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Reprinted from CD Proceedings, Indoor Air 2002, 9th International Conference on Indoor Air Quality and Climate in Monterey, California.
June 30-July 5, 2002

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ABSTRACT
Residential and commercial gaseous air cleaning technologies have not gained wide acceptance in the marketplace, in part due to the lack of performance data from field tests or simulation studies. This paper describes a field study of the performance of two gaseous air cleaners in a single room test house and simulations based on these tests with an indoor air quality model (CONTAMW). Air cleaner effective cleaning rates (ECR) were experimentally measured for toluene and ranged from 93 m^3/h to 202 m^3/h compared to the average toluene loss rates of 18 m^3/h due to infiltration and 7.7 m^3/h due to sorption on surfaces in the house. As a result, the effectiveness of the air cleaners for toluene in these tests ranged from 82 % to 94 % for different experimental conditions. CONTAMW proved to be an effective tool for predicting the impact of air cleaner performance in the single zone environment.

INDEX TERMS
Air cleaners, Indoor air, VOC transport, Field study, Model validation

INTRODUCTION
To date, the residential and commercial air cleaning market has focused on particle removal. However, recent interest has emerged related to gaseous air cleaning systems for the residential/commercial indoor environment. Current performance evaluation of these cleaners has primarily occurred in the laboratory, often using high challenge concentrations of chemicals, low airflow rates, single contaminant species, and controlled temperature and relative humidity (Silberstein, 1991; VanOsdell, 1994). Before the potential benefits of gaseous air cleaning devices are realized, however, there is a need for performance data from field tests as well as performance prediction tools based on indoor air quality modeling.

To this end, the National Institute of Standards and Technology (NIST) is conducting tests to measure and simulate the performance of several gaseous air cleaners. This paper focuses on experiments completed in a single room test house to determine the removal effectiveness of toluene using a portable room air cleaner with adsorption media and an in-duct air cleaner with chemisorption media. Environmental conditions and tracer concentrations were measured on a semi-real time basis to allow for calculation of all removal mechanisms including sorption on surfaces, infiltration, and air cleaner removal. Air cleaner performance was determined two ways including a direct upstream versus downstream measurement and empirical determination with a single zone mass balance model. Results from these experiments were then used to evaluate the predictive capability of CONTAMW.

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METHODS

The removal efficiencies of the air cleaners were measured in a test house located in Gaithersburg, MD (≈ 35 km NW of Washington, D.C.). The test house was of typical residential construction and consists of a single room with an attic. The conditioned space has a volume of 85 m^3 and a floor area of 37 m^2. A more detailed description of the test house and its heating, ventilating and air conditioning (HVAC) system may be found in Emmerich and Nabinger (2001).

The house infiltration rate was determined by measuring the decay of sulfur hexafluoride (SF_6) (ASTM, 2001). Every 8 h, SF_6 was automatically injected into the house to an initial concentration of approximately 0.72 mg/m^3. Subsequent SF_6 concentrations were measured every 10 min in 3 indoor locations, the attic and outside with a gas chromatograph and electron capture detector (GC/ECD). The measurement range of the GC/ECD was 0.03 mg/m^3 to 0.9 mg/m^3 with an accuracy of approximately ±2 %. A linear regression of the natural logarithm of the SF_6 decay data was used to predict the house air change rate every hour. The estimated uncertainty of the measured air change rates was approximately ±10 %.

Toluene was used as the challenge contaminant for testing of the gaseous air cleaners. Toluene is a prevalent indoor air pollutant and is commonly studied in indoor air research as well. Toluene was continuously injected to the house from a pressurized cylinder at a rate of 10 mg/h to 20 mg/h as regulated by a flow controller. Resulting steady-state concentrations in the house reached 0.5 mg/m^3 to 1.1 mg/m^3. Toluene concentrations were automatically measured every 30 min using portable gas chromatographs equipped with flame ionization detectors (GC/FID). Samples were collected for 10 min at 0.006 m^3/h using an air sample pump and Teflon® 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 toluene concentrations ranging from 0.02 mg/m^3 to 1.4 mg/m^3 in the test house. The uncertainty associated with toluene concentration measurements was estimated to be approximately ±10 %.

