Evaluation of gas-phase air cleaning devices—full-scale chamber test methods and results

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ABSTRACT
Various air cleaning technologies and products are commercially available to remove VOCs from indoor environment. By conducting full-scale chamber tests, this paper compares the removal characteristics for VOCs between three commercial portable room air cleaners, representing three major types of technology: sorption filtration, ultraviolet-photo-catalytic oxidation (UV-PCO) and ozone oxidation. Experimental results show that some portable room air cleaners might not have the pollutant removal efficiency as high as people expect. Cleaners that generate ozone may also lead to unsafe ozone concentration levels. This paper also discusses the challenges in evaluating cleaner performance under full-scale and multi-compound conditions.

INDEX TERMS
VOCs; Air cleaning; Activated carbon filter; UV-PCO; Ozone oxidation

INTRODUCTION
Poor indoor air quality (IAQ) can significantly affect people's health, comfort, satisfaction and productivity. Volatile organic compounds (VOCs), which can be emitted from many new building materials, furnishings and office machines, represent a major group of indoor contaminant sources and have been linked to sick building syndrome and building related illness. Various air cleaning devices have been developed to remove VOCs from indoor environment. However, there is still lack of comprehensive knowledge for related technologies and there are no test standards for performance evaluation of these products, although some draft standards have been proposed by ASHRAE.

A research project was initiated in Syracuse University recently to evaluate 15 commercial gas-phase air cleaning/purification devices. The objective was to provide comparison between different devices as well as their related technologies and provide insights to the development of standard test methods for evaluating their performance. This paper assesses the VOC removal characteristics of three commercial portable room air cleaners from pilot full-scale chamber tests. These devices represent three types of technologies commercially used for gas-phase indoor air cleaning. Sorption filtration, especially activated carbon for a general removal purpose, is the traditional and most widely used method today. Most commercial products are based on this technology. Ultraviolet-photocatalytic oxidation (UV-PCO), which removes VOCs via chemical reactions on catalyst surface under UV irradiation, has received more and more attention in recent years. However, its application in indoor air cleaning is still at the beginning stage and there are only a few products available in the US market. Products using ozone oxidation technology have a small market share in the US. They claim to remove VOCs by producing ozone—an oxidizer that can react with trace-level VOCs indoors.

EXPERIMENTAL METHOD, FACILITY AND PROCEDURE
A 'pull-down' test method was used to conduct the experiments. Figure 1 shows a conceptual schematic of this method. It consisted of three test periods: injection period, static period and

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dynamic period. Injecting known amount of contaminants into the experimental system during the injection period, followed by a static period, generated stable initial high concentration levels. Then from time zero, the dynamic period began. The room air cleaner placed inside the test chamber was turned on and the decay of contaminant concentration was measured, from which the 'clean-air delivery rate' (CADR) as well as removal efficiency of the cleaner could be calculated.

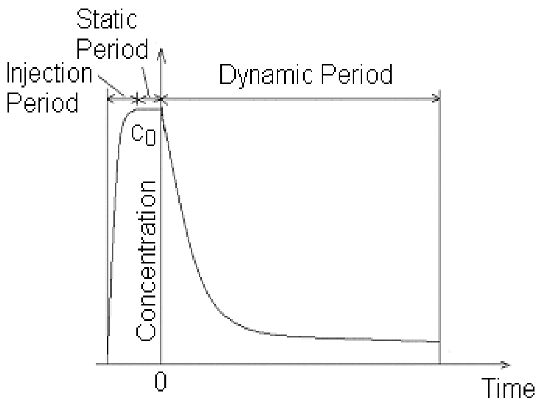

Figure 1 Conceptual schematic of 'pull-down' test method

Figure 2 Full-scale environmental chamber system

All the tests were conducted in a full-scale chamber (Figure 2), which is 4.88 m × 3.66 m × 3.05 m high (16 ft × 12 ft × 10 ft 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. Detailed description of this chamber facility and its performance evaluation (i.e. air mixing, control accuracy, etc.) can be found in Zhang et al. (2002). The chamber was operated under full-recirculation mode during the cleaner test.

