EFFECTIVENESS OF PORTABLE ROOM AIR CLEANERS FOR CONTROL OF VOLATILE ORGANIC COMPOUNDS IN INDOOR AIR

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ABSTRACT (IAQ T1S3)

Eleven commercially available portable room air cleaners have been tested on a mixture of 16 representative volatile organic compounds (VOC) in a full-scale stainless steel chamber and their initial VOC removal efficiencies have been evaluated. These products use different gas-phase contaminant removal technologies including adsorption, photocatalytic oxidation under UV irradiation (UV-PCO), ozone oxidation, air ionization and plasma decomposition. All sorption-based products were found to have reasonable initial removal efficiency for most tested VOCs (except dichloromethane, formaldehyde and acetaldehyde). The measured *CADRs* (clean air delivery rate) varied a lot from product to product, which are mainly due to the difference of air flow rate passing through the device, the property and amount of adsorbent material used and their packing density. The measured *CADRs* also varied from compound to compound, indicating that the properties of VOC would influence its removal rate by sorbent material. Products based on other technologies showed insignificant removal efficiency for most test VOCs (except d-Limonene) and some of them were found to lead to unsafe ozone concentrations. The low removal efficiency of UV-PCO based products may be attributed to poor product design, while the poor performance of ozone oxidation method is expected due to slow reaction rate between ozone and most VOCs under typical indoor conditions. The selection of experimental parameters (i.e. the number of injected VOCs, target VOC initial concentration levels, the test period) and data analysis procedure is also discussed in this paper, which will be useful for developing a performance test standard (similar to ANSI/AHAM Standard AC-1-2002) for gas-phase room air cleaners.

INTRODUCTION

Room air cleaners (including desktop units), which are portable and can be easily operated on a room-by-room basis, have held a substantial market for use in residences and offices for removing various indoor contaminants. For particulates removal, the Association of Home Appliance Manufacturers (AHAM) has developed a performance test standard (ANSI/AHAM Standard AC-1-2002). Under this standard, the effectiveness of room air cleaners is rated by clean air delivery rate (CADR) for cigarette smoke, dust and pollen, respectively. In recent years, more and more manufacturers have claimed that their devices are also effective for removal of chemicals such as volatile organic compounds (VOCs) and for odor control. Different technologies have been employed in these devices, including adsorption, photocatalytic oxidation (PCO), ozone oxidation, air ionization and plasma decomposition. Concerns about allergies, coupled with heightened worries over terrorism and diseases like SARS (severe acute respiratory syndrome), have further spurred the sales of air cleaners with such claims. 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 room air cleaners.

The objectives of this research were to: (1) provide information needed for development of standard test methods for evaluating gaseous pollutant removal performance of air cleaning devices, (2) evaluate the available technologies and identify the most promising technologies for enhancement, and (3) expand the database on the effectiveness of commercial air cleaners for VOCs removal.

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EXPERIMENTAL METHODS AND RESULTS

Description of Air Cleaning Devices and Technologies Evaluated

Eleven commercial air cleaning devices, representative of four types of technologies, were tested in this study. Sorption filtration, which removes gaseous contaminants from indoor air by adsorption on solid adsorbents, is the traditional but most widely used technology. Most of commercial products are based on this technology. Depending on different application requirements, adsorbents such as activated carbons, zeolite and activated aluminum with various coating density can be used as filtration media. Activated carbon is the most common media for general pollutant removal purpose. The effectiveness of cleaners based on this technology depends on the properties and amount of sorbents, the coating (or packing) density of sorbent layer, the face velocity and flow rate of air flow passing through the sorbent media, and environmental conditions such as relative humidity and temperature. UV-PCO, which removes VOCs via chemical reactions on semiconductor catalyst surface under UV irradiation, has received more and more attentions in recent years although only a very few products are available in US market. The key design parameters influencing the effectiveness of this technology include the photoactivity of catalyst, the UV light intensity on the catalyst surface, contact time between the contaminated air flow and catalyst surface, and environmental conditions such as relative humidity and temperature. Ozone has been successfully used for decades in industrial application as a powerful oxidizing substance. In today's market, some ozone generators are sold as air purifiers for regular use in homes and offices. Theoretically, ozone is a strong oxidizer and can react with many VOCs found indoors. However, it is questionable how safe and effective ozone oxidation is for typical indoor application. Air ionization is a process, or result of process, whereby an electrically neutral atom or molecule acquires either a positive or a negative electrical charge (Daniels, 2002). Ion generators (or ionizers), which are initially advertised for particulates removal, hold a remarkable market. Recently, some ionizers and plasma units also claim to be able to remove chemicals and odors. Theoretically, air ionization forms "nonthermal" plasmas –cluster ions, which can chemically react and destroy low concentration VOCs. Destruction efficiency and reaction by-products will depend on ion density, treatment time and chemical structures of VOCs. However, the related fundamental studies and knowledge are very limited. In addition, many ionizers produce ozone as a by-product, which is claimed to help the oxidation of indoor chemical pollutants.

