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Characterizing gaseous air cleaner performance in the field

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Abstract

As part of an ongoing effort to better understand the performance of indoor air cleaners in buildings, the National Institute of Standards and Technology (NIST) has completed a series of gaseous air cleaner field tests and model simulations. This paper focuses on experiments to measure the removal of decane with a sorption-based in-duct gaseous air cleaner and a sorption-based portable air cleaner in a single-zone test house. Due to the lack of standardized gaseous air cleaner field testing protocols, a field test method was developed using semi-real-time concentration measurements and mass balance analysis. A total of 24 experiments were completed with directly measured single-pass removal efficiencies ranging from 24% to 56% and removal efficiencies based on a transient whole building mass balance ranging from 30% to 44%. Experimental results revealed important factors affecting field performance such as air cleaner contaminant loading for the in-duct air cleaner and room air mixing for the portable air cleaner. An additional six tests were conducted to evaluate the predictive capability of the indoor air quality model CONTAM.
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Keywords: Activated carbon air cleaner; Building study; Indoor air; Model evaluation; VOC transport

1. Introduction

Air cleaners that remove gaseous contaminants have primarily been used for protecting materials and artifacts (e.g., in museums) and for industrial applications (e.g., in semi-conductor manufacturing facilities). However, the use of gaseous air cleaners in other types of buildings could potentially reduce occupant exposure to a myriad of hazardous volatile organic compounds (VOCs). Exposure to VOCs, even at low non-industrial concentrations, has been linked to a number of health outcomes, including upper respiratory irritation, neurological symptoms, and cancer [1]. Using gaseous air cleaners in non-industrial buildings also has the potential to save the United States billions of dollars by reducing sick building syndrome symptoms and improving worker productivity [2].

At present, residential and commercial gaseous air cleaning technologies have not gained wide acceptance in the marketplace, in part due to the lack of test methods and rating systems and the existence of only limited field performance data. Currently, there are no standard test methods for gaseous air cleaners, and there is no system in place to rate the performance of these devices in the field. For the most part, gaseous air cleaning performance data are based on laboratory testing, which often involves high challenge concentrations, a limited number of contaminant species, and controlled temperature and relative humidity (RH) [3,4]. In real buildings, air cleaners may be exposed to hundreds of contaminants over a broad range of concentrations, temperatures and relative humidities, all of which may impact air cleaner performance [5]. Additional issues impacting field performance include whole building mixing for a portable device, bypass of contaminated air around an in-duct air cleaner, and reduction of contaminant removal capacity over time for both types of cleaners.

The testing and standardization needs raised above are part of the broader issue of understanding and evaluating the installed performance of filtration and gaseous air cleaning systems in buildings. While laboratory, including chamber, performance has been studied and some important particle filtration standards exist [6–8], significant questions remain regarding the impact of these devices on indoor contaminant levels as installed in the field, and how

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well these tests relate to such performance. For example, air cleaner manufacturers typically report their products' performance as single pass removal efficiency based on contaminant concentrations measured at the inlet and outlet of the device. This single pass removal performance metric may be used to compare different air cleaners; however, it does not indicate the device's impact on building contaminant concentrations relative to other removal mechanisms (e.g., air exchange and sinks) [9]. The Association of Home Appliance Manufacturers (AHAM) established another performance metric, the clean air delivery rate (CADR), which is based on an air cleaner's reduction of particles as measured in a room size chamber [8]. This is a useful metric for comparing contaminant removal of devices for a given room volume and environmental conditions, but, again, it does not predict an air cleaner's impact when installed in a multi-zone building with variable air change rates, nonuniform air distribution patterns, variable temperature and relative humidity, and contaminant sinks associated with building materials and furnishings.

In order to address some of these issues, the National Institute of Standards and Technology (NIST) is conducting a study to better characterize building air cleaner performance as it relates to device efficiency and installation conditions. To meet this objective, several tasks are being pursued, including: (1) measuring the impact of gaseous air cleaners in single and multi-zone test houses, (2) determining important factors affecting gaseous air cleaner field performance, and (3) using an IAQ model to relate laboratory chamber performance metrics to whole building air cleaner performance. This paper provides data from the initial phase of air cleaner tests and model simulations using a single zone test house. The primary objective of these initial tests was to develop a field test method that could be used to assess air cleaner performance in a relatively simple building. The test protocol was evaluated using a portable sorption-based room air cleaner and an ''in-duct'' sorption-based air cleaner to remove decane. Additional objectives of these initial tests were to identify potential factors that may impact air cleaner performance, as well as to evaluate the capability of the IAQ model CONTAM [10] to predict gaseous air cleaner performance in a real building. The lessons learned from these initial tests are being applied to the next phase of experiments and simulations in a multi-zone building.