Indoor and outdoor environmental conditions were monitored during the tests. Temperature was measured every minute in a central indoor location and outdoors with a thermistor (accuracy of approximately ±0.4 °C). Relative humidity was also measured every minute in a central indoor location and outdoors using bulk polymer resistance sensors with an accuracy of ±3 %. Wind speed and direction were measured with both a rotational anemometer and a sonic anemometer mounted 3.5 m above the test house roof.

The portable air cleaner (PORT) had a cylindrical design that consisted of a layer of zeolite sorbent, 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 shroud to enclose the air cleaner and performing a traverse with a hot wire anemometer. Using this method the maximum airflow setting corresponded to a flow rate of 340 m^3/h (estimated uncertainty of ±20 %).

The in-duct air cleaner (DUCT) 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 that had an accuracy of approximately ±2 %. The duct airflow rate was an average of 386 m^3/h with the air cleaner installed.

Two methods were used to determine the air cleaners' ability to remove toluene from the test house. For most tests, toluene concentrations were measured immediately upstream ($C_{upstream}$) and downstream ($C_{downstream}$) of the air cleaner. Using these measurements, the single pass removal efficiency (f_{dir}) of the cleaner may be directly calculated as:

$$f_{dir} = 1 - \frac{C_{downstream}}{C_{upstream}} \tag{1}$$

The second method used to calculate air cleaner performance was based on a two-phase single-zone mass balance model of the test house:

$$V\frac{dC}{dt} = QC_{out} - QC - k_a CA + k_d MA - f_{mb} Q_{ac} C \tag{2}$$

$$A\frac{dM}{dt} = Ak_a C - Ak_d M \tag{3}$$

where V is the volume of the house, C is the indoor concentration of toluene, t is time, Q is the airflow rate into and out of the house, C_{out} is the concentration of toluene in the outside air, k_a and k_d are empirical adsorption and desorption coefficients respectively, A is the area of surfaces in the room, M is the mass of toluene per unit area on the room surfaces, f_{mb} is the average single pass efficiency of the air cleaner, and Q_{ac} is the airflow rate through the air cleaner. The effective cleaning rate (ECR) of the air cleaner is the product of the single pass removal efficiency and air cleaner airflow rate. Equations 2 and 3 were solved simultaneously as shown in Tichenor *et al*. (1991). Due to the dynamic nature of the test house conditions (e.g., changing air change rate, etc.), the mass balance solutions were solved numerically. All necessary parameters to the model solution were directly measured or assumed except for k_a, k_d, and f_{mb}. To estimate these parameters, the experiments were divided into two phases. In the first phase, toluene was injected at a constant rate and allowed to reach a quasi-steady-state condition (see Figure 1). During this loading period, without the presence of an air cleaner, the empirical sorption parameters were estimated using a best-fit solver routine in Microsoft Excel™. In the second phase of the experiment, the air cleaner was added and room air concentrations were allowed to reach a new steady-state. Using the sorption parameters determined in the previous phase, the air cleaner ECR was calculated, again using Excel's™ best-fit solver routine.

To show the impact of using an air cleaner in this single zone environment, the air cleaner effectiveness was estimated based on the method outlined in Nazaroff (1999). At steady-state, air cleaner effectiveness may be directly measured as follows:

$$\varepsilon = 1 - \frac{C_{ctrl}}{C_{ref}} \tag{4}$$

where ε is air cleaner effectiveness, C_{ref} is the steady-state concentration of toluene without an air cleaner operating and C_{ctrl} is the steady-state concentration of toluene with an air cleaner operating. As shown in Figure 1, the experiments were designed to allow for the measurement of both C_{ref} and C_{ctrl}.

RESULTS

A total of 13 experiments (see Table 1) were completed with the portable (PORT) and in-duct (DUCT) air cleaners. Experiments were designed to evaluate the effects of HVAC status, air change rate, air cleaner location (PORT experiments), room temperature, and room relative humidity. A room humidifier was used to elevate the water vapor level for some higher humidity tests. For each experiment, toluene removal rates due to infiltration, sorption, and air cleaning were determined. Of all the removal mechanisms, air cleaning was by far the most significant. The average hourly infiltration rate for all air cleaner experiments was 0.21 h^{-1}, ranging from 0.08 h^{-1} to 0.41 h^{-1}. These values corresponded to an average infiltration rate (Q) of 18 m^3/h, ranging from 6.8 m^3/h to 35 m^3/h.

