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Comparison of Test Methods for Determining the Particle Removal Efficiency of Filters in Residential and Light-Commercial Central HVAC Systems

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Central heating, ventilating, and air-conditioning (HVAC) filters are often the dominant mechanism for particle removal in buildings. However, little is known about filter performance in real environments, particularly in residential and light-commercial buildings where particle concentrations and compositions can be very different from laboratory test conditions. This article explores differences in HVAC filter test protocols and refines a whole-house method for *in situ* testing of filters for size-resolved particle removal efficiencies. Results from the *in situ* method are compared with those from a simple upstream–downstream method for three types of commercially available filters in an unoccupied test house. Results from both field methods are compared with standardized laboratory test results as measured by an independent laboratory and as reported by the manufacturer. In general, comparisons between filter efficiency as measured by the refined whole-house method and as measured by the upstream–downstream method resulted in similar values of particle removal efficiency for many particle sizes and compared well with standardized lab tests, although experimental uncertainties were generally greatest for the whole-house method. However, the refined whole-house method has the added benefit of allowing an investigation of more particle interactions in an indoor environment, including deposition to ductwork and other HVAC system components, exfiltration through duct leakage, and bypass airflow around filters. Both field methods can be used to investigate the effects of HVAC system characteristics and dust loading on filter efficiency in real environments.

[Supplementary materials are available for this article. Go to the publisher's online edition of *Aerosol Science and Technology* to view the free supplementary files.]

INTRODUCTION

Exposure to airborne particulate matter is consistently associated with adverse human health effects, including an increased risk of respiratory symptoms, cardiopulmonary mortality, and lung cancer (Pope et al. 2002; Pope and Dockery 2006; Miller et al. 2007; Brook et al. 2010). However, because Americans spend nearly 90% of their time indoors (Klepeis et al. 2001) and particles can penetrate through building envelope structures (Mosley et al. 2001; Chao et al. 2003; Liu and Nazaroff 2003; Thatcher et al. 2003; Williams et al. 2003; Zhu et al. 2005; Rim et al. 2010), much of human exposure to ambient particles often occurs inside buildings (Long et al. 2001; Riley et al. 2002; Meng et al. 2004; Bekö et al. 2008). There are also many indoor sources of particles present in most indoor environments, particularly in residences (Abt et al. 2000; Afshari et al. 2005; Hussein et al. 2006; Wallace 2006). The use of heating, ventilating, and air-conditioning (HVAC) filters in buildings is one strategy to reduce exposure to particulate matter and improve the health of building occupants (Hanninen et al. 2005; Lin et al. 2011). Centralized space conditioning has become ubiquitous in the United States, particularly in residential and light-commercial buildings that comprise a significant fraction of the US building stock and represent spaces where Americans spend most of their time (Stephens et al. 2011, and references therein). Thus, the performance of HVAC filters in these smaller buildings can have a profound effect on airborne particulate matter exposures of a wide population.

However, little is known about how HVAC filters actually perform in real environments, particularly in residential and light-commercial buildings. This work (1) explores differences in a variety of HVAC filter test protocols, (2) refines a method for *in situ* testing of HVAC filters in residential and light-commercial buildings for size-resolved particle removal efficiency, (3) compares the results of those filter tests to simple upstream–downstream measurements, both applied in an unoccupied test house, and (4) compares both test house results with laboratory test results as measured by an independent laboratory and as reported by the manufacturer.

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Filter Testing: Laboratory Settings

HVAC filters are typically tested only in laboratory settings. Hanley et al. (1994) first reported on a laboratory apparatus and test procedure to quantify the fractional filtration efficiency of in-duct air cleaners, including filters. The work was later used by the American Society for Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as a basis for the most widely used standard for measuring filter efficiency in the United States, ANSI/ASHRAE Standard 52.2-2007 (ASHRAE 2007). ASHRAE Standard 52.2 details a test procedure to determine two filter performance characteristics of importance: size-resolved particle removal efficiency and resistance to airflow. The test procedure involves measuring particle concentrations in 12 size ranges (0.3–10 μm in diameter) upstream and downstream of a filter, and the size-resolved particle removal efficiency is calculated by subtracting the average ratio of downstream-to-upstream particle concentrations from unity. The test is performed first with a new filter in place, and then repeated several times under incrementally increasing artificial dust loading conditions. Dust loading tests are performed because particle removal efficiency has been shown to be highly dependent not only on particle size, but also on airflow rate and the amount of dust loading (Hanley et al. 1994, 1999; Raynor and Chae 2003). Size-resolved particle removal efficiency curves are developed for the filter using average efficiency values for each of the clean, incrementally loaded, and final dust loading conditions. A minimum efficiency curve is then developed using the minimum average efficiency value recorded at each of the 12 particle sizes, regardless of the loading condition. Finally, a minimum efficiency reporting value (MERV) is assigned by averaging the minimum efficiency values across four particle sizes in each of three size bins (0.3–1.0, 1.0–3.0, and 3.0–10 μm).

