Methyl-1-Propanol by MS scan analysis with NIST library (matching quality = 81%) and most likely came from the new product itself. As a result, an increase of TVOC level was observed during the experiment. However, it did reduce concentration of most of the injected VOCs very significantly. Product P15, which is a prototype UV-PCO device, also significantly reduced the TVOC level until the detection limit of the instrument, although not as quickly as the best sorption-based products. The reduction of TVOC level by other tested products (P8 to P12 and P14[A]) was similar to or only slightly larger than that during the empty chamber test, meaning that these products had negligible removal effects.

For the removal of formaldehyde and acetaldehyde, results indicate that product P15 worked best. The $C_{formal+acetal}$ level at the end of test was lowest for product P15, although the initial decrease of $C_{formal+acetal}$ level for product P15 was slower than that for product P14(B), P13, and P4. For sorption-related products, product P4 and P13, which contain either impregnated carbon/zeolite mixture or impregnated activated carbon/activated alumina mixture, significantly reduced the $C_{formal+acetal}$ level. However, products with activated carbon only could not remove or removed only a small amount of formaldehyde and acetaldehyde, except for product P14(B), which has a thick (approximately 3.5 in.) pleated filter. Product P12 also significantly reduced the $C_{formal+acetal}$ level. The effectiveness of other products was either insignificant or marginal.

CADR and Single-Pass Removal Efficiency for Individual VOC

Figures 6a and 6b present the measured concentration decay (normalized by initial concentrations) of several VOCs (e.g., alkane group, formaldehyde, and acetaldehyde) during the dynamic period for products P1 and P15, respectively. Similar concentration decay curves were obtained for each air cleaner tested, from which the CADR and the single pass

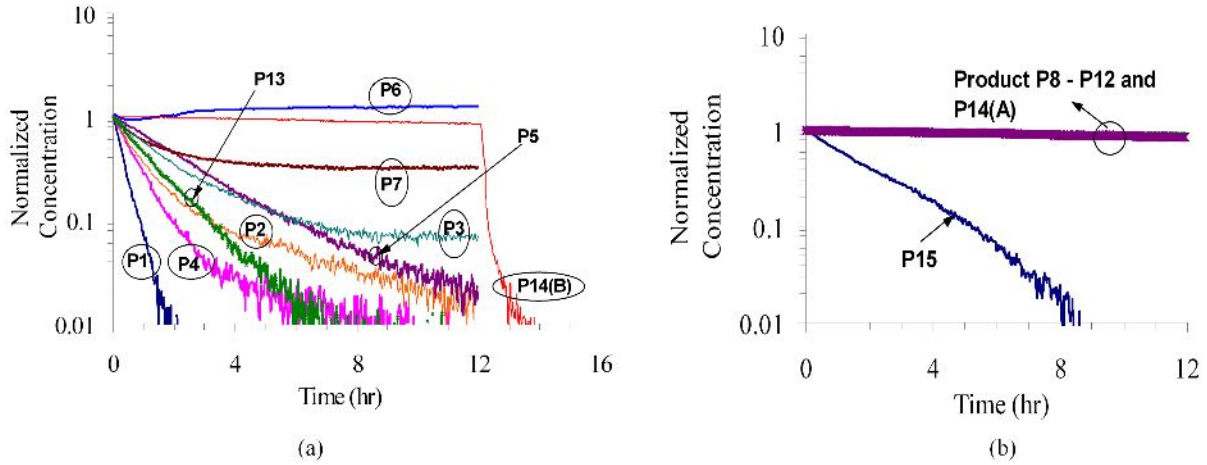


Figure 4 TVOC_{toluene} for air cleaners based on sorption filtration (a) and other technologies (b).