2. Experimental methodology

The most direct way to measure the removal efficiency (η_{dir}) of an air cleaner is based on the contaminant concentrations at the device inlet and outlet using the equation:

$$\eta_{dir} = 1 - \frac{C_{out}}{C_{in}}, \tag{1}$$

where η_{dir} is the single pass removal efficiency of the device measured directly (-), and C_{in} and C_{out} are the inlet and outlet contaminant concentrations (mg/m^3), respectively. This direct single pass removal efficiency, however, does not account for air cleaner installation issues (e.g., short-circuiting, bypass, whole house mixing, etc.) and is not a measure of the air cleaner's ability to remove contaminants from the whole building [9]. To account for several of these installation issues, AHAM developed a test protocol for evaluating a portable air cleaner's ability to remove particles from a room size chamber [8]. The test method consists of two particle decays—one to measure the decay of the particles in the chamber due to other mechanisms such as deposition and dilution, and a second to measure the decay of particles with the air cleaner operating. The difference between these two decay rates is attributed to the air cleaner. The resulting removal rate is expressed as the clean air delivery rate (CADR)

$$CADR = V(k_e - k_n), \tag{2}$$

where CADR is the equivalent volume of clean air provided to the space by an air cleaner (m^3/h), V is the volume of the test chamber (m^3), k_e is the total decay rate with air cleaner operating (1/h), and k_n is the natural decay rate without air cleaner operating. Although written for particle removal by portable air cleaners, this method has been applied to measure the removal of gaseous contaminants by air cleaners in chambers [3,11]. While this method is more realistic than the direct measure of air cleaner performance, it still does not take into account zonal mixing and dynamic mass transport issues in a real building.

In order to fully understand an air cleaner's ability to reduce contaminant concentrations in a real building requires field-testing. However, there is not a standardized field method currently available. The CADR approach outlined above cannot be easily applied in the field due to the dynamic mass transport conditions (e.g., weather dependent air change rates, variable temperature and relative humidity, and multiple sorption sites) present in real buildings and the multi-zone airflow characteristics of buildings. As a result, a transient mass balance model is needed to account for dynamic conditions during air cleaner field evaluations.

2.1. Measurement approach

The field evaluation of two types of air cleaners was conducted in a single zone test house located in Gaithersburg, MD (approximately 35 km northwest of Washington, DC). A floor plan of the house with experimental equipment and sampling locations is shown in Fig. 1. The test house was of typical residential, wood-frame construction and consisted of a single room with an attic. The conditioned space had a volume of 85 m^3 and a floor area of 37 m^2. The house was unfurnished except for monitoring equipment and had painted gypsum board
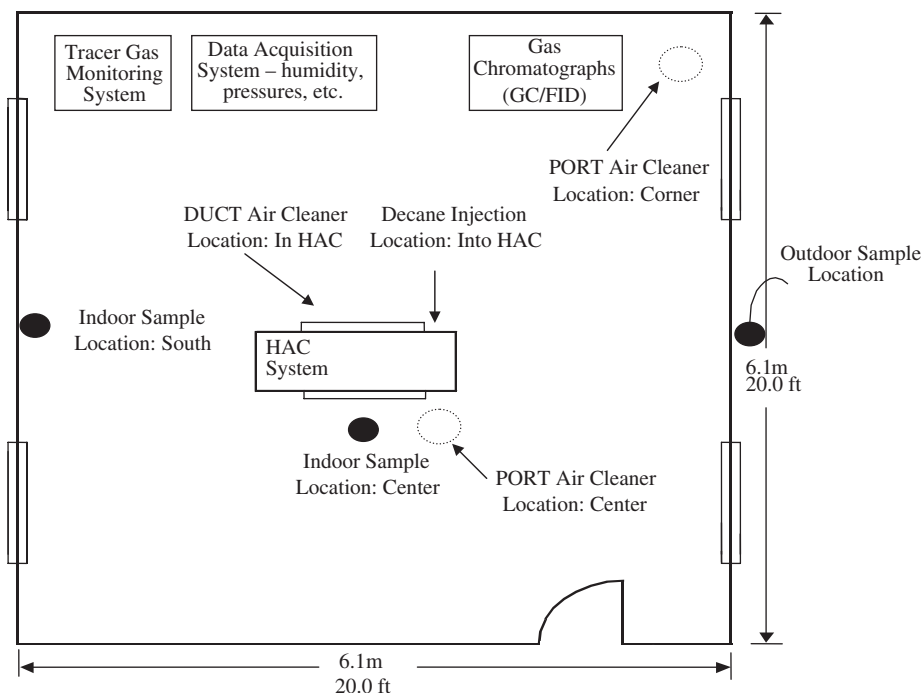
Fig. 1. Test house floor plan with instruments and sample locations.

ceiling and walls and a concrete floor, resulting in an approximate surface area-to-volume ratio of $1.5\,m^{-1}$. The test house had a relatively small recirculating heating and air-conditioning (HAC) system (approximate airflow of $340\,m^3/h$ with air cleaner installed) that included a 4.1 kW electric-resistance furnace and a 3.8 kW air conditioner. A more detailed description of the test house and its HAC system is found in Emmerich and Nabinger [12].

The house infiltration rate was determined by measuring the decay of sulfur hexafluoride (SF_6) concentration as described in ASTM E 741 [13]. Every 6 h, SF_6 was automatically injected into the house to an average initial concentration of approximately $0.72\,mg/m^3$. Subsequent SF_6 concentrations were measured every 10 min at three indoor locations, the attic and outside with a gas chromatograph and electron capture detector (GC/ECD). Multiple indoor sample locations were used to ensure the variation in indoor SF_6 concentration among the indoor locations was within 10%, thereby meeting the ASTM E 741 uniformity requirement. The measurement range of the GC/ECD was $0.03–0.9\,mg/m^3$ with an accuracy of approximately $\pm 2\%$. A linear regression of the natural logarithm of the SF_6 decay data was used to estimate the house air change rate every hour. The estimated uncertainty of the measured air change rates was approximately $\pm 10\%$.