Since more than 300 VOCs have been found indoors and all these compounds may not be removed by air cleaning device with same efficiencies, it is not easy to select representative VOCs for testing. There was no standard to follow and we chose a mixture of 14 VOCs, which is listed in Table 1. They cover major chemical categories and a wide range of molecular weight and boiling point for VOCs commonly found indoors. During the injection period, known amount of VOC mixture was directly heated inside the chamber and evaporated into the air.

Table 1 Components of challenge VOC mixture and their properties

Group no.	Chemical category	Chemical name	Molecular formula	MW	BP (°C)
1	Alkane	*n*-Hexane	C_6H_{14}	86.2	69
		n-Octane	C_8H_{18}	114.2	126
		n-Decane	$C_{10}H_{22}$	142.3	174
		n-Undecane	$C_{11}H_{24}$	156.3	196
		n-Dodecane	$C_{12}H_{26}$	170.3	216
2	Aromatic	Toluene	C_7H_8	92.1	111
		Ethylbenzene	C_8H_{10}	106.2	136
3	Halocarbon	Dichloromethane	CH_2Cl_2	84.9	40
		Tetrachloroethylene	C_2Cl_4	165.8	121
		1,2-Dichlorobezene	$C_6H_4Cl_2$	147.0	180
4	Aldehyde	*n*-Hexanal	$C_6H_{12}O$	100.2	128
5	Ketone	2-Butanone	C_4H_8O	72.1	80
		Cyclohexanone	$C_6H_{10}O$	98.2	156
6	Alcohol	*sec*-Butanol	$C_4H_{10}O$	74.1	99.5

Two methods have been used to measure VOC concentration levels in the chamber. A ppbRAE (Model PGM-7240) was used to continuously monitor the total organic carbon (TOC) as isobutylene. Since the ppbRAE responded to VOCs in the mixture with different sensitivity and response factor, the TVOC (represented by isobutylene) was only used as a semi-quantitative measure to characterize the trend of contaminant concentration change over time and how they differ for different air cleaning devices. At the same time, sorbent tube samples were taken during experiments and analyzed by GC-MS to obtain quantitative results of each individual compound. Ozone (O_3) concentration was continuously monitored using two demo units (API Model 265 Chemiluminescence O_3 analyzer and API Model 400A UV O_3 analyzer). In addition, CO_2 was injected into the chamber as a tracer gas and its concentration was measured to check the air leakage rate during the experiments.

Before tests for room air cleaners were made, an empty chamber test was conducted for comparison purposes, in which 0.5 ACH clean air was supplied during the dynamic period. For each air cleaner test, the air cleaner was placed inside the chamber before the injection period and turned on only during the dynamic period. The experimental conditions for each test are summarized in Table 2.

RESULTS AND DISCUSSIONS

Figures 3 and 4 show the measured TVOC as well as CO_2 level for the four tests conducted. The time length of static period and VOC initial concentrations for empty chamber test and product 1 test were the same as those used to study the sink effect of the full-scale chamber in Zhang et al. (1999). However, comparison of the TVOC level of the empty chamber test and product 1 test during the static period (Figure 3) indicated that VOCs could be adsorbed by activated carbon due to air movement inside the chamber even without turning on the room air cleaner itself. Therefore, the static period was reduced to 1 h during later tests. The reason for fluctuations of TVOC levels during static period in Figure 3 was not very clear and perhaps due to the temperature, relative humidity and pressure fluctuation in chamber under the small recirculation flow rate. The fluctuations became much smaller when increasing the recirculation flow rate to 272 m^3/h (160 CFM) for tests of products 2 and 3. The target initial contaminant concentration for each VOC was reduced to 1 mg/m^3 because observations from product 1 test indicated that the removal efficiency of air cleaner was not as high as expected. In Figures 3 and 4, CO_2 measurements showed that the air leakage rate of the chamber was small and stable during all the experiments (0.003 ACH by calculation). The decay of TVOC level during the static period for empty chamber (about 10%) reflected the effect of sampling and leak rate and the sink effect of chamber itself. Among all the tests, the TVOC was removed most effectively by 0.5 ACH clean air ventilation. Activated carbon filter had very good removal efficiency on TVOC initially, but quickly dropped down, indicating that adsorption equilibrium might have been reached. The removal efficiencies of both the ozone oxidation device and the UV-PCO device for TVOC were insignificant.

