PREDICTING 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 real buildings, the National Institute of Standards and Technology (NIST) has completed a series of air cleaner field tests and model simulations. This paper focuses on experiments to measure the removal of decane with two different gaseous air cleaners in a test house. Due to the lack of gaseous air cleaner field testing protocols, a field test method was developed using semi-real-time measurements and mass balance analysis. To date, 24 experiments have been completed with single-pass removal efficiencies ranging from 30 % to 44 %. A full factorial analysis revealed that factors such as air cleaner location, status of the heating and air conditioning system, relative humidity and temperature significantly affect air cleaner performance. These results have been used to develop a regression model to predict air cleaner removal rates based on these factors, as well as to evaluate the predictive capability of the indoor air quality model CONTAM.

INDEX TERMS
Field study, gaseous air cleaners, indoor air, model evaluation, VOC transport

INTRODUCTION
Residential and commercial gaseous air cleaning (GAC) technologies have not gained wide acceptance in the marketplace, in part due to the lack of rating methods and field performance data. Currently, there are no standard test methods available for gaseous air cleaners, and there is no system in place to rate the performance of these devices in the laboratory or field. For the most part, GAC performance data have been based on laboratory testing, which often involves high challenge concentrations, low airflow rates, few contaminant species, and controlled temperature and relative humidity (R.H.) (Chen et al. 2005, VanOsdell 1994). In real buildings, air cleaners are exposed to hundreds of contaminants at many concentrations, as well as a wide range of airflow rates, temperatures and relative humidities, all of which may impact air cleaner performance. Additional field issues include bypass around the device, proper maintenance, and replacement schedules. Lack of field performance data has also hindered the ability to simulate GAC. Currently available air cleaner models use a first order removal rate that is based on a single removal efficiency obtained in the laboratory.

To obtain field data and predict the impact of air cleaner technologies on the indoor environment, NIST is conducting a study to 1) measure the impact of using air cleaners in single and multi-zone test houses, 2) determine important factors that affect air cleaner field performance, 3) develop more complete air cleaner models, and 4) determine the capability of the indoor air quality (IAQ) model CONTAM to predict the impact of different types of air cleaner technologies. To date, tests and model evaluations have been completed on the performance of particle filtration devices in a single zone (Emmerich and Nabinger 2001) and a multi-zone building (Emmerich et al. 2005) and gaseous air cleaners in a single zone building (Howard-Reed et al. 2004). This paper presents a series of experiments completed in a single zone test house to develop regression models to predict gaseous air cleaner removal efficiencies based on field performance factors. Results from these experiments were then used to evaluate the predictive capability of CONTAM for use as a simulation tool to demonstrate air cleaner performance in a building.

RESEARCH METHODS
The house and methods used for this study have been described elsewhere (Howard-Reed et al. 2004, Emmerich and Nabinger 2001). In summary, all experiments were completed in a single zone test house with a forced-air heating and air conditioning (HAC) system. The conditioned space had a volume of 85 m^3 and a floor area of 37 m^2. Semi-continuous measurements included the house's air change rate (ACR) based on SF_6 decay (ASTM 2001), indoor and outdoor temperatures with thermistors, indoor and outdoor R.H. with bulk polymer resistance sensors,

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and wind speed and direction with a sonic anemometer.

The challenge contaminant for this series of air cleaner experiments was decane, which was generated using a permeation tube and heated oven. Decane was emitted from the permeation system at a rate of 20 mg/h resulting in steady-state concentrations of approximately 1 mg/m^3 in the test house. 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 included at least one central indoor location, upstream and downstream of the air cleaner, and outside. Samples were concentrated on the GC sorbent trap before injection into the GC column for analysis. The GC/FIDs were calibrated regularly to measure decane concentrations up to 1.5 mg/m^3 ± 5 %.

Two types of air cleaners were tested: an in-duct model that was installed in the HAC system; and a portable air cleaner located either in the center or corner of the room. The portable air cleaner had a cylindrical design that consisted of a layer of zeolite sorbent, 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 then performing a velocity traverse with a hot wire anemometer of a duct exiting the shroud. The maximum airflow setting corresponded to an average flow rate of 360 m^3/h. The in-duct air cleaner consisted of a pleated fiber matrix impregnated with potassium permanganate in a 30 cm x 61 cm x 10 cm filter housing. The removal rate for this type of air cleaner is 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 m^3/h with the air cleaner installed.

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 R.H., HAC usage, and room location of the portable air cleaner. To vary the indoor R.H., a room humidifier was used to elevate the water vapor level for high R.H. tests. This method varied the room R.H. levels to within a range of 17 % and 70 % for the different test conditions. HAC usage was varied between on and off for the portable air cleaner and between heating and air conditioning for the in-duct air cleaner. Only the portable air cleaner location could be changed, and two positions 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 in-duct air cleaner and a 2^3 factorial design with replication was used for the portable air cleaner. The response variable for both designs was air cleaner removal rate of decane, which was then multiplied by the airflow rate through the air cleaner to get the effective cleaning rate (ECR).