Indoor and outdoor environmental conditions were continuously monitored during the tests. Temperature was measured every minute in a central indoor location and outdoors with thermistors (accuracy of approximately $\pm 0.4\,^{\circ}C$). Relative humidity was also measured every minute in a central indoor location and outdoors using bulk polymer resistance sensors with an accuracy of $\pm 3\%$ RH. Wind speed and direction were measured with a sonic anemometer mounted 3.5 m above the crest of the test house roof. The anemometer was capable of measuring wind speeds from 0 to 50 m/s ($\pm 5\%$) with a resolution of 0.1 m/s. For wind speeds above 4.5 m/s, the wind direction had an accuracy of $\pm 5\%$ but there was no specification of the accuracy for lower wind speeds.

For simplicity, a single challenge contaminant, decane, was used for these initial phase tests to develop a field methodology. A more comprehensive test protocol would presumably include a wide range of contaminants to evaluate air cleaner performance. Decane was generated using a refillable permeation tube in the heated oven of a gas generator and injected into the test house at an average rate of 20 mg/h ($\pm 2\%$) corresponding to a steady-state concentration of approximately $1\,mg/m^3$ in the test house, a similar concentration level used in other air cleaner testing [3]. Decane concentrations were measured every 30 min using portable gas chromatographs equipped with flame ionization detectors (GC/FID). Samples were collected for 10 min at $0.0006\,m^3/h$ using an air sample pump and polytetrafluoroethylene (PTFE) tubing. Measurement locations generally included a central indoor location, upstream and downstream of the air cleaner, and outside. Samples were concentrated on the GC sorbent trap before desorption and injection into the GC column for analysis. The GC/FIDs were calibrated regularly to measure decane concentrations up to $1.5\,mg/m^3$ with an uncertainty of $\pm 5\%$.

Two types of air cleaners were tested: an in-duct model (DUCT) that was installed in the HAC system return; and

a portable air cleaner (PORT) located either in the center or corner of the room. The in-duct air cleaner media consisted of a pleated fiber matrix impregnated with approximately 0.6 kg of activated carbon, alumina, and potassium permanganate in a 30 cm × 61 cm × 10 cm filter housing. The overall effective cleaning rate for this type of air cleaner is also dependent on the duct airflow rate, which was continuously measured during tests with a hot wire anemometer with an accuracy of approximately ±2%. The average duct airflow rate was 340 m³/h ± 15 m³/h with the air cleaner installed and was not significantly affected by the use of either the furnace or air conditioner. The HAC system operated continuously during the DUCT air cleaner tests.

The portable air cleaner had a cylindrical design that consisted of an inner sorbent cartridge containing approximately 2.7 kg of charcoal, potassium permanganate, and zeolite. The air cleaner filtering system also included a high-efficiency particulate air (HEPA) filter, an activated carbon pre-filter, and an outer protective screen. The air cleaner's diameter was 40 cm, resulting in a 125 cm circumference through which air can be recirculated. The air cleaner airflow rate was measured using a plastic shroud to enclose the device and performing a velocity traverse with a hot wire anemometer of a duct exiting the shroud. The tests were conducted with the air cleaner set at its maximum airflow setting resulting in an average flow rate of 350 m³/h with an uncertainty of 20%. Additional measurements were made to determine whether the existence of any backpressure within the shroud impacted the airflow through the air cleaner, and no significant impact was found. The measured airflow rate is considerably lower than the manufacturer reported airflow rate of 510 m³/h. However, the configuration of the air cleaner used in these tests has changed since the manufacturer determined the higher airflow rate. In addition, measuring a lower airflow rate than reported by the manufacturer is not uncommon, as documented by others [11,14].

In addition to evaluating different methods to predict air cleaner performance, experiments were designed to identify important factors that affect air cleaner performance in the field. The scope of this work does not include air cleaner design parameters (e.g., bed depth, packing density, type of adsorbent, residence time of air flow, etc.), which are better studied in a laboratory. The focus, rather, was on application parameters including building sinks, variable air change rates, environmental conditions and mixing. To account for these factors, the following conditions were varied: RH, HAC operation, and portable air cleaner location in the room. To vary the indoor RH, a room humidifier was used to elevate the water vapor level for high RH tests. This method created a range of RH levels between 17% and 70% (within the house) for the different test conditions. For DUCT air cleaner tests, HAC operation was set to heating or air conditioning. For PORT air cleaner tests, the HAC fan was set to on and off, with no furnace filter present. Only the PORT air cleaner

Table 1
Air cleaner experimental design

	Factors		
	RH	HAC	Location
DUCT			
1	Low	On/AC	Duct
2	High	On/AC	Duct
3	Low	On/heat	Duct
4	High	On/heat	Duct
PORT			
1	Low	On	Center
2	High	On	Center
3	Low	On	Corner
4	High	On	Corner
5	Low	Off	Center
6	High	Off	Center
7	Low	Off	Corner
8	High	Off	Corner

location could be changed. Two locations were chosen including the center and corner of the room. To study these application factors, a 2^2 factorial design with replication was used for the DUCT air cleaner and a 2^3 factorial design with replication was used for the PORT air cleaner (see Table 1). The response variable for both designs was the air cleaner removal rate of decane.