Table 2 Summary of test conditions

Test no.	Test name	Category of air cleaning technology	Target initial contaminant concentration for each VOC (mg/m^3)	Recirculation flow rate (m^3/h)	Chamber temperature set point (°C)	Chamber relative humidity set point (%)
Test 1	Empty chamber		10	136 ± 17	23 ± 1	50 ± 10
Test 2	Product 1	Sorption by activated carbon	10	136 ± 17	23 ± 1	50 ± 10
Test 3	Product 2	UV-PCO	1	272 ± 14	23 ± 0.5	50 ± 5
Test 4	Product 3	Ozone oxidation	1	272 ± 14	23 ± 0.5	50 ± 5

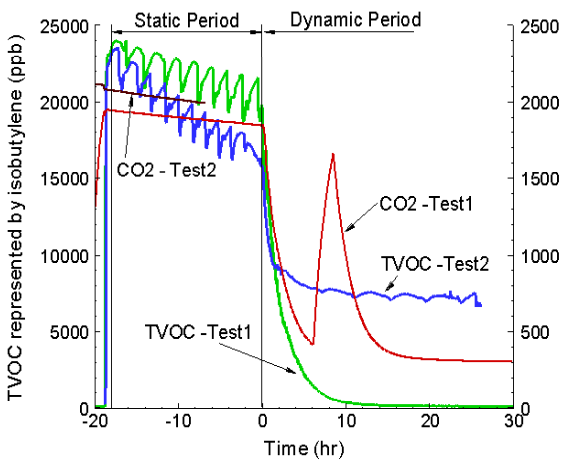

Figure 3 TVOC and CO_2 measurements for Tests 1 and 2

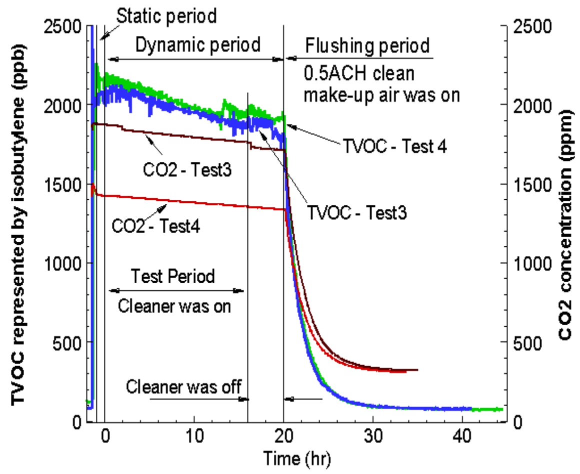

Figure 4 TVOC and CO_2 measurements for Tests 3 and 4

Assuming perfect mixing in chamber and neglecting sink effect, the mass-balance of contaminants during the dynamic period can be written as:

$$V\frac{\mathrm{d}C}{\mathrm{d}t} = -Q_c \cdot C(t) - Q_{cl}\eta \cdot C(t) \quad (t \geq 0) \quad C|_{t=0} = C_0 \tag{1}$$

where,

V = volume of the chamber system;
C = contaminant concentration inside the chamber;
t = time from beginning of dynamic period;
Q_c = clean make-up air flow rate;
Q_{cl} = air flow rate through the air cleaner;
η = remove efficiency of air cleaner.

The dimensionless concentration decay can be obtained from Eqn (1) if η is constant:

$$\bar{C}(t) = \frac{C(t)}{C_0} = e^{-\left(\frac{Q_c + Q_{cl}\eta}{V}\right)t} = e^{-\left(\frac{Q_c + \mathrm{CADR}}{V}\right)t} = e^{-(N_c + N_e)t} \quad (2)$$

where, $N_c = Q_c / V$ is the clean air exchange rate and $N_e = \mathrm{CADR} / V$ can be called the 'equivalent' clean air exchange rate for the air cleaner.