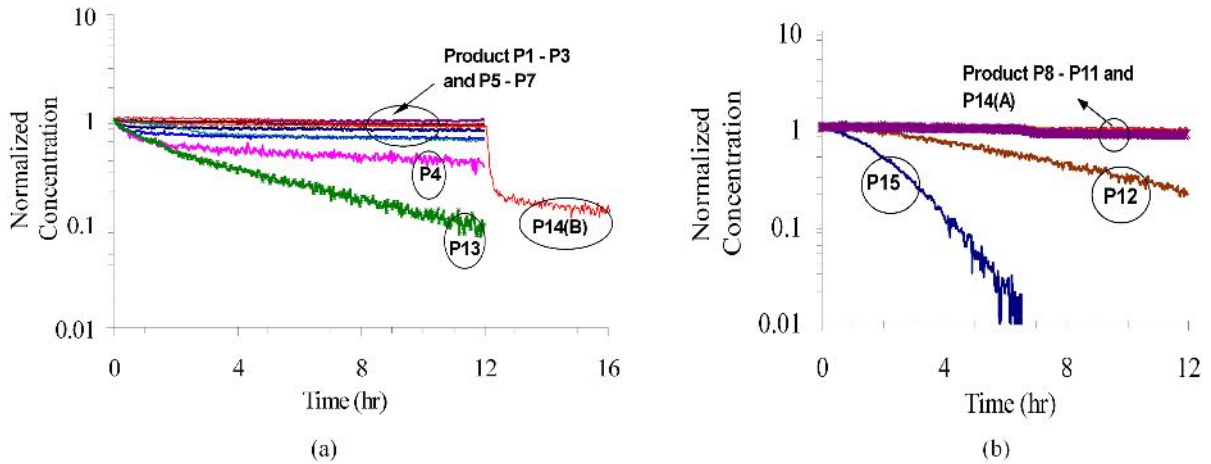


Figure 5 C_{formal+acetal} for air cleaners based on sorption filtration (a) and other technologies (b).

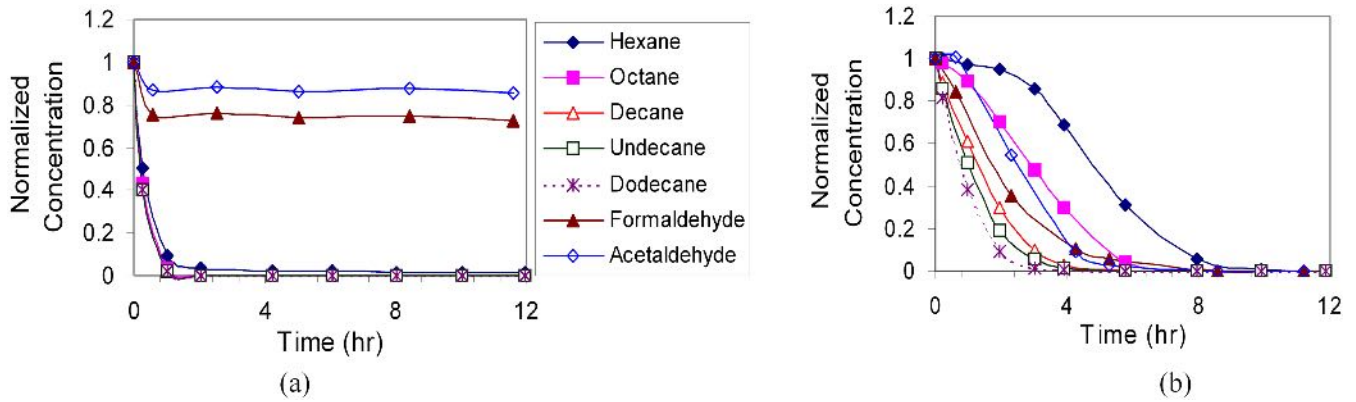


Figure 6 Measurement results of some selected individual VOCs for Product P1 (a) and Product P15 (b).

removal efficiency were then calculated. Results are summarized in Table 3. They clearly indicate that the VOC removal characteristics varied a lot from product to product and were in good agreement with the decay trend of $\text{TVOC}_{\text{toluene}}$ and $C_{\text{formal+acetal}}$ measured by the gas monitor. In addition, results indicate that the removal efficiencies varied from compound to compound even for the same air cleaner. None of the tested products could equally remove all the test VOCs at the same rate. The characteristics of the concentration decay curve depended on the properties of the compound, the technology used, as well as the product design.