Table 1 summarizes the room air cleaners tested in this research. Most of them are products readily purchased online or from local store. According to manufacturer's descriptions, P1 to P6 are purely sorption-based products. P1 uses a special high grade activated carbon. P2 has 7.5lbs of carbon and zeolite mixture. P3 claims use of a " V.O.C. filter" without clearly stating the sorbent used. P4 to P6 have typical activated carbon (charcoal) pre-filter or post-filter. P7 has both activated charcoal filter and plasma deodorization unit. P8 and P9 use photocatalytic oxidation technology. P10 produces a purifying plasma and ozone. P11 uses ion-producing electrodes to generate high-density ions and has ozone as a by-product. All these products are advertised for use in residential or office room with a floor area of $18 - 47$ m^2 ($200 - 500$ ft^2).

Table 1 Summary of Tested Products

Device No.	Purchase Price	Type of air cleaning technologies (Stated by manufacturer)	Flow rate [a] (m^3/h)
P1	$120	(1) Special high grade of activated carbon filter, and (2) Allergy relief filter	510
P2	$300	(1) Pre-filter, (2) Cotton retaining filter, (3) 6.5lbs.of Carbon-Zeolite mixture with potassium iodide, and (4) True Medical HEPA filter Media	272
P3	$360	(1) Washable foam pre-filter, (2) HEPA filter, and (3) V.O.C. filter	340
P4	$158	(1) Activated carbon pre-filter, and (2) HEPA filter	569
P5	$315	(1) Aluminum mesh pre-filter, (2) HEPA filter, (3) Polyester fiber filters treated with an anti-microbial solution, and (4) Activated charcoal filter	425
P6	$470	(1) Pre-filter, (2) Electronic cell, and (3) Activated carbon post-filter	544
P7	$299	(1) HEPA filter, (2) Plasma deodorization unit, and (3) Activated charcoal filter	408
P8	$399	(1) High-intensity UV lamp, and (2) Photo-catalytic semi-conductor	187
P9	$699	(1) Photo-ionization Module, including UV lamp and tri-metallic catalyst, and	24

		(2) Electron generator	
P10	$200	(1) Photoplasma/Photochemistry	14
P11	$150	(1) Needlepoint ionization – use 16 stainless steel, ion-producing electrodes to produce a high intensity of negative ions and generate ozone as a byproduct	0 [b]

Note: (a) Measurement methods can be found later in section of air flow rate measurements. Results shown here were for maximum speed level for each air cleaning device; (b) Product P11 is an ionizer with no fan unit.
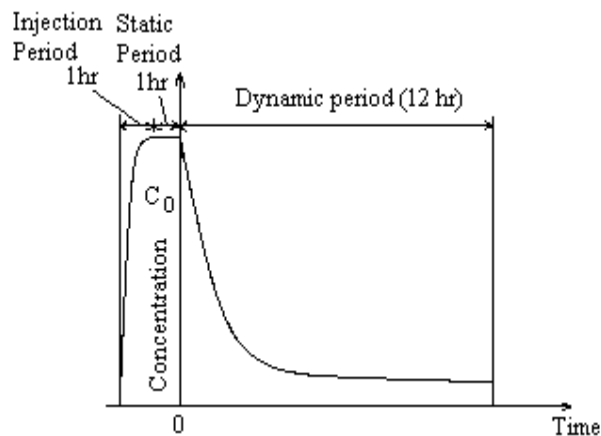

Figure 1 Full-scale Chamber System

Figure 2 Conceptual Schematic of "pull-down" Test Method

Test Facility

All the tests for characterizing the VOCs removal efficiencies were carried out in a full-scale chamber (Figure 1), which has an interior volume of 54.4 m^3 (4.88m x 3.66m x 3.05m high). 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 HVAC system to control the airflow rates and environmental conditions in the chamber. For details, refer to Zhang et al. (2002).