Other filter standards for testing and reporting particle removal efficiency exist outside of the United States, including EN 779 from the European Committee for Standardization (CEN 2002). ASHRAE Standard 52.2 is used herein; however, a relationship can be drawn between MERV and the CEN standard using a recent analysis of the two methods (Tronville and Rivers 2006).

Filter Testing: Field Settings

ASHRAE Standard 52.2 acknowledges that the test method involves particle concentrations, particle compositions, airflow rates, pressure drops, temperature, and humidity levels that are almost certain to be different from those the filter will encounter when installed in a real system, which raises questions about how HVAC filters actually perform in real buildings. The *in situ* performance of filters and other HVAC components that may remove particles has been field tested using two primary methods: (1) by measuring concentrations upstream and downstream of the filter or component in question (Burroughs and Kinzer 1998; Fugler et al. 2000; Jamriska et al. 2000; ASHRAE 2008), and (2) by measuring the difference in overall particle loss rates in an indoor environment with and without a filter installed (Offermann et al. 1992; Howard-Reed et al. 2003; Wallace et al. 2004; MacIntosh et al. 2008).

The first field method, which involves measuring filter efficiency by an upstream–downstream method, is a relatively quick procedure to perform that can isolate the impact of the filter alone, or can be extended to other sections of the HVAC system to measure the removal efficiency of other components. However, some challenges exist in accurately performing the test method, which can introduce large uncertainty. First, either two particle counters are required to measure upstream and downstream concentrations simultaneously (which requires accurate calibration of the instruments), or a switching valve must be used with only one instrument (which may introduce additional sampling losses). Second, physical access to locations immediately upstream and downstream of the filter in a real HVAC system is not always possible. Access constraints may also increase the requirements for sampling line length, which can increase losses before reaching the particle instrumentation. Third, isokinetic sampling is not trivial to achieve inside of an HVAC system; nonisokinetic sampling can lead to an inaccurate representation of different particle sizes. Fourth, the sampling location along a duct or an air-handling unit (AHU) can lead to errors due to unmixed flow and large amounts of turbulence located near blower fans. Finally, upstream–downstream methods do not provide any further information about particle interactions in a real environment (e.g., deposition to indoor surfaces or other HVAC system components).

The second field method, which involves measuring the differences in overall particle loss rates in an environment with and without a filter installed, can also be referred to as a “whole-house” method. Whole-house methods can be used to quantify the effects of HVAC filters on particle decay rates in an environment, and the difference in decay rates between multiple filter conditions can be used to calculate clean air delivery rates or filter removal efficiencies, if the airflow rate through the HVAC system is known. Advantages of whole-house test methods are that they can capture the effects of the entire HVAC system (including filters, deposition to ducts and other components, losses and gains by duct leakage, and bypass airflow around filters) and can fully characterize indoor particle dynamics in an environment. However, attempts to perform accurate whole-house decay methods are met with some challenges. First, whole-house number or mass balance decay approaches have generally assumed complete mixing in the environment and a negligible influence of outdoor particles. Second, multiple types of instrumentation are required to measure both particles and air exchange rates (AERs) simultaneously. Third, in order to calculate filter or system efficiency (dimensionless) from removal rates (in units of inverse time), both the airflow rate through the filter and the volume of the space must be known. Measuring HVAC airflow rates accurately in residential and light-commercial systems is not trivial, and is complicated by highly nonuniform and developing flows. Finally, whole-house test methods are generally time intensive. Single test durations were 4–5 h in Offermann et al. (1992) and were reduced to approximately 2 h in MacIntosh et al. (2008), whereas upstream and downstream particle concentrations can be measured in minutes.

Previous investigations on the effects of HVAC systems and filters on indoor particle dynamics remain limited, due in part to the difficulty, duration, and expense of test methods. In order to address some of these concerns, this work presents a refined whole-house test method to estimate size-resolved removal efficiencies of HVAC systems and filters by comparing particle loss rates measured during different filter and HVAC operation conditions. Estimations of particle removal efficiency are compared for three types of commonly available filters (MERV <5, MERV 7, and MERV 11, as rated by manufacturers) determined by four methods: (1) the refined whole-house test method and (2) upstream–downstream measurements, both applied in an unoccupied test house, and by ASHRAE Standard 52.2 laboratory tests (3) as reported by the filter manufacturer and (4) as tested by an independent laboratory during only the initial stages of loading.