The air cleaners' single pass removal efficiency of decane was determined directly with an upstream and downstream measurement and indirectly using a two-phase single zone mass balance model of the test house. Based on pilot study results using toluene (Howard-Reed et al. 2004), the mass balance method was determined to be the most representative of the air cleaner's impact on the house's contaminant concentration. The mass balance model of the test house included the decane source, infiltration, a boundary layer diffusion controlled (BLDC) sink model (Axley 1990), and the air cleaner removal efficiency.

$$M_Z \frac{dC}{dt} = G + QC_{out} - QC + \frac{h\rho A}{K_p} C_m - h\rho AC - fQ_{ac}C \tag{1}$$

$$M_S \frac{dC_m}{dt} = -\frac{h\rho A}{K_p} C_m + h\rho AC \tag{2}$$

where M_Z and M_s are the building mass of air and mass of adsorbent material, respectively; C, C_{out}, and C_m are the decane concentration indoors, outdoors, and in the sorbent, respectively; G is the decane emission rate; Q is the outdoor air ventilation rate; h is the film mass transfer coefficient acting over the sorbent surface; ρ is the air density; A is the sorbent surface area; K_p is the equilibrium partition coefficient; f is the average single pass efficiency of the air cleaner; Q_{ac} is the airflow rate recirculated through the air cleaner; and t is time.

Experiments were completed in two phases. In the first phase, decane was injected into the test house without the air cleaner operating until a quasi-steady-state concentration was reached (C_{ref}). In the second phase, the decane injection continued but the air cleaner was turned on, and a new steady-state toluene concentration was achieved (C_{ctrl}). These steady-state values are used to determine the impact or effectiveness (ε) of using an air cleaner in this single zone environment. Nazaroff (2000) 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:

$$\varepsilon = 1 - \frac{C_{ctrl}}{C_{ref}} \tag{3}$$

RESULTS
The measured removal efficiency of the portable air cleaner ranged from 32 % to 44 % for the different experimental conditions (see Table 1). Although the difference in removal efficiency was relatively small, a regression analysis did show the use of the HAC fan ($p < 0.005$) and air cleaner location ($p < 0.05$) to have a significant effect on air cleaner removal. When the HAC fan was operating, air cleaner removal is 3.7 units of removal efficiency greater than when the HAC fan is off. When the air cleaner is located in the center of the room, the removal efficiency is 2.0 units less than when the air cleaner is located in the corner of the room. Both of these results suggest a localized cleaning effect for the portable air cleaner. The regression analysis showed no significant impact of R.H. or temperature for this air cleaner. A complete regression model for this air cleaner is:

$$f=33.1+3.7X_1+0.0014X_2+0.19X_3-2.0X_4 \tag{4}$$

where f is the removal efficiency (%); X_1 is the HAC fan status (fan on = 1, fan off = 0); X_2 is the R.H. (%); X_3 is temperature (°C); and X_4 is room location (center = 1, corner = 0). The model's residual standard error was 2.2 with a multiple R^2 of 0.80.

Table 1. *Air cleaner test conditions and removal efficiencies measured in test house*

Expt. #	Location	HAC Setting	Temp. (°C)	R.H. (%)	ACR (h^{-1})	Removal Eff. (%)	ECR (m^3/h)	ε (%)
Portable Air Cleaner								
1a	Center	On/none	28	35	0.23	40	144	87
1b	Center	On/heat	21	20	0.36	38	137	83
2a	Center	On/heat	22	66	0.50	35	126	80
2b	Center	On/heat	24	60	0.35	43	155	86
3a	Corner	On/none	19	31	0.31	43	155	84
3b	Corner	On/heat	20	19	0.28	44	158	86
4a	Corner	On/heat	19	66	0.37	43	155	86
4b	Corner	On/heat	22	64	0.23	42	151	88
5a	Center	Off	30	36	0.38	32	115	86
5b	Center	Off	26	34	0.20	33	119	87
6a	Center	Off	27	60	0.32	35	126	87
6b	Center	Off	31	60	0.19	33	119	86
7a	Corner	Off	20	39	0.39	35	126	83
7b	Corner	Off	24	35	0.22	35	126	86
8a	Corner	Off	27	70	0.43	39	140	87
8b	Corner	Off	27	61	0.24	34	122	89
In-Duct Air Cleaner								
1a	In-duct	On/ac	22	31	0.12	33	112	89
1b	In-duct	On/ac	26	28	0.11	36	122	90
2a	In-duct	On/ac	21	46	0.20	30	108	87
2b	In-duct	On/ac	24	42	0.11	32	109	90
3a	In-duct	On/heat	22	23	0.38	38	129	84
3b	In-duct	On/heat	21	17	0.49	38	129	84
4a	In-duct	On/heat	20	66	0.37	35	119	82
4b	In-duct	On/heat	21	64	0.26	35	119	86