2.2. Analysis approach

In order to address the material sorption impacts in the single zone building employed in the testing described in this paper, a two-phase mass balance model was used to characterize the removal of mass in a building. In this effort, the mass balance model was for a single zone test house and included a decane source, weather-driven air infiltration, a boundary layer diffusion controlled (BLDC) sink model [15], and an effective air cleaner removal efficiency. The equations used to determine the room air concentration (C) and sorbent concentration (C_m) are:

$$V\frac{dC}{dt} = G + QC_{out} - QC + \frac{hA}{K_p}C_m - hAC - \eta_{mb}Q_{ac}C,$$

(3)

$$A\frac{dC_m}{dt} = hAC - \frac{hA}{K_p}C_m,$$

(4)

where V is the volume of building air (m³) and A is the sorbent material surface area (m²); C and C_{out} are the decane concentration indoors (mg/m³) and outdoors (mg/m³), respectively; C_m is the decane concentration in the sorbent (mg/m²); G is the decane emission rate (mg/h); Q is the outdoor air ventilation rate (m³/h); h is the film mass transfer coefficient acting over the sorbent surface (m/h); K_p is the equilibrium partition coefficient (m); η_{mb} is the effective single pass removal efficiency of the installed

air cleaner (-); Q_{ac} is the airflow rate recirculated through the air cleaner (m^3/h); and t is time (h).

Eqs. (3) and (4) were solved simultaneously to determine C and C_m. Due to the dynamic nature of the test house conditions (e.g., variable air change rate, etc.), the mass balance solutions were solved numerically as described by Persily et al. [16]. All necessary parameters for the model solution were directly measured or estimated except for K_p, A, M_s, and η_{mb}. To determine these parameters, the experiments were divided into two phases. In the first phase, decane was injected at a constant rate and allowed to reach a quasi-steady-state concentration (C_{ref}) (see Fig. 2). During this initial injection period, without the presence of an air cleaner, the sorption parameters (K_p, A, and M_s) were estimated using a curve fitting routine based on the generalized reduced gradient (GRG2) nonlinear optimization code [17]. In the second phase of the experiment, the air cleaner was added and decane concentrations were reduced to a new steady state (C_{ctrl}). Using the sorption parameters determined in the previous phase, the air cleaner removal efficiency (η_{mb}) was calculated, again using the GRG2 nonlinear optimization code.

It is also possible to eliminate the curve-fitting part of this method to determine air cleaner whole house removal by using the steady-state solution to Eqs. (3) and (4). However, this method may involve some loss of accuracy if conditions are not at a true steady state, i.e., sinks are not at equilibrium or an air change rate is highly variable (e.g., during a windy day). Assuming a constant Q, the associated steady-state solution of Eqs. (3) and (4) are rearranged as follows:

$$C_{ctrl} = \frac{G + QC_{out} + (hA/K_p)C_{m,ctrl}}{Q + \eta_{ss}Q_{ac} + (hA/K_p)}, \tag{5}$$

$$C_{m,ctrl} = C_{ctrl}K_p, \tag{6}$$

where C_{ctrl} is the steady-state concentration of decane with an air cleaner operating (mg/m^3), η_{ss} is the effective single pass removal efficiency of the air cleaner based on

steady-state conditions (-), and $C_{m,ctrl}$ is the steady-state concentration in the sorbent (mg/mg), corresponding with time of C_{ctrl}.

Substituting Eq. (6) into Eq. (5) results in

$$C_{ctrl} = \frac{G + QC_{out}}{Q + \eta_{ss}Q_{ac}}. \tag{7}$$

For a given experiment, all variables in Eq. (7) are directly measured except the single pass removal efficiency (η_{ss}) of the air cleaner. So when a steady-state concentration is reached, the mass balance in Eq. (7) allows the determination of the air cleaner removal efficiency.

For Phase I of the experiment when the air cleaner is off, Eq. (7) may be simplified to

$$C_{ref} = \frac{G}{Q} + C_{out}, \tag{8}$$

where C_{ref} is the steady-state concentration of decane without an air cleaner operating (mg/m^3).

The steady-state concentration values of Eqs. (7) and (8) may also be used to determine the impact or effectiveness (ε) of using an air cleaner in this single zone environment. Nazaroff [9] defined effectiveness as "the fractional reduction in pollutant concentration that results from application of a control device." At steady state, air cleaner effectiveness may be directly determined as follows:

$$\varepsilon = 1 - \frac{C_{ctrl}}{C_{ref}}. \tag{9}$$

3. Experimental results

Sixteen experiments were completed with the portable (PORT) air cleaner and eight experiments were completed with the in-duct (DUCT) air cleaner (see Table 2). A primary objective of this work was to explore different methods to assess air cleaner performance in the field. For each experiment, the air cleaner removal rate was determined three different ways: (1) direct measurement of the decane concentration at the inlet and outlet of the device (η_{dir}), (2) a transient mass balance model fit to the decane concentration measured in the center of the room (η_{mb}), and (3) a steady-state mass balance (η_{ss}) using the steady-state concentration of decane measured in the center of the room. The removal efficiencies for each method are presented in Table 2. In most cases, the direct measurement method (η_{dir}) yielded the highest removal efficiencies with an average value of 38% (standard deviation ± 11%) for the DUCT air cleaner and 43% (± 9%) for the PORT air cleaner. The mass balance curve fit approach (η_{mb}) tended to predict the next highest removal efficiencies with an average of 35% (± 3%) for the DUCT air cleaner and 38% (± 4%) for the PORT air cleaner. Finally, the average removal efficiencies determined with the steady-state approach (η_{ss}) were 31% (± 6%) and 34% (± 6%) for the DUCT and PORT air
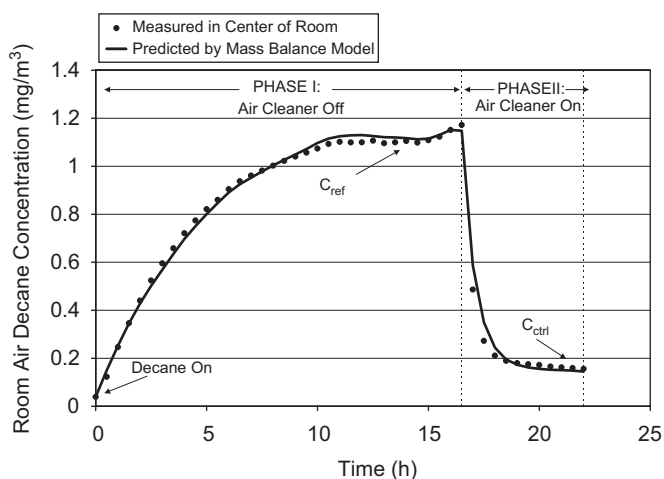

Fig. 2. Two-phase experimental design and transient mass balance curve fit.

Table 2
Air cleaner test conditions and removal efficiencies measured in test housed

Expt. #	Location	HAC setting	Indoor temp. (°C)[a]	Indoor RH (%)[a]	Air change rate (h⁻¹)[a]	η_{dir} (%)[b]	η_{mb} (%)[c]	η_{ss} (%)[d]	ε (%)
DUCT air cleaner									
1a	In-duct	On/AC	22 ± 3.1	31 ± 1.7	0.12 ± 0.02	43 ± 8	33 ± 8	23 ± 5	89
1b	In-duct	On/AC	26 ± 2.5	28 ± 2.2	0.11 ± 0.01	24 ± 11	36 ± 9	26 ± 6	90
2a	In-duct	On/AC	21 ± 1.4	46 ± 3.2	0.20 ± 0.03	29 ± 10	30 ± 8	28 ± 7	87
2b	In-duct	On/AC	24 ± 2.5	42 ± 2.6	0.11 ± 0.02	51 ± 7	32 ± 8	24 ± 6	90
3a	In-duct	On/heat	22 ± 0.7	23 ± 0.5	0.38 ± 0.03	35 ± 9	38 ± 10	40 ± 9	84
3b	In-duct	On/heat	21 ± 1.7	17 ± 1.0	0.49 ± 0.06	45 ± 8	38 ± 10	38 ± 9	84
4a	In-duct	On/heat	20 ± 1.4	66 ± 2.6	0.37 ± 0.02	27 ± 10	35 ± 9	34 ± 8	82
4b	In-duct	On/heat	21 ± 0.6	64 ± 2.9	0.26 ± 0.03	51 ± 7	35 ± 9	32 ± 7	86
PORT air cleaner									
1a	Center	On/none	28 ± 2.6	35 ± 0.7	0.23 ± 0.04	43 ± 8	40 ± 10	35 ± 8	87
1b	Center	On/heat	21 ± 1.0	20 ± 0.6	0.36 ± 0.01	53 ± 7	38 ± 10	36 ± 8	83
2a	Center	On/heat	22 ± 1.1	66 ± 2.6	0.50 ± 0.04	29 ± 10	35 ± 9	35 ± 9	80
2b	Center	On/heat	24 ± 0.5	60 ± 2.3	0.35 ± 0.05	51 ± 7	43 ± 11	43 ± 10	86
3a	Corner	On/none	19 ± 1.2	31 ± 0.2	0.31 ± 0.01	35 ± 9	43 ± 11	28 ± 7	84
3b	Corner	On/heat	20 ± 0.7	19 ± 0.5	0.28 ± 0.02	45 ± 8	44 ± 11	42 ± 10	86
4a	Corner	On/heat	19 ± 1.2	66 ± 2.7	0.37 ± 0.04	27 ± 10	43 ± 11	39 ± 9	86
4b	Corner	On/heat	22 ± 0.8	64 ± 3.1	0.23 ± 0.03	51 ± 7	42 ± 11	42 ± 10	88
5a	Center	Off	30 ± 2.4	36 ± 0.9	0.38 ± 0.06	43 ± 8	32 ± 8	25 ± 7	86
5b	Center	Off	26 ± 1.8	34 ± 0.6	0.20 ± 0.05	38 ± 9	33 ± 8	27 ± 6	87
6a	Center	Off	27 ± 1.9	60 ± 2.9	0.32 ± 0.04	41 ± 8	35 ± 9	33 ± 8	87
6b	Center	Off	31 ± 1.8	60 ± 2.6	0.19 ± 0.02	37 ± 9	33 ± 8	25 ± 6	86
7a	Corner	Off	20 ± 1.3	39 ± 1.2	0.39 ± 0.08	56 ± 6	35 ± 9	37 ± 9	83
7b	Corner	Off	24 ± 2.6	35 ± 0.9	0.22 ± 0.02	40 ± 9	35 ± 9	30 ± 7	86
8a	Corner	Off	27 ± 1.1	70 ± 1.1	0.43 ± 0.09	56 ± 6	39 ± 10	39 ± 9	87
8b	Corner	Off	27 ± 1.9	61 ± 2.8	0.24 ± 0.06	42 ± 8	34 ± 9	32 ± 8	89