METHODOLOGY

The whole-house test methods in Offermann et al. (1992), Howard-Reed et al. (2003), Wallace et al. (2004), and MacIntosh et al. (2008) were refined for the purposes of this work. The method consists of the same general practices: artificially elevating indoor particle concentrations and measuring the subsequent concentration decay with and without a filter installed in the operating HVAC system, while simultaneously measuring the AER through the building by tracer gas decay. Therefore, the total particle deposition rate (to indoor surfaces and HVAC components) can be measured for each HVAC condition, and particle removal efficiencies can be calculated by comparing the differences in deposition rates between conditions. The refined methodology differs from previous work in four distinct ways: (1) high-efficiency particulate air (HEPA)- and activated-carbon-filtered outdoor air is supplied to the house in an attempt to maintain positive pressurization with respect to outdoors, which should eliminate the infiltration of outdoor particles, diminish the potential effects of secondary organic aerosol formation from reactions of ozone and unsaturated organic compounds (Weschler and Shields 1999), and shorten the test duration; (2) system airflow rates are measured with a more accurate flow plate device; (3) several mixing fans are operated in an attempt to achieve reasonably well-mixed conditions; and (4) a nonlinear least-squares regression with multiple parameters is performed on the data to provide accurate estimates of particle loss rates, even if a particle source exists.

The whole-house method relies on a well-mixed size-resolved number balance of particles of diameter i in the space, assuming no indoor sources of particles, as shown in Equation (1):

$$\frac{dC_{i,in}}{dt} = \frac{Q_{OAS}}{V}(1-\eta_{i,OAS})C_{i,out} - \lambda C_{i,in} - \beta_i C_{i,in} - \frac{\eta_{i,HVAC}Q_{HVAC}}{V}C_{i,in}, \qquad [1]$$

where $C_{i,in}$ is the size-resolved indoor particle concentration (m^{-3}), t is the time (h), Q_{OAS} is the airflow rate of the HEPA- and activated-carbon-filtered outdoor air supply ($\mathrm{m}^3\ \mathrm{h}^{-1}$), $\eta_{i,OAS}$ is the size-resolved particle removal efficiency of the outdoor air supply HEPA filter (dimensionless), $C_{i,out}$ is the size-resolved outdoor particle concentration (m^{-3}), λ is the AER (h^{-1}), β_i is the size-resolved deposition rate of particles to indoor surfaces (h^{-1}), $\eta_{i,HVAC}$ is the size-resolved particle removal efficiency of the HVAC system (dimensionless), Q_{HVAC} is the airflow rate through the HVAC system ($\mathrm{m}^3\ \mathrm{h}^{-1}$), and V is the volume of the building (m^3). Equation (1) accounts for the change in indoor particle concentration of diameter i in time due to the addition of any ambient particles from the filtered outdoor air supply and losses of particles due to AER, deposition to indoor surfaces, and losses by airflow through the HVAC system (assuming that it is operating). If the indoor space is pressurized by 100% efficient HEPA-supplied outdoor air or outdoor particle concentrations are negligibly small, the first term in Equation (1) goes to zero and the number balance reduces a simple exponential decay from an initial elevated indoor particle concentration; previous methods have relied on this assumption. However, if the HEPA-filtered outdoor air supply does not supply particle-free air for any reason (e.g., air infiltration through other leaks in the building or bypass around the HEPA filter housing), and outdoor particle concentrations are relatively large, the first term in Equation (1) is solved for as a constant positive source term in a nonlinear regression.

All of the loss mechanisms present in Equation (1) (λ, β_i, and $\eta_{i,HVAC}Q_{HVAC}/V$) can be combined into one lumped loss term for each particle size in the number balance and the test procedure can be repeated for three basic conditions: (1) with no filter installed and the HVAC system off (i.e., background decay), (2) with the HVAC system operating and no filter installed, and (3) with the HVAC system operating with a test filter installed. Because AER is measured simultaneously, λ can be subtracted from the total loss rate to determine the "effective" loss rate, L (h^{-1}), due to surface, HVAC system component, and duct interactions alone (in the no-filter case) or the combined effects of surface, HVAC component, duct, and filter interactions (in the filter installed case). Then, the particle loss rates estimated from regressions of Equation (1) can be used against each other to determine the relative contribution of a filter or an HVAC system condition for each particle size. A comparison of the loss terms of each of the three operation systems is shown in Table 1.

The size-resolved particle removal efficiency of the nonfilter HVAC system components alone (e.g., ducts, coils, and fans) can

TABLE 1
Comparison of loss terms of each of the three HVAC and filter operating conditions

Operating condition	Effective[a] loss term, L (h^{-1})	Losses to
(1) HVAC off	β_i	Surfaces
(2) HVAC on, no filter	$\beta_i + \frac{\eta_{i,ducts} Q_{HVAC}}{V}$	Surfaces and nonfilter HVAC components and ducts
(3) HVAC on, filter	$\beta_i + \frac{\eta_{i,ducts+filter} Q_{HVAC}}{V}$	Surfaces, HVAC components and ducts, and filter

[a] Excludes losses due to AER (λ), which are independently measured during each test run.

be estimated by comparing the effective loss rates of conditions (2) and (1), as shown in Equation (2).

$$\eta_{i,ducts} = \frac{V(L_2 - L_1)}{Q_{HVAC}}, \qquad [2]$$

where L_1 is the effective loss rate of particles of diameter i from condition (1) and L_2 is the effective loss rate of particles of diameter i from condition