Ozone Emission and Its Effect on VOC Removal

Ozone concentrations much higher than the safety limit set by OSHA (100 ppb) were observed during the dynamic test period for products P9 and P11 (Figure 7). Product P10 also had significant ozone generation. Test results indicate that these products only significantly reduced the concentration of d-Limonene. Figure 8 compares the measured d-Limonene concentration and ozone concentration for products P9, P10, and P11. It clearly shows the effect of ozone concentration on the decay of d-Limonene concentration. The decay of d-Limonene concentration was quickest for product P11 and slowest for product P10, which had the largest and smallest ozone emissions, respectively. Stable products (e.g., organic acids and organic aerosols) might be generated from ozone/d-Limonene reaction but were not detected due to the limitation of experimental design as well as the sampling and analyzing techniques used in this study. Small ozone emissions were detected during the test for P7 (< 20 ppb) and P3 (< 4 ppb) due to the use of electronic cell (P7) and plasma unit (P3). Ozone generations from other devices were negligible (< 1 ppb).

DISCUSSION

Comparison with Previous Studies

Test results obtained in this study were compared with some of the previous researchers' work (Daisey and Hodgson 1989; Niu et al. 1998; Reed et al. 2002). Daisey tested four portable air cleaners (all contained a certain amount of activated carbon) for their initial effectiveness for removing NO_2 and six representative VOCs (dichloromethane, 2-butanone, n-heptane, toluene, tetrachloroethylene, and hexanal). Niu tested 27 portable air cleaners for their initial effectiveness of gaseous contaminant removal by using toluene as the test compound. Reed tested both a portable and an in-duct gaseous air cleaner using a different test procedure. Only toluene was used as test VOC and it was continuously injected to the house at a constant rate. Once a steady-state concentration had been reached, the air cleaner was turned on and concentration decay was measured until a new steady-state concentration had been achieved. Both CADR and single-pass efficiency were calculated. Their test results indicate that (1) none of the tested air cleaners could significantly remove dichloromethane, (2) no

effects were observed for air cleaners only employing ionization technologies, and (3) the removal efficiency for toluene varied a lot from product to product for sorption-based air cleaners, ranging from 0.3% to 53%. Our test results agree with their observations. The present study provides results for more VOCs and more types of air cleaning technologies.

Correlation between Removal Efficiency and Properties of VOC

It is generally acknowledged that the adsorbability of gases and vapors on the adsorbent material depends on their molecular size (weight), boiling point, and vapor pressure. For sorption-based products, the general trend observed in this study was that the efficiency increased with the increase of molecular weight and boiling point of the compound and decreased as the vapor pressure of the compound increased. However, the relationship was not linear but a stepwise one (Figure 9).

Results indicate that for the very volatile organic compounds, such as formaldehyde, acetaldehyde, and dichloromethane, their removal characteristics were different from other tested compounds and they were difficult to remove. Use of other sorbent materials with special impregnants besides activated carbon may improve the removal efficiencies for these compounds, but the improvement varied from product to product. For the tested compounds with vapor pressure less than 2 mmHg at 23°C, the removal efficiencies by the same air cleaner were similar (Table 4). This suggests that the number of test compounds may be reduced and decane can be selected to represent heavier compounds (e.g., $\text{VP} < 2 \text{ mmHg}$ at 23°C) for the purpose of testing. Since toluene ($\text{VP} = 25.64 \text{ mmHg}$ at 23°C) is often selected as the reference compound for quantifying TVOC, the removal efficiency of toluene and the average removal efficiency of test compounds with vapor pressure less than toluene (including toluene) but larger than decane was also compared (Table 5). Results indicate that we could have a reasonably good estimation for the removal efficiency of VOCs with middle range vapor pressure (e.g., $2 < \text{VP} < 26 \text{ mmHg}$ at 23°C) if toluene was used as the representative compound for the purpose of testing.