[a] Average value during air cleaner installation ± standard deviation.
[b] Based on upstream and downstream measurement ± uncertainty.
[c] Based on best-fit line to transient data.
[d] Based on steady-state value ± uncertainty.

cleaners, respectively. When compared to chamber test results for similar gaseous air cleaners [3,11], the air cleaners tested for this project appear highly effective at removing VOCs. For example, Chen et al. [3] found the average single pass removal efficiencies of decane to be 3.4% and 31% for a similar in-duct gaseous air cleaner and portable gaseous air cleaner, respectively. Also, as shown in the last column of Table 2, the predicted effectiveness (ε) for both air cleaners while operating was always greater than 80%, a rating criteria set by AHAM's CADR method for portable particle air cleaners [8].

As shown in Table 2, each experimental condition was completed twice to assess the reproducibility of the results. The transient mass balance approach produced the most consistent results for a given test conditions, with all but two test conditions within 10% of one another. It is unclear why the direct measurement did not give more reproducible results for a given test condition. One possibility is that the sample line for the air cleaner outlet may have slipped during some experiments resulting in a mixed sample volume of air cleaner exhaust air as well as room air, thereby reducing the directly measured removal efficiency in some cases. Another possibility is that the decane concentration varied across the outlet of the air cleaners. Due to its consistent results and ability to account for the

effects of dynamic test conditions, the mass balance fit results (η_{mb}) was used for the factorial analysis portion of this paper.

Another objective of this work was to evaluate the impact of several factors on air cleaner performance in a real building. Over the course of the experimental schedule, however, an additional factor was identified that may overwhelm the impact of the predefined factors. The single DUCT air cleaner used in all experiments showed a marked decrease in removal as a function of contaminant mass loading, and to a much lesser extent, so did the single PORT air cleaner. In Fig. 3a, a linear fit of the data ($R^2 = 0.62$) shows a decrease in the decane removal efficiency of the DUCT air cleaner as a function of the integrated mass of decane passing through the device over the course of the testing, with a slope of negative 0.0013% per mg of decane. Over the period of all eight experiments, the DUCT air cleaner was exposed to approximately 5000 mg of decane making the absolute difference between the initial and final experiment 7%. With the measured range of removal efficiencies only 30% to 38% for the given experimental factors, it was not possible to account for this loss in capacity of the DUCT air cleaner and complete the factorial analysis. It should also be noted that the stoichiometric amount of decane that
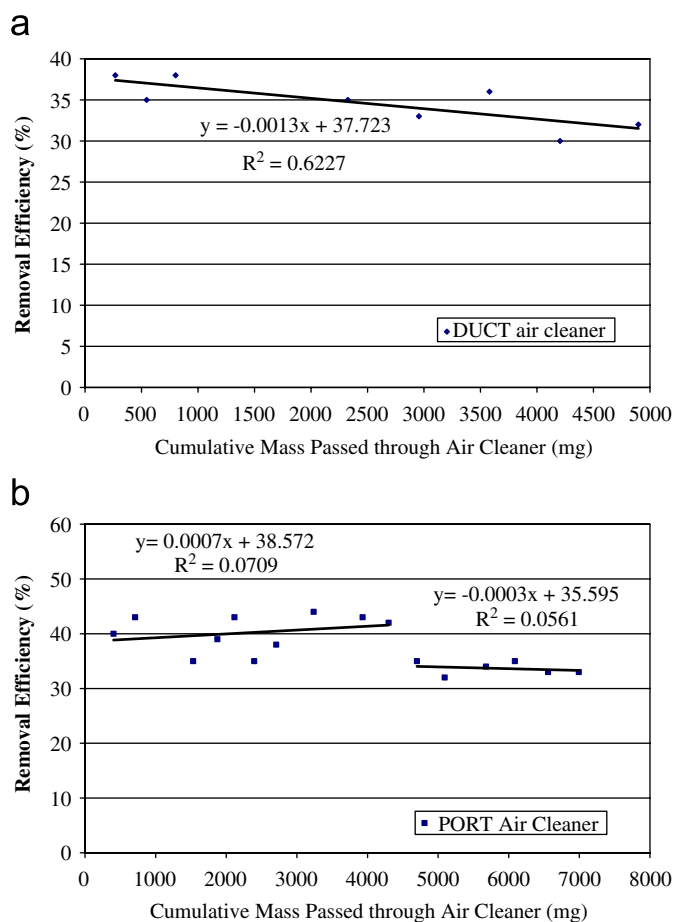
a

b

Fig. 3. Removal efficiency (η_{mb}) as a function of cumulative mass passed through (a) DUCT air cleaner and (b) PORT air cleaner.

Fig. 4. Factorial analysis for PORT air cleaner using mass balance fit removal efficiencies.

4. Discussion

Although use of air cleaners are clearly effective at removing decane in this test house ($\varepsilon \geqslant 80\%$), the issue is whether they are as effective as a laboratory chamber test would predict. Results from these initial air cleaner tests and simulations provide some insight regarding this question and form the foundation for future multi-zone building tests.