Table 1. Air cleaner removal rates.

Expt. #	Avg. R.H. (%)	Avg. air change rate (h^{-1})	Mass Balance f_{mb} (%)	Mass Balance ECR (m^3/h)	Direct f_{dir} (%)	Direct ECR (m^3/h)	Effectiveness $1 - C_{ctrl}/C_{ref}$
Portable Air Cleaner Tests							
PORT1	n/a	0.08	53	179	n/a	n/a	0.94
PORT2	n/a	0.08	45	154	66	224	0.93
PORT3	42	0.13	58	197	n/a	n/a	0.92
PORT4	30	0.15	59	202	n/a	n/a	0.93
PORT5	n/a	0.23	50	170	60	211	0.91
In-Duct Air Cleaner Tests							
DUCT1	31	0.15	39	157	26	105	0.93
DUCT2	31	0.16	38	155	30	126	0.91
DUCT3	n/a	0.19	49	178	n/a	n/a	0.91
DUCT4	n/a	0.24	46	167	35	127	0.88
DUCT5	22	0.41	45	182	38	152	0.87
DUCT6	60	0.32	32	122	33	127	0.82
DUCT7	66	0.35	25	93	22	83	0.84
DUCT8	33	0.32	39	148	41	156	0.89

Removal rates due to adsorption on surfaces were usually smaller than infiltration and often difficult to detect and quantify. An attempt was made to estimate adsorption by fitting the mass balance model to the measured data during the "no air cleaner" phase of the tests. The resulting best-fit solutions were rather inconsistent with k_a ranging from < 0 m/h to 0.44 m/h. Assuming that the sorption parameters remain relatively constant in the test house, five previous sorption test results were used to obtain a best estimate of 0.059 m/h (± 0.017 m/h) for k_a and 0.38 h^{-1} (± 0.29 h^{-1}) for k_d. These values were used for all tests described herein, corresponding to an average sorption removal rate of 7.7 m^3/h during toluene injections.

Air cleaner ECRs are given in Table 1 for both the mass balance (Equations 2 and 3) and direct measurement (Equation 1) calculation methods. The mass balance solution yields the ECR directly, and the single pass removal efficiency is estimated by dividing ECR by the measured Q_{ac}. Due to the uncertainty associated with the measurement of Q_{ac} and installation factors, the more robust estimate of air cleaner performance for this method is the ECR, which ranged from 154 m^3/h to 202 m^3/h for PORT and 93 m^3/h to 182 m^3/h for DUCT. Conversely, when using Equation 1, f_{dir} was directly measured and then used to calculate the system's ECR. Single pass removal efficiencies for the direct method ranged from 60 % to 66 % for PORT and 22 % to 41 % for DUCT. As expected, due to the increased competition for

chemisorption sites, the DUCT air cleaner had reduced performance when tested with relative humidity greater than 60 %.

These experimental results were used to evaluate the capability of CONTAMW to predict the effectiveness of a gaseous air cleaner in a single zone. A single test (DUCT3) was chosen for model evaluation and data from the remaining tests were used to estimate model inputs. The CONTAMW model of the test house is described in Emmerich and Nabinger (2001). In this comparison, CONTAMW was used to predict the infiltration rate based on building leakage information and the measured indoor/outdoor temperature difference and wind speed for the test case. The model allows for reversible sink effects based on a boundary layer diffusion controlled (BLDC) model with a linear isotherm (Axley, 1990). Model sorption parameters calculated for the test house included a mass transfer coefficient of 0.068 m/h, a film density of air of 1.2 kg/m^3, surface mass of material of 780 kg, and a partition coefficient of 941 (Zhang *et al*., 2001). The model was evaluated with two different estimates of air cleaner removal. One estimate is based on the average ECR as predicted with the mass balance model and the second estimate used the directly measured removal efficiency. Figure 1 shows the measured concentrations and the predicted concentrations using Equations 2 and 3. As shown in Figure 1, CONTAMW was able to predict C_{ctrl} within 0.01 mg/m^3 using f_{mb} and within 0.02 mg/m^3 using f_{dir}.