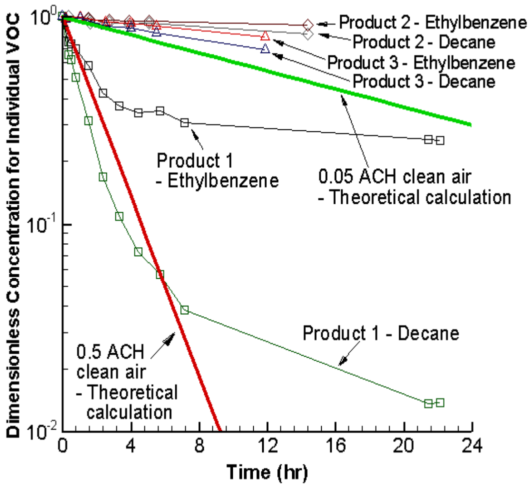

Figure 5 Comparison between tested room air cleaners

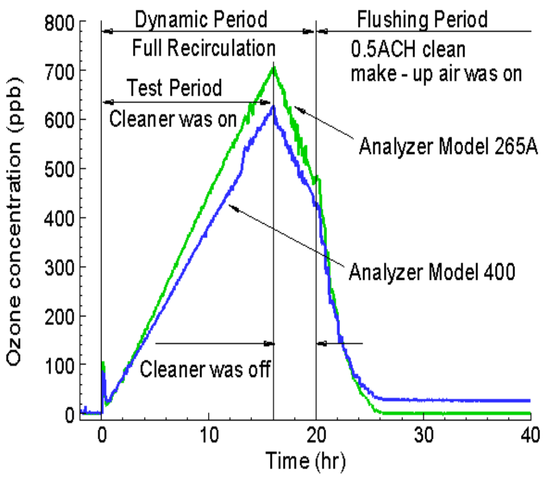

Figure 6 Possible unsafe ozone concentration with ozone oxidation technology

Figure 5 compares the concentrations of two individual VOCs measured during the dynamic period between tested room air cleaners. Concentration decay curves based on the theoretical calculation for 0.05 and 0.5 ACH clean air ventilation, respectively, are also presented in Figure 5. The dimensionless concentrations were used to facilitate the comparison. Results indicated that the room air cleaner with activated carbon filter was effective. However, it did not remove all the VOCs at the same rate. For example, it removed decane more quickly and efficiently than ethylbenzene under experimental conditions, indicating that carbon filter might have adsorption affinity to heavier compound when challenged by a group of VOCs. For ozone oxidation device, individual VOC analysis results verified that they could not effectively remove any of the tested VOCs (N_e < 0.05 ACH). Weschler (2000) also found that ozone has very slow reaction rate with most of VOCs under low concentration levels, indicating that it may not be an effective method for typical indoor VOC removal. In addition, recommended upper limits on ozone concentration in the air are in the range of 80–120 ppb. A much higher ozone concentration was observed during the test of product 3 (Figure 6), which means the use of this ozone oxidation air cleaner is potentially harmful to human health. The difference of the two ozone analyzer measurements were mainly caused by the interferences of some of VOCs used in experiments on the commonly used UV O_3 analyzer. As for the UV-PCO device tested, individual VOC analysis indicated that its removal efficiency for any of the tested VOCs was insignificant (N_e < 0.05 ACH), which was not in agreement with published results of other UV-PCO devices (Hall *et al.*, 1998). By taking a further step to investigate the internal structure of the device, it was found that the product did not have an efficient design to provide good contact between contaminated airflow, catalyst coated surface and UV light.

SUMMARY AND CONCLUSIONS

Three commercial portable room air cleaners, which were advertised as using three different technologies capable of removing VOCs and odours, have been tested on a selected VOC mixture and their performance have been compared. Comparison has also been made between air cleaning devices and ventilation (0.5 ACH). Results showed that:

1. Ventilation, if adequate, was a reliable and effective way for contaminant removal and it removed different VOCs at the same rate.
2. Among the three air cleaners tested, activated carbon filter showed the best removal efficiency and it was more effective for heavier VOCs under the contaminant concentration level tested. Both ozone oxidation and UV-PCO device showed insignificant removal efficiency for the VOCs tested, indicating that specific commercial products may not work as advertised.
3. Additional attentions should be given on possible unsafe ozone concentration whenever room air cleaners with ozone generation are used.
4. Since the air cleaner may have different removal efficiency for different compounds, TVOC can be only used as a semi-quantitative measure. It is necessary to conduct multi-compound test and calculate CADR for each VOC.
5. The 'pull-down' test method is applicable for comparing and rating the initial VOC removal characteristics between different room air cleaners.

ACKNOWLEDGEMENT
The authors are grateful for the support of Niagara Mohawk - a National Grid Company, New York State Energy Research and Development Authority (NYSERDA), NYIEQ Center Inc., and CASE Center at Syracuse University.

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