In an ideal situation, the three different approaches to predict air cleaner removal would yield the same result. However, if the room air concentration was not being reduced at the same rate as the air cleaner inlet concentration, there will be a discrepancy between the methods. For the single zone test case, the removal efficiency methods did not vary too much in their predictions; however, there was a clear trend where removal efficiencies predicted by the direct measurement (η_{dir}) were usually greater than the removal efficiencies predicted by the transient mass balance fit method (η_{mb}). Also, the removal efficiencies predicted by the transient mass balance fit method tended to be consistently greater than the values predicted by the steady-state solution method (η_{ss}). This trend indicates that the room air concentration is not being cleaned at the same rate as the air cleaner inlet air and that room conditions were not consistently reaching steady state. Corroborating this evidence for the portable air cleaner is the limited factor analysis results, which showed a higher removal efficiency (as measured by the transient mass balance approach) when the HAC fan was on and mixing the room air. In fact, the average of the transient mass balance removal efficiencies for this condition is 43%, matching the overall average removal efficiency as measured by the direct method.

These initial tests also revealed the potential importance of gaseous air cleaner capacity on field performance. Contaminant loading is an important field factor that is not taken into account in current laboratory performance metrics for gas-phase air cleaners. These tests showed that

can be decomposed by the potassium permanganate in the DUCT air cleaner was predicted to be approximately 3000 mg.

Similar to the DUCT air cleaner, the PORT air cleaner also showed a trend of a reduced capacity over time. However, as shown in Fig. 3b, the decrease for this air cleaner appears to follow a step function where there is no apparent loss of capacity until approximately 4500 mg, at which point the remaining experiments produced lower removal efficiencies. Since it is unclear as to the true cause of this reduction, six of the first 10 PORT experiments were regrouped to examine the field factors of relative humidity and room air mixing by the HAC fan on the mass balance predicted removal rates. The air cleaner was located in the corner for these six tests, thereby removing air cleaner location as a factor. A scatter plot of the measured removal efficiencies for Experiments 3a, 3b, 4a, 4b, 7a, and 8a is shown in Fig. 4. Based on this analysis, an absolute difference of approximately 40% RH did not have a significant impact on the decane removal by the PORT air cleaner, whereas the use of the HAC fan did affect the result. This finding suggests a localized cleaning effect for the portable air cleaner.
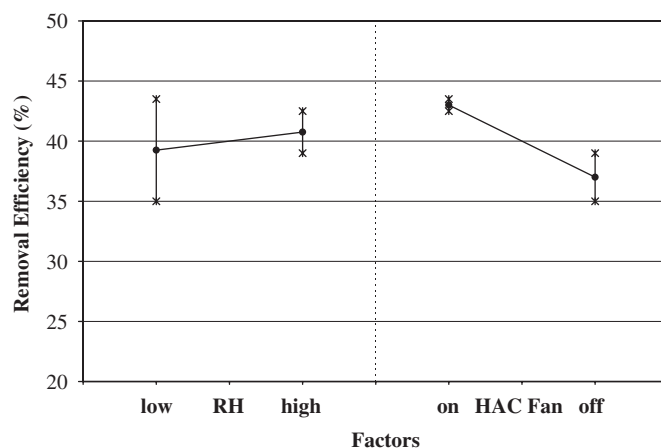
despite their different media mass and configuration, there was not a significant advantage of the PORT air cleaner over the DUCT air cleaner in terms of their initial ability to reduce contaminants in a single zone house. However, results also indicated that the performance of the DUCT air cleaner degraded at a faster rate over time than the PORT air cleaner, a phenomenon that should be reflected in an air cleaner's performance rating. Several researchers have measured reductions in the CADRs of gaseous air cleaners after several hours of use [3,11,18]. In fact, Chen et al. [3] report CADR values for sorption-based air cleaners based on a 12 h average to account for the significant reduction in performance. Although this 12 h CADR is an improvement over the initial CADR value, it is still a single value to represent an air cleaner's removal rate. In order to capture this reduction in efficiency, air cleaner models need to be expanded from a single removal efficiency value to functions that take this factor into account. Also, in order to do any sort of factor analysis, a new air cleaner should be used for every test.

One way to demonstrate the impact of an air cleaner on contaminant concentrations in a building is with an IAQ model. For this study, the predictive capability of the multi-zone IAQ model CONTAM [10] was evaluated with the objective of extending the experimental results to apply to different scenarios. To evaluate the model, six additional experiments were completed with the portable and in-duct air cleaners in the test house. These independent tests were conducted for different combinations of temperature, RH, HAC status, and location for the portable air cleaner. In addition, several of the simulations went beyond the experimental tests by allowing the air cleaners to cycle on and off. The CONTAM model of the test house is described in Howard-Reed et al. [19] and predicts the

infiltration rate based on building leakage information and indoor/outdoor temperature difference and wind speed. The model allows for reversible sink effects based on a BLDC model with a linear isotherm [15]. Although the test house contained relatively small areas for contaminant sorption (i.e., no furniture, concrete floor), sink parameters were included in the model. Model sorption parameters calculated for the test house included a mass transfer coefficient of 0.05 m/h, a film density of air of 1.2 kg/m^3, surface mass of material of 1000 kg, and a partition coefficient of 0.002 mg/mg. The model was evaluated using the environmental and weather conditions measured during the tests, and the average air cleaner removal efficiency as predicted by the directly measured concentrations (38% for DUCT air cleaner and 43% for PORT air cleaner). The directly measured values were used since they most likely represent values measured in the laboratory, thereby evaluating CONTAM's ability to relate laboratory performance to whole building performance.