As for the effective UV-PCO device (i.e., P15), the highest single-pass removal efficiencies were observed for n-hexanal, cyclohexanone, and 2-butanol (7.0%, 7.1%, and 5.9%, respectively). The lowest removal rates were observed for dichloromethane, hexane, and tetrachloroethylene (0.3%, 0.6%, and 0.7%, respectively). For some compounds, such as dichloromethane, hexane, and tetrachloroethylene, the removal rates were very low at the beginning and became larger later during the test period, which was quite different from the removal characteristics for sorption-based products. It seems that the reactions of these compounds on the catalyst surface were prohibited by the coexistence of other VOCs at high concentration levels at the beginning, possibly due to the competition of the available adsorption sites. Once the other, more reactive VOCs have been decomposed, the reactions for these compounds became faster. In the previous studies by

Table 3. Summary of CADR and Single-Pass Efficiency for Individual VOC for Tested Air Cleaners

VOC Name*	CADR _{12h} (CFM) ±15%										
	P1	P2	P3	P4	P5	P6	P7	P12	P13	P14(B)	P15
Formaldehyde	1.7	0.8	2.8	6.4	1	2.9	0.8	4.6	11	24	13
Acetaldehyde	0.8	0.1	1.3	4.4	0.9	0.1	0	4.3	5.8	14	11
Dichloromethane	0.4	0.3	0.6	12	0.8	0.6	0.4	0	4	97	2
n-Hexane	53	12	8.9	49	10	19	2.4	0	23	328	4.5
2-Butanone	20	8.5	5.2	40	7.1	12	2	0	18	329	11
Toluene	96	26	16	31	14	52	6.4	0	28	337	14
Tetrachloroethylene	94	20	14	53	13	45	4.7	0.1	26	373	5.4
2-Butanol	53	17	11	27	11	33	3.7	3	29	345	47
n-Octane	107	33	20	51	15	89	11	0	28	344	9.1
Hexanal	114	35	23	50	15	93	11	4.9	43	370	56
Ethylbenzene	117	35	22	55	16	98	11	0.3	30	355	21
Cyclohexanone	117	32	22	29	16	69	8.8	2.4	36	364	57
n-Decane	120	42	23	50	15	124	26	0	27	358	20
1,2-Dichlorobenzene	129	43	24	42	14	104	22	0.8	32	356	21
n-Undecane	121	44	23	47	14	122	36	0.6	27	345	24
n-Dodecane	117	47	22	43	13	110	44	0.9	28	333	32
VOC Name ^a	η _{12h} (%) ±21%										
	P1	P2	P3	P4	P5	P6	P7	P12	P13	P14(B)	P15
Formaldehyde	0.6	0.2	1.2	4.0	0.4	1.5	0.3	20.9	1.4	3.0	1.6
Acetaldehyde	0.3	0.0	0.5	2.8	0.4	0.1	0.0	19.5	0.7	1.8	1.4
Dichloromethane	0.1	0.1	0.3	7.5	0.3	0.3	0.1	0.0	0.5	12.1	0.3
n-Hexane	17.7	3.6	3.7	30.6	4.0	9.5	0.8	0.0	2.9	41.0	0.6
2-Butanone	6.7	2.5	2.2	25.0	2.8	6.0	0.6	0.0	2.3	41.1	1.4
Toluene	32.0	7.8	6.7	19.4	5.6	26.0	2.0	0.0	3.5	42.1	1.8
Tetrachloroethylene	31.3	6.0	5.8	33.1	5.2	22.5	1.5	0.5	3.3	46.6	0.7
2-Butanol	17.7	5.1	4.6	16.9	4.4	16.5	1.2	13.6	3.6	43.1	5.9
n-Octane	35.7	9.9	8.3	31.9	6.0	44.5	3.4	0.0	3.5	43.0	1.1
Hexanal	38.0	10.4	9.6	31.3	6.0	46.5	3.4	22.3	5.4	46.3	7.0
Ethylbenzene	39.0	10.4	9.2	34.4	6.4	49.0	3.4	1.4	3.8	44.4	2.6
Cyclohexanone	39.0	9.6	9.2	18.1	6.4	34.5	2.8	10.9	4.5	45.5	7.1
n-Decane	40.0	12.5	9.6	31.3	6.0	62.0	8.1	0.0	3.4	44.8	2.5
1,2-Dichlorobenzene	43.0	12.8	10.0	26.3	5.6	52.0	6.9	3.6	4.0	44.5	2.6
n-Undecane	40.3	13.1	9.6	29.4	5.6	61.0	11.3	2.7	3.4	43.1	3.0
n-Dodecane	39.0	14.0	9.2	26.9	5.2	55.0	13.8	4.1	3.5	41.6	4.0