Test VOCs

More than 300 VOCs have been found indoors. All these compounds may not be of equal importance in a single environment and may not be removed by air cleaning device at the same efficiencies. 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 device 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 test initial concentrations also proves to be a problem, because the removal efficiencies of air cleaners may not be constant under different contaminant concentration levels. 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 injecting and vaporizing known amount of VOC liquid mixture during the injection period.

Table 2   Components of Challenge VOC Mixture

Group No.	Chemicals category	Chemical Name
1	Alkane HC	n-Hexane, n-Octane, n-Decane, n-Undecane, n-Dodecane
2	Aromatic HC	Toluene, Ethylbenzene
3	Halogenated HC	Dichloromethane, Tetrachloroethylene, 1,2-Dichlorobezene
4	Aldehyde	Formaldehyde, Acetaldehyde, n-Hexanal
5	Ketone	2-Butanone, Cyclohexanone
6	Alcohol	sec-Butanol
7	Terpene HC	d-Limonene*[a]

Note: (a) Compound with * was only used in tests for product P9, P10 and P11.

Test Procedure

A "pull-down" test method, similar to that used by Daisey et al. (1989) and Niu et al. (1998), was used to conduct all the tests. It consisted of three test periods under full-recirculation condition: injection period, static period and dynamic period (Figure 2). The injection of 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 dynamic period, equivalent clean air delivery rate (CADR) as well as the removal efficiency of the cleaner could then be calculated for each VOC tested. For all the tests, air temperature in the chamber was maintained at $23 \pm 0.5^{\circ}C$ and relative humidity was maintained at $50 \pm 5\%$. 5ACH air recirculation rate was used to provide good mixing. 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.

Test Specimen

The air cleaners were tested as received without modification. Each air cleaner was positioned at the same place inside the chamber (1 m away from corner) and operated at its maximum speed setting except for P10, which was run at "Low" operation level for the size of the chamber according to the product's user guide.

Instrumentation for Sampling and Analysis

A precalibrated 1312 gas monitor was used for real-time measurements of the concentration of total organic carbon as toluene equivalent (TVOC $_{toluene}$), the concentration of total formaldehyde and acetaldehyde as formaldehyde equivalent ($T_{formal+acetal}$), and the concentration of tracer gas (CO_2 or SF_6). For TVOC $_{toluene}$ and $T_{formal+acetal}$, 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 and the total formaldehyde and acetaldehyde concentration over time and how they differ for different air cleaning devices. For qualification of individual VOCs, air samples were collected at the outlet of the chamber using sorbent tubes. These sample tubes were then analyzed by GC-MS to determine the concentration of each individual compound except for formaldehyde and acetaldehyde. The detection limit was estimated to be 0.004 mg/m^3 for a 0.75L sample. For formaldehyde and acetaldehyde, DNPH-Silica cartridges were used to collect samples and then analyzed by HPLC. The detection limit was estimated to be 0.02 mg/m^3 for a 15L sample. Both GC-MS and HPLC were pre-calibrated by multiple-point calibration. The measurement uncertainty for individual VOC was estimated to be $\pm 15\%$. A chemiluminescene ozone analyzer was used to measure ozone concentration.

Air Cleaner Flow Rate Measurement

Air flow rate measurements were made at each speed setting of each air cleaning device. Since flow rates of tested devices varied from a few CFM to hundreds of CFM, two different experimental set-ups were used. For flow rate above 50 CFM, a flow hood system was used to directly measure the flow rate. For flow rate below 50 CFM, the velocities and cross section area at air intake (or outlet) were measured and the flow rate was then calculated. The measurement uncertainty was estimated to be $\pm 15\%$.