Fig. 5 shows the measured and the predicted concentrations for a model validation test with the portable air cleaner. For this test, the decane was continuously emitted with the air cleaner operating intermittently in the center of the room. The HAC fan was on with an average indoor temperature of 21 °C and an average RH of 34%. As shown in Fig. 5, the CONTAM results agree relatively well with the measured data. In fact, as shown in Table 3, all six CONTAM model validation tests met the statistical criteria for assessing the accuracy and bias of model results compared to measured data as outlined in D5157-03 *Standard Guide for Statistical Evaluation of Indoor Air Quality Models* [20].

Based on the success of the single zone test case, CONTAM has the potential to provide a link between
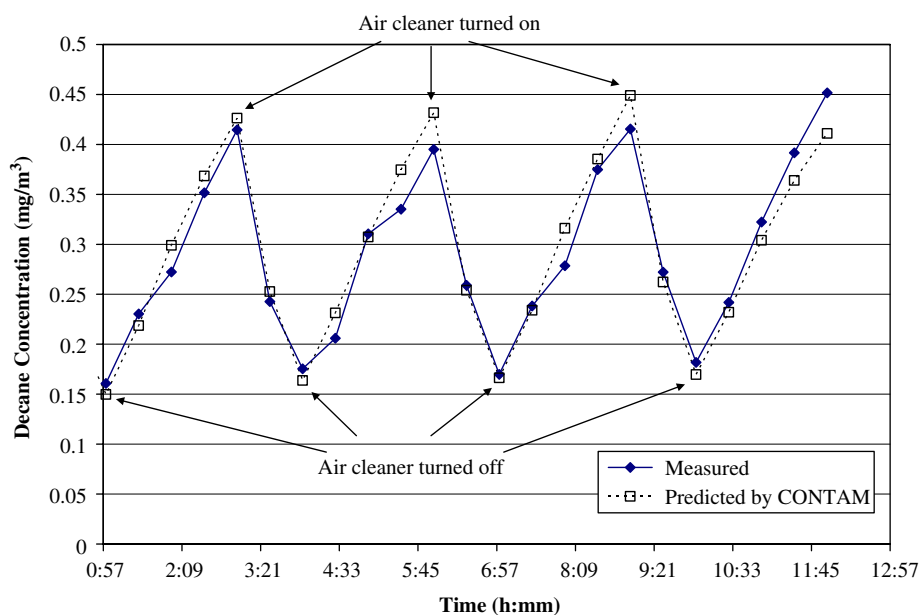

Fig. 5. Comparison of measured and predicted decane concentrations.

Table 3
Statistical parameters for simulated and measured decane concentrations

Case	η_{dir}[a] (%)	$\overline{C_o}$[b] (mg/m³)	$\overline{C_p}$[c] (mg/m³)	R[d]	b[e]	a/C_o (%)[f]	NMSE[g]	FB[h]	FS[i]
ASTM D5157 Criteria	n/a	n/a	n/a	>0.9	0.75 < m < 1.25	<25	<0.25	<0.25	<0.5
DUCT021204	38	0.12	0.11	0.99	0.89	7.8	0.0037	−0.032	−0.21
DUCT021904	38	0.48	0.47	0.99	0.85	12	0.012	−0.025	−0.29
DUCT062304	38	0.51	0.44	0.998	0.84	2.9	0.033	−0.15	−0.35
PORT021004	43	0.11	0.11	0.996	0.92	5.2	0.0011	−0.029	−0.16
PORT030804	43	0.28	0.28	0.95	1.0	−2.6	0.0097	−0.025	0.095
PORT062404	43	0.70	0.59	0.99	0.84	−0.33	0.080	−0.17	−0.30

[a]Used overall average removal efficiency as predicted by direct measurement.
[b]Average observed toluene concentration.
[c]Average predicted toluene concentration.
[d]Correlation coefficient for relationship between C_p and C_o.
[e]Slope of line of regression between C_p and C_o.
[f]Intercept of line of regression between C_p and C_o normalized by the observed concentration.
[g]Normalized mean square error indicating the prediction error relative to C_p and C_o.
[h]Fractional bias of the average values of C_p and C_o.
[i]Fractional bias of the variance of C_p and C_o.

laboratory test results and whole building performance. With further validation in a more complex building, CONTAM may also be a useful tool for comparing the performance of different air cleaners in a given building, estimating air cleaner lifetime, and identifying effective placement of portable air cleaners.

5. Conclusion

As building operators and consumers consider strategies for improving indoor environments and for building air protection in the event of intentional or accidental contaminant releases, it is unclear how well gaseous air cleaning devices will work in a real building. As this study shows, gaseous air cleaners can be highly effective at removing certain indoor air contaminants; however, there are several installation and operating conditions that can alter their performance in the field. As a result, there is a need to evolve from using single removal efficiency values measured in a controlled laboratory to characterize air cleaner performance and incorporate field installation impacts on contaminant removal. Before this link can be established, however, there is a need to standardize a field test protocol for evaluating gaseous air cleaners in buildings. Modeling has proven to be an effective tool for predicting air cleaner performance in the field and should be evaluated further for more building types.

Acknowledgments

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