* The test VOCs are listed in the order of decreasing vapor pressure

Note: For product P8 - P11 and P14(A), none of the injected VOC except d-Limonene was significantly removed ($N_{cl} \leq 0.05ACH$). Therefore, they are not included here.

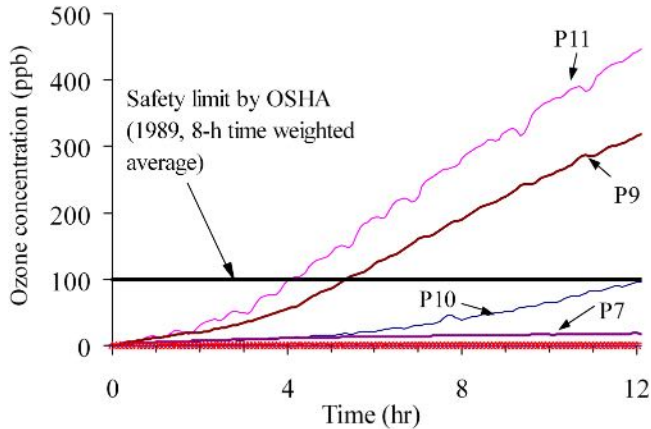


Figure 7 Measured ozone concentration.

Hall et al. (1998) and Hossain et al. (1999), the contaminants were often treated on a non-interacting basis when developing the design model for the UV-PCO device with honeycomb configuration. However, the above test results suggest that the interference effect among different VOCs should be considered even under indoor contaminant concentration levels. Currently, there is no such model available. In addition, the increase of reaction rate as the increase of molecular weight and hydroxyl radical reaction rate constant was reported for the single-compound test for the alkane group (Obee and Hay 1999; Sattler 1996). A similar trend was observed for the alkane group in our test, suggesting that it is possible to predict the removal rate of each VOC in a multi-component system using the removal rate obtained from a single VOC test. More fundamental studies are needed in this research area to verify this hypothesis and establish the appropriate correlations.

Effect of Design Configuration on the Performance of Air Cleaners

As seen from our test results and previous researchers' work, the measured CADRs and single pass efficiencies varied a lot from product to product for sorption-based cleaners. Table 3 and Figure 9 indicate that the 12-h average efficiencies for all test compounds were less than 15% for products P2, P3, P5, P7, and P13, and ranged from 25% to 55% for most of the test compounds for products P1, P4, P6, and P14 (B). To have a better understanding about the range of single-pass efficiency a sorption type device may provide, we further discuss the relationship between single-pass efficiency and the filter design. For products P1 and P14, pleated media filter are used (1 in. thick for P1 and 3.5 in. thick for P14). Since the pleated media filters provide more surface area and better contact between contaminated airflow and the adsorbent granular, both of them showed high efficiencies. For product P4, it has 6.5 lbs of sorbent pellets packed in a cylindrical design (approximate 1 in. thick). As we know from fundamentals of