Data Analysis Procedure for Determination of Performance Parameters

Three parameters have been commonly used to quantify the performance of air cleaning devices: single-pass efficiency (η), clean-air delivery rate (CADR), and effectiveness of the device (ϵ)

(Nazaroff 2000). Since CADR is the parameter that can be directly determined from "pull-down" test and better reflects the "overall" effectiveness of the air cleaner, it is selected for comparing different products in this study. CADR is defined as:

$$CADR = \eta \cdot Q_{cl} \cdot E_d \qquad (1)$$

where

η – single-pass removal efficiency, $\eta = \frac{C_{in} - C_{out}}{C_{in}}$, where C_{in} and C_{out} are the contaminant concentration at the inlet and outlet of the air cleaner, respectively;

Q_{cl} – the air flow rate through the air cleaner; and

E_d – the short-circuiting factor of the air cleaner, $E_d = C_{in}/C$, where C is average concentration in test chamber.

The data analysis procedure was similar to that used by Daisey et al. (1989) and Niu et al. (1998). Assuming perfect mixing in chamber and neglecting sink effect and any mass loss due to the chamber leakage and air sampling, the mass balance for a test VOC under full-recirculation mode during the dynamic period can be written as:

$$V \frac{dC}{dt} = -CADR \cdot C(t) \qquad (2)$$

where

C – the average VOC concentration in the test chamber

V – the volume of chamber system

t - time from beginning of dynamic period

Define an equivalent clean air change rate for the room air cleaner as: $N_{cl} = CADR/V$, Equation (2) can be rewritten as:

$$\frac{dC}{dt} = -N_{cl} \cdot C(t) \qquad (2a)$$

The perfect mixing assumption held valid because 5ACH air recirculation was provided by HVAC system using a mixing type square air diffuser. The assumption of neglecting mass loss due to chamber leakage and air sampling also proved to be valid, because tracer gas measurement was made for every test and the measured decay rate ranged from 0.001 to 0.004ACH, which can be regarded as negligible for the tests conducted. An empty chamber test was first made to characterize the chamber sink effect, in which 0.5ACH ventilation was provided and samples were taken for additional 48 hrs after the end of full-recirculation period. Results showed that the decay rate of TVOC $_{toluene}$ and T$_{formal+acetal}$ (0.005ACH) was only a little higher than that of SF$_6$ (0.003ACH) during the full-recirculation period, indicating small sink effect. Individual VOC analysis results also showed small decay rates (from 0.003ACH for dichloromethane to 0.02ACH for dodecane) during the full-recirculation period. In addition, during the flush period following the full-recirculation period, TVOC$_{toluene}$ and T$_{formal+acetal}$ decayed at almost the same rates as SF$_6$ until monitor's detection limit, which further verified that the reversible sink effect of chamber was small. Assuming that this small reversible sink effect was the same for all the tests, we neglected it in calculation of *CADR* in this study.

If *CADR* remains constant (i.e. η doesn't change with time and contaminant concentrations) during the experiments, an analytical solution can be obtained from Equation (2a) as:

$$C(t) = C_0 \cdot e^{-N_{cl} \cdot t} \qquad (t \geq 0) \qquad (3)$$

N_{cl} can then be obtained by the least squares analysis of $ln(C_{(t)}/C_0)$ vs. *t* from measured data.

However, the decrease of *CADR* was observed during the later part of the 12 hrs dynamic period for some sorption-based air cleaners, which made the direct fitting of all experimental data to

Equation (3) inappropriate. To account for this effect, the $CADR_{1hr}$ and $CADR_{12hr}$ were defined respectively and calculated as following:

1. Calculate $N_{cl\text{-}1hr}$ by fitting the first hour experimental data to Equation (3) and obtain $CADR_{1hr}$ by $CADR_{1hr} = N_{cl\text{-}1hr} \times V$.

2. Calculate a 12-hr average equivalent clean air change rate $N_{cl\text{-}12hr}$ by letting

$$\int_0^{T=12\ hr} \frac{C(t)}{C_0} \cdot dt = \int_0^{T=12\ hr} e^{-N_{cl-12\ hr} \cdot t}\, dt \qquad (4)$$

Then obtain $CADR_{12hr}$ by $CADR_{12hr} = N_{cl\text{-}12hr} \times V$.