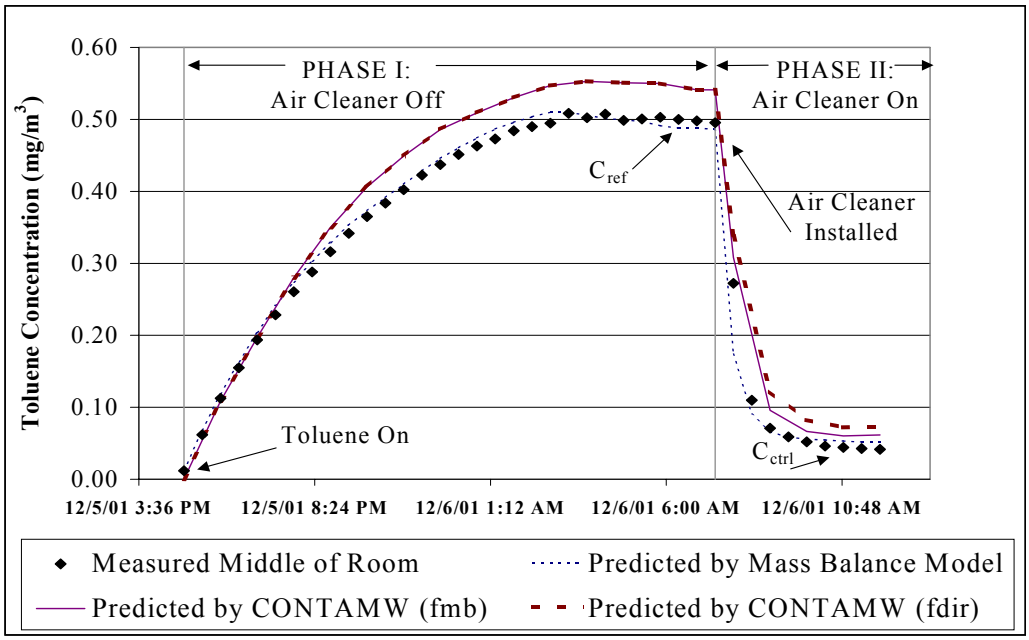

Figure 1. Measured and predicted toluene concentrations for Experiment DUCT3.

DISCUSSION

Based on these results, CONTAMW and other models should be able to provide a useful tool to evaluate the benefits of gaseous air cleaners and to compare air cleaner removal to other control strategies. As an example, the effectiveness of air cleaner removal was compared to that of increased ventilation. A reference model was developed in CONTAMW with a constant air change rate of 0.23 h^{-1}, constant sorption removal (as shown in Results section), a constant source of toluene (10 mg/h), and no air cleaner operating. The resulting steady-state concentration for this reference case was 0.51 mg/m^3. If the air change rate was doubled for this case, the steady-state concentration was reduced to 0.26 mg/m^3, a 50 % reduction. Alternatively, if an air cleaner with a removal efficiency of 34 % is added to the reference case, the steady-state concentration was reduced to 0.06 mg/m^3, a reduction of 88 %. In order to match the air cleaner effectiveness in this particular house, the air change rate would need to be as high as 2 h^{-1}.

While CONTAMW is an effective tool for the specific comparison described above, it is limited by the theory on which it is based, in particular the specific models of air cleaning used in the program. For example the model uses a constant removal efficiency, when in reality air cleaner performance can degrade over time and is dependent on environmental conditions. As a result, there is a need to develop dynamic air cleaner models that allow for changing conditions and a range of relative humidities, temperatures, face velocities, etc.

CONCLUSION AND IMPLICATIONS

Field experiments in a single zone environment showed two types of gaseous air cleaners to have a dramatic impact on toluene concentrations. The methods developed for these experiments will next be applied in a multi-zone testing environment. Overall, there did not appear to be any significant advantages of the portable air cleaner over the in-duct air cleaner. This result could change, however, in a multi-zone environment, where air cleaner location, volumetric flow rate, and flow distribution could become more important. CONTAMW performed well in predicting toluene concentrations in the single zone environment and is a potentially useful tool to demonstrate the benefits of air cleaning technologies.

DISCLAIMER

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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