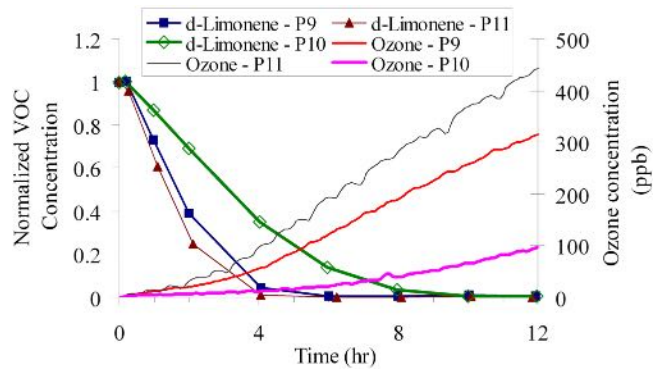


Figure 8 Ozone effect on removal of d-Limonene.

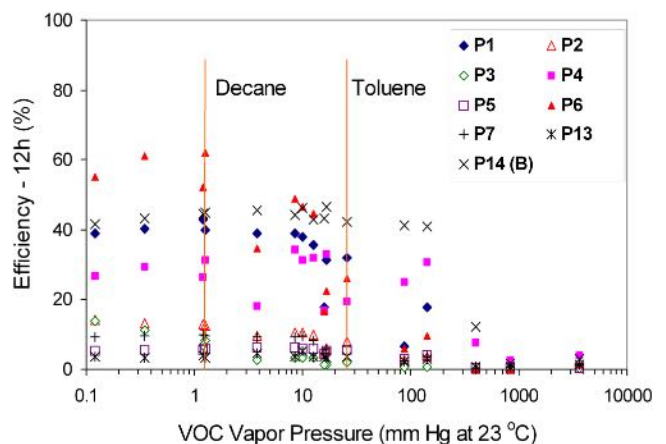


Figure 9 η vs. VP of test VOCs for sorption-related air cleaners.

the sorption process, for the VOC molecule to be adsorbed, it must first be transported from air across the boundary layer surrounding the adsorbent granule (or pellet) and then diffuse into the pores to reach the internal surface of the adsorbent. In this product configuration, it means that the VOC molecules have to travel for a longer path due to the porosity of the packed bed and the larger radius of pellets. Therefore, the single-pass efficiencies for P4 were a little smaller than P1 and P14, although the amount of sorbents is large. The design of sorption filter is similar for product P3, P5, and P13. All have granular adsorbents loosely packed in a frame or between other filter media. The packed adsorbent layer is thin and void space between the adsorbent granule can be easily seen by the naked eye, indicating that a significant amount of flow may bypass the adsorbent granule each time. As a result, the single-pass efficiencies for these products were low. As for products P2,

Table 4. Summary of Single-Pass Efficiency for Compounds with VP < 2 mm Hg at 23°C

η_{12h}	Device No.								
	P1	P2	P3	P4	P5	P6	P7	P13	P14(B)
Decane	40.0	12.5	9.6	31.3	6.0	62.0	8.1	3.4	44.8
Average*	40.6	13.1	9.6	28.4	5.6	57.5	10.0	3.6	43.5
S.D.†	1.7	0.6	0.3	2.3	0.3	4.8	3.1	0.3	1.4

* Average was calculated for decane, 1,2-dichlorobenzene, undecane, and dodecane.

† S.D. means "standard deviation."

Table 5. Summary of Single-Pass Efficiency for Compounds with 2 < VP < 26 mm Hg at 23°C

η_{12h}	Device No.								
	P1	P2	P3	P4	P5	P6	P7	P13	P14(B)
Toluene	32.0	7.8	6.7	19.4	5.6	26.0	2.0	3.5	42.1
Average*	33.2	8.4	7.6	26.4	5.7	34.2	2.5	3.9	44.4
S.D.†	7.6	2.2	1.9	7.9	0.7	12.9	1.0	0.7	1.7

* Average was calculated for toluene, tetrachloroethylene, 2-butanol, octane, n-hexanal, ethylbenzene, and cyclohexanone.