It can be easily proved that the larger the decrease of *CADR*, the larger the difference between $N_{cl\text{-}1hr}$ and $N_{cl\text{-}12hr}$. If *CADR* remains constant, $N_{cl\text{-}1hr}$ would be equal to $N_{cl\text{-}12hr}$.

Test Results

Flow Rates: Flow rate varied a lot from product to product (Table 1). P1 to P8 have large fan unit, which lead to relative high flow rate (from 187 m^3/h to 569 m^3/h). P9 and P10 have very small flow rate (14 m^3/h to 24 m^3/h) because they use small fan unit (i.e. computer fan). P11 is an ionizer and has no fan unit. In this study, 5ACH recirculation was provided by air diffuser of the HVAC system to achieve good mixing. It should be noted that the cleaner itself, if the flow rate is small, may not be sufficient to provide the mixing needed in an actual room environment and hence may further reduce its overall performance.

Measured Ozone Concentrations: Ozone concentrations in chamber during the dynamic period were much higher than the safety limit set by OSHA (100ppb) in tests for P9 and P10 (Figure 3). P11 also had significant ozone generation. P6, which has an electron cell for particulate removal also generated some ozone. Other products tested had almost no ozone generation.
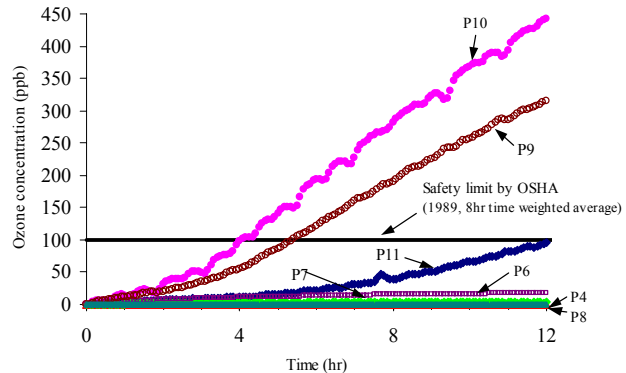

Figure 3 Ozone Concentration in Test Chamber

TVOC and T_formal+acetal from Gas Monitor: Figure 4 presents the measured TVOC_toluene during the dynamic period for 11 air cleaners tested. For P9, P10 and P11, the initial TVOC levels were a little higher than rest of the tests due to the injection of an additional compound (d-Limonene). For all sorption-based products except for P3, a significant decrease of TVOC level was observed during the test. For product P3, GC-MS analysis of tube samples showed presence of significant amount of a new compound – (S)-(+)-3-Bromo-2-Methyl-1-Propanol (identified by MS scan analysis) although concentration of each injected VOC decreased significantly. As a result, an increase of TVOC level was observed during the experiment. For P8, the TVOC level decreased almost at the same rate during the test as that in empty chamber test. Individual compound analysis showed the same trend with the maximum decay rate identified as 0.03ACH. For P9, P10 and P11 in which an additional compound (d-Limonene) was added, the TVOC level gradually decreased and reached almost the same level as that in empty chamber at the end of dynamic period. Individual compound analysis showed that only d-Limonene was effectively removed and the maximum decay rate for other injected VOCs was only 0.04ACH. Figure 5 shows the measured T_formal+acetal during the dynamic period. Results indicated that only P2 significantly removed the formaldehyde and (or) acetaldehyde. P3 and P7 removed some formaldehyde and (or) acetaldehyde, while the effectiveness of other products was insignificant.
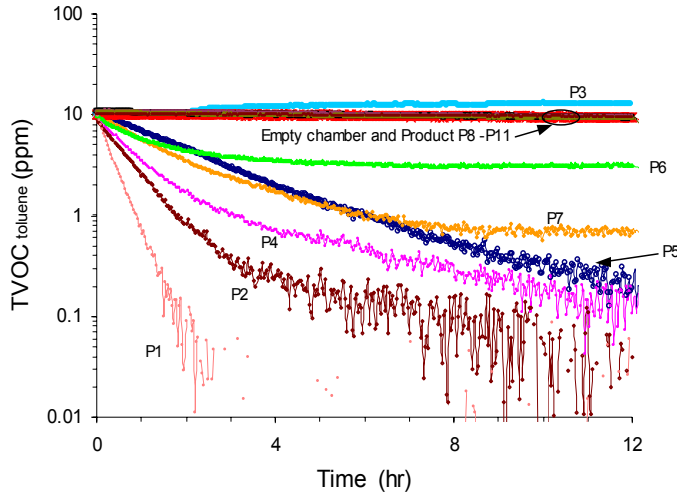
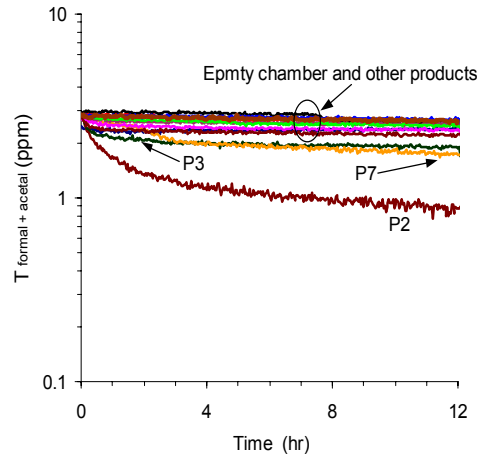*Figure 4 Decay of TVOC$_{toluene}$ during dynamic period*