The removal efficiency of the in-duct air cleaner was similar to the portable air cleaner and ranged from 30 % to 38 % for the different experimental conditions (see Table 1). Again the relative difference in removal was small, but the regression analysis showed the HAC status ($p < 0.005$), R.H. ($p < 0.05$), and temperature ($p < 0.05$) to have a significant effect on the in-duct air cleaner's removal efficiency. When the heat is on, the removal efficiency is 2.9 units greater than when the air conditioner is operating. An increase of one unit of R.H. leads to a decrease of 0.06 units of removal efficiency, and an increase of one unit in temperature results in an increase of 0.75 units of removal efficiency. The full regression model for this air cleaner is:

$$f=20.3+2.9Y_1-0.06Y_2+0.75Y_3 \quad (5)$$

where Y_1 is HAC heat status (heat on = 1, air conditioner on = 0); Y_2 is R.H. (%); and Y_3 is temperature (°C). The residual standard error was 0.87 with a multiple R^2 of 0.95.

One way to demonstrate the impact of an air cleaner on contaminant concentrations in a building is with an IAQ model. As part of this study, the predictive capability of the multizone IAQ model CONTAM was evaluated. 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, R.H., HAC status, and location for the portable air cleaner. The CONTAM model of the test house is described in Howard-Reed et al. (2004) 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 (Axley 1990). 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 with two different estimates of air cleaner removal. One estimate is based on the average ECR over all portable or in-duct air cleaner tests as predicted with the mass balance model, and the second estimate used the removal efficiency predicted by the regression model (see Eqns 4 and 5).

Figure 1 shows the measured concentrations 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 in the center of the room. The HAC fan was on with an average indoor temperature of 25 °C and an average R.H. of 25 %. As shown in Figure 1, the CONTAM results using the removal efficiency based on the regression model was a better fit to the measured data than the results using the average removal efficiency; however, both predictions agree relatively well with the measured data. In fact, all six CONTAM model validation tests met all statistical criteria for assessing the accuracy and bias of model results compared to measured data as outlined in ASTM's *Standard Guide for Statistical Evaluation of Indoor Air Quality Models* (2003).

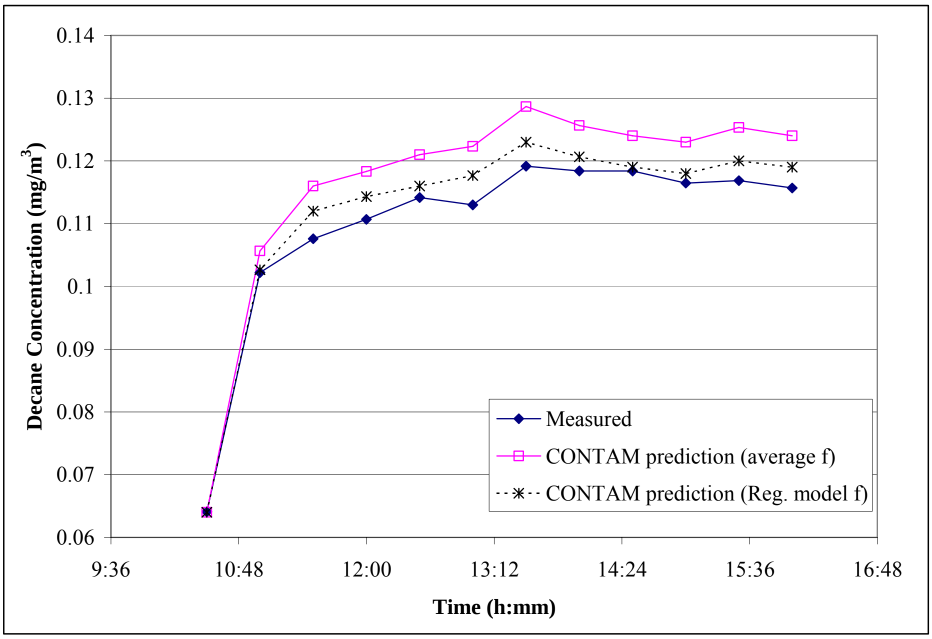

Figure 1. *Comparison of measured and predicted decane concentrations*

DISCUSSION

Results from the field tests clearly confirm laboratory tests showing that gaseous air cleaners can have a significant impact on indoor VOC concentrations. For this study, the gaseous air cleaners were responsible for at least 80 % of the removal of decane in the house (see ε in Table 1). These tests also show that, while laboratory tests are important for characterizing the air cleaner and contaminants it will remove, field tests are needed to characterize the air cleaner's true performance. This study identified several field installation factors that can significantly affect air cleaner performance. Other factors that should still be tested include air cleaner bypass and short-circuiting, performance changes over time, effects of maintenance, and multiple challenge contaminants. To better understand field performance, all of these factors should be studied and incorporated into predictive models of air cleaner performance.

With better estimates of air cleaner removal efficiencies, IAQ models can then be used to assess the benefits of air cleaner technologies for specific applications. Modeling could also be used with a wide range of field operating conditions to derive a minimum removal efficiency for the air cleaner.

CONCLUSION AND IMPLICATIONS

As building operators and consumers consider strategies for improving indoor environments and for additional building air protection, it is still 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. 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.

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