† S.D. means "standard deviation."

P6, and P7, the activated carbon is finely impregnated in the fibrous filter and cannot be separated from the fibers. For product P6, it has two layers of filter media impregnated with activated carbon (total 7/16 in. thick). Therefore, it had relatively high removal efficiencies. For product P7, the filter media impregnated with activated carbon is very thin (less than 1/8 in. thick). Therefore, its single-pass efficiencies were low. In addition, the removal efficiencies for this type of filter design seemed to vary most from compound to compound. Since the adsorption of VOCs by filtration media is a complex process, a more quantitative analysis will involve detailed considerations of flow arrangement, external mass transfer of VOC molecules through the boundary layer, diffusion of VOC molecules inside the micro-pores, and adsorption equilibrium on the internal surface of adsorbent granule, which is a subject for future studies.

As for the UV-PCO devices, test results indicate that a properly designed UV-PCO device (P15) was effective for all test compounds, although the removal efficiency was different from compound to compound. However, poorly designed UV-PCO devices (e.g., P8 and P14[A]) could not significantly remove any of the test VOCs. Experiments confirmed that only UV irradiation could not effectively remove VOCs. An effective UV-PCO device must have properly selected catalyst, a sufficiently large surface area with catalyst coating, and a good common interface for UV light, catalyst, and contaminated airflow. Longer contact (residence) time could increase the single-pass removal efficiency. A comprehensive model, simultaneously describing the UV light distribution, surface reaction kinetics, and contaminant mass transfer, is needed for designing an efficient UV-PCO device.

Technology Evaluation and Comparison

Five types of technologies have been used in the tested products: sorption filtration, UV-PCO, ozone oxidation, air ionization (plasma decomposition), and botanical air cleaning (plant and its special soil).

For all sorption-related products (P1 to P7, P13, and P14 [B]), significant removal efficiencies have been observed for most test VOCs. The light and very volatile gases, such as dichloromethane, formaldehyde, and acetaldehyde, were difficult to remove by activated carbon only. However, the removal efficiencies for these gases could be improved if specific sorption media (e.g., activated alumina impregnated with potassium permanganate) were added. Therefore, the sorption filtration should be regarded as an effective and practical technology for general indoor VOC control purpose if sorbent materials are properly selected. However, it must be noted that only the *initial* performance characteristic for each air cleaner was tested under the current "pull-down" test method. Since the adsorbent media only have limited lifetime and must be replaced on a regular basis (typically three to six months according to manufacturer's recommendations) to maintain good performance, more research is needed to accurately measure or predict the useful lifetime of sorption type devices.

The UV-PCO technology has been successfully demonstrated in lab reactors and prototype devices (Hall et al. 1998) and has been regarded as a promising technology for air purification (Hoffmann et al. 1995). Our test results show that a properly designed UV-PCO device (P15) had removal efficiencies competitive to sorption type devices. Only one by-product with significant amount (positively identified as acetic

acid [CH_3COOH] by comparing its retention time with acetic acid standard injection) was detected by ATD-GC/MS analysis under the test conditions. However, there are only a few commercial products readily available in the US market and some of them (e.g., P8), although advertised as UV-PCO based, were not good implementation of this technology and could not effectively remove any of the test VOCs. It is clear that the UV-PCO technology lacks widespread and mature commercialization for indoor applications, which may be caused by two reasons: (1) relatively large power consumption requirement and low quantum efficiency and (2) difficulty of efficiently bringing UV light, catalyst, and contaminated airflow together. According to Raissi et al. (2003), even when a low-pressure mercury lamp (LPML) is used as the source of UV light, the electricity to UV energy conversion is less than 40%, and a considerable amount of wasted thermal radiation is given off. After UV photons are adsorbed by TiO_2 and electron/hole pairs are generated, lots of them are recombined instead of participating in further chemical reactions, resulting in the further decrease of quantum efficiency. Henschel (1998) estimated the overall quantum efficiency was only about 0.1% at the low VOC concentrations. In addition, since the underlying reaction mechanisms and kinetics of photocatalytic oxidation for many VOCs, especially in the multiple-component systems, are not very well understood, there is lack of universal model for UV-PCO device design optimization.