Figure 5 Decay of T$_{formal+acetal}$ during dynamic period

Measured Concentration and *CADR* Calculation for Individual VOC: Figure 6 and Figure 7 present the measured concentration (normalized by initial concentration C$_0$) of several VOCs during the dynamic period for P1 and P6, respectively. Similar concentration decay curves were obtained for each room air cleaner tested, from which the *CADR* was then calculated. The *CADRs* reported here (Table 3) are only for products that significantly removed the majority of tested VOCs. They are all sorption-based products (P1 to P7). For P8 to P11, none of the injected VOC except d-Limonene was effectively removed ($N_{cl} \leq 0.05$ACH). Therefore, they are not included in Table 3.

Results showed that all these seven air cleaners were reasonably effective in removing most VOCs except dichloromethane, formaldehyde and acetaldehyde. Only P2 had significant removal for dichloromethane. It also had better removal rate for formaldehyde and acetaldehyde. Some test products, especially P6, had very different *CADR$_{1hr}$* for different test VOCs. The general trend was the *CADR$_{1hr}$* would decrease as the decrease of compound molecular weight and increase of compound vapor pressure. Significant difference was observed between *CADR$_{1hr}$* and *CADR$_{12hr}$* for n-hexane, 2-butanone and sec-butanol for many air cleaners tested, which may be caused by possible competition for the available adsorption sites between the multiple VOCs and occurrence of equilibrium status. An average *CADR$_{1hr}$* and *CADR$_{12hr}$* was also calculated, according to which the initial efficiencies of the seven sorption-based air cleaners could be ranked as P1>P3>P2>P4>P7>P6≈P5. This result agreed well with measured TVOC$_{toluene}$ from 1312 gas monitor. The slower decrease of TVOC$_{toluene}$ for P6 and P7 than that for P5 during the later part of 12 hrs period could be explained by the significant decrease of removal rate for some VOCs, such as 2-butanone, during the later part of test period.

Table 3 Summary of CADR for Each Individual VOCs for Tested Air Cleaners

Compound	Individual VOC removal CADR$_{1hr}$ (m^3/h)						
	P1	P2	P3	P4	P5	P6	P7
Dichloromethane [a]	-	49	-	-	-	-	-
n-Hexane	128	84	72	37	24	11	30
2-Butanone	94	78	60	38	23	12	23
Sec-Butanol	137	48	101	51	26	18	34
Toluene	180	75	129	60	28	25	40
n-Octane	181	87	160	62	27	34	39
Tetrachloroethylene	159	91	111	49	27	20	35
Hexanal	194	84	165	68	30	33	44
Ethylbenzene	199	94	168	67	30	35	43
Cyclohexanone	199	50	138	65	31	29	44
n-Decane	204	87	213	73	27	58	43