For portable air cleaners that use air ionization and ozone oxidation (P9 to P11), results show that they did not significantly remove any of test VOCs except d-Limonene. Instead, all of them, especially P11 and P9, generated significant amounts of ozone. Therefore, such products are not recommended for use in office or residential rooms for VOC control purpose. For ozone oxidation, reaction rate data summarized by Weschler (2000) indicated that the majority of indoor VOCs, except for the small subset with unsaturated carbon-carbon bonds (e.g., d-Limonene), cannot react with ozone (below 50 ppb) fast enough to compete with typical ventilation rates. The current test results are in agreement with the theory. As for air ionization, the technology is theoretically feasible and has been demonstrated in some lab reactors (Yan et al. 1998). However, products tested did not show significant removal effectiveness for the majority of test VOCs under the current test procedure. Further study is needed to examine the design and performance of this technology.

Finally, for botanical air cleaning (plant and its special soil), only one prototype product (P12) was tested. Results show that it significantly removed n-hexanal, formaldehyde, and acetaldehyde. The single-pass removal efficiencies were approximately 20%, although the CADR numbers were not very large. For other contaminants, the device showed either insignificant or marginal removal characteristics. In addition, an obvious increase of 2-butanone concentration was observed during the test and reasons were not very clear. Currently, it is not a mainstream technology for indoor air purification, but potential exists due to its performance for removing aldehydes and its attractive appearance.

CONCLUSIONS

The major findings from this study are:

1. Sorption filtration is still the most effective off-the-shelf commercial technology, at least in the initial period, for general removal of indoor VOC pollutants. For all sorption-based products tested, significant removal efficiencies were observed for most test VOCs. The light and very volatile gases, such as dichloromethane, formaldehyde, and acetaldehyde, could not be efficiently removed by activated carbon only. However, the removal efficiencies for these gases could be improved if specific sorption media (e.g., activated alumina impregnated with potassium permanganate) were added.
2. For sorption-based products, the removal efficiencies and clean air delivery rates (CADRs) varied a lot from product to product. The sorption filter design plays an important role. In general, the filters, which could provide more surface area and better contact between contaminated airflow and the adsorbent granular, had higher efficiencies. In addition, the removal efficiencies depend on the properties of VOCs. A reasonably good estimation of the removal efficiency can be made for compounds with $\text{VP} < 26 \text{ mmHg}$ (at 23°C) by using toluene and decane as the test VOCs.
3. UV-PCO is an attractive technology because it appears to convert most VOCs into CO_2 and water under typical indoor concentration levels. Results show that a properly designed UV-PCO device (P15) had removal efficiencies competitive to sorption-based devices with only one modest by-product detected under the specific experimental and measurement conditions used in this study. However, the commercialization of this technology as room air cleaners is still in the beginning stage. The off-the-shelf UV-PCO-based air cleaners did not perform well due to poor product designs. The key issues for successful commercialization seem to be the improvement of overall quantum efficiency and system design optimization. Test results also suggest that the interference effect among different VOCs should be considered even under indoor contaminant concentration levels.
4. It is not recommended to use room air cleaners (such as ozone generators and ionizers) that either intentionally generate ozone or produce ozone as a by-product for indoor VOC control purpose. Although this type of product may be very quiet and use less power, their removal efficiencies for most indoor VOCs cannot compete with even moderate ventilation (e.g., 0.1 ACH), and they are likely to lead to unsafe ozone concentration levels.

More studies are needed to investigate the long-term performance of sorption type devices, develop the design optimization model for the UV-PCO device, and integrate performance data of air cleaners into building system design in conjunction with source control and ventilation strategies for better IAQ.

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