1,2-Dichlorobenzene	219	82	179	77	30	54	46
n-Undecane	205	84	209	78	27	70	43
n-Dodeane	198	81	189	84	26	82	44
Formaldehyde [b]	-	-	-	-	-	-	-
Acetaldehyde [b]	-	-	-	-	-	-	-
Average [c]	177	79	146	62	27	37	39
Individual VOC removal CADR$_{12hr}$ (m^3/h)							
	P1	P2	P3	P4	P5	P6	P7
Dichloromethane [a]	1	21	1	1	1	1	1
n-Hexane	90	83	32	21	16	4	15
2-Butanone	34	68	20	15	12	3	9
Sec-Butanol	89	46	56	28	18	6	18
Toluene	164	53	89	45	23	11	27
n-Octane	181	87	151	56	25	18	34
Tetrachloroethylene	159	91	77	34	21	8	24
Hexanal	194	84	158	59	26	18	39
Ethylbenzene	199	94	166	59	27	18	37
Cyclohexanone	199	49	117	54	27	15	37
n-Decane	204	85	210	71	25	45	39
1,2-Dichlorobenzene	219	73	177	73	24	37	41
n-Undecane	205	81	207	75	25	62	40
n-Dodeane	198	75	187	80	22	75	38
Formaldehyde [b]	3	11	6	1	2	1	5
Acetaldehyde [b]	1	9	0	0	1	0	2
Average [c]	164	75	127	52	22	25	31

Note: (a) For dichloromethane, *CADR$_{1hr}$* was calculated only when *CADR$_{12hr}$* was significant;

   (b) For formaldehyde and acetaldehyde, only *CADR$_{12hr}$* was calculated because the number of samples collected during the 1st hour was too limited.

   (c) Average was calculated for all the other VOCs except dichloromethane, formaldehyde, and acetaldehyde.
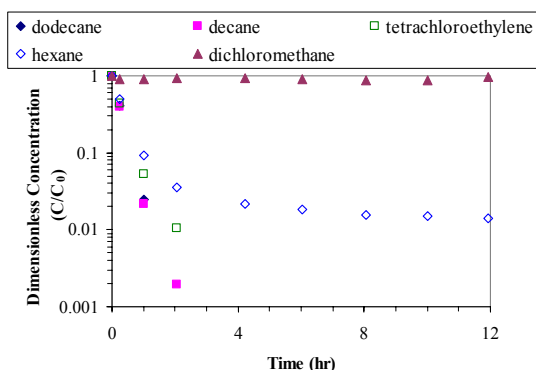

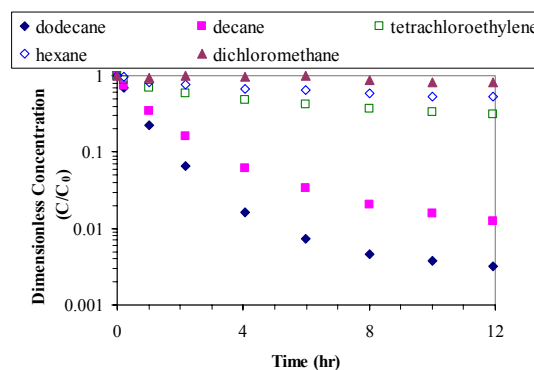*Figure 6 Individual VOC result for P1*

Figure 7 Individual VOC result for P6

DISCUSSIONS

The UV-PCO technology has been successfully demonstrated in lab reactors and prototype in-duct device (Hall et al. 1998) and regarded as a very promising technology for indoor air cleaning (Hoffmann et al. 1995). However, there are a very few commercial portable UV-PCO air cleaners available in US market. Test results showed that P8 and P9, which are UV-PCO based, could not effectively remove most test VOCs. P9 did remove d-Limonene quickly, which, however, was most likely caused by ozone oxidation. Close inspection on internal structure of these two devices revealed that the catalyst may not be properly selected and the device did not have an efficient design to provide good contact between contaminated air flow, catalyst coated surface and UV light.

For products using air ionization (plasma) and ozone oxidation (P9 to P11), results showed that they could not significantly remove any of injected VOCs except d-Limonone. Instead, all of them, especially P10 and P9, generated significant amount of ozone, which is a potent lung irritant and

is harmful to people at elevated levels. Therefore, such products are not recommended for use in office or residential rooms. 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 (i.e. d-Limonene), cannot react with ozone (below 50ppb) fast enough to compete with typical ventilation rates. The current test results are in agreement with the theory. As for the ionizers, the technology seems theoretically feasible and has been demonstrated in some lab reactors (Yan Keping et al., 1998). However, products tested did not show significant removal effectiveness for the majority of test VOCs under the current test procedure and generated significant ozone. Further study is needed to examine the design and performance of this technology.

For all sorption-based products (P1 to P7), reasonable removal of most VOCs (except dichloromethane, formaldehyde, and acetaldehyde) has been observed. The measured *CADRs* varied a lot from product to product, which are mainly due to the difference of air flow rate passing through the device, the property and amount of adsorbent material used and their packing density, and contact time between contaminated air and adsorbents. The measured *CADRs* also varied from compound to compound, indicating that the properties of VOC would influence its removal rate by sorbent material. Therefore, it is more reasonable to test gas-phase air cleaning devices with multiple "representative" VOCs instead of with toluene only as representative of TVOC. Since test results indicated that *CADRs* tend to have larger variations for lighter compounds, they should be given more priority when selecting representative compounds for testing. In addition, all these seven products have either HEPA filter or Electronic Cell to remove particulates as well and some of them have marked *CADRs* for dust, tobacco smoke and pollen by AHAM. It was found that the gas-phase filtration efficiencies are significantly lower than that of particulates. For example, the ratio of the calculated average $CADR_{1hr}$ for tested VOCs to the average *CADR* for dust, tobacco smoke and pollen was 28% for product P4 and only 11% for product P6. The same phenomenon has been observed by Niu et al. (1998).

Although the above "pull-down" test procedure has successfully identified the difference of initial removal efficiencies between different room air cleaners and between different VOC for each room air cleaner, the measured *CADRs* could be influenced by the selection of experimental parameters, such as the number of injected VOCs, target VOC initial concentration levels, the time length of test period, temperature and relative humidity. Most of experimental parameters selected in this study worked reasonably well, except that lower formaldehyde and acetaldehyde initial concentrations (i.e. $0.5 - 1$ mg/m^3) should be used for better representation of indoor conditions. In addition, for sorption-based products, only initial performance can be measured under the above procedure. Knowing that their long-term performance might be quite different due to the gradual saturation of adsorbents, it is perhaps necessary to also develop a standard test method for long-term performance evaluation of sorption-based products. Niu et al. (1998) proposed to test performance lifetimes of gas-phase filters by continuously injecting test compound until the jump of contaminant concentration level was observed in the chamber. Again, experimental parameters, such as the number of injected VOCs and target VOC generation rate, need to be carefully selected and validated by pilot tests.

CONCLUSIONS

Eleven commercially available portable room air cleaners have been tested on a mixture of 16 representative VOCs in a full-scale stainless steel chamber and their initial removal efficiencies have been evaluated. These products use different gas-phase contaminant removal technologies including adsorption, photocatalytic oxidation under UV irradiation (UV-PCO), ozone oxidation, air ionization and plasma decomposition. Results indicated that:

(1) Sorption filtration is still the most effective commercial technology, at least initially, for general removal of indoor gaseous pollutants, although products with activated carbon (charcoal) filter only are not effective for very light compounds such as formaldehyde, acetaldehyde and dichloromethane.

(2) Although UV-PCO has been identified as a very promising technology, its commercialization for room air cleaners is still in the beginning stage and commercially available UV-PCO based air cleaners may not perform as well as one would expect due to poor product design.

(3) 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 byproduct. They are likely to lead to unsafe ozone concentration and their removal efficiencies for most indoor VOCs cannot compete with even moderate ventilation (i.e. 0.1ACH).

(4) The "pull-down" test method is applicable for comparing and rating the initial VOC removal characteristics between different room air cleaners. The key experimental parameters (i.e. the number of injected VOCs, target VOC initial concentration levels, and the test period) and the data analysis procedure need to be specified for the method to be a standard test method similar to ANSI/AHAM Standard AC-1-2002.

This research project is still in progress. Some selected air cleaners will also be tested by continuously injecting VOCs at relatively low but constant levels to simulate more realistic indoor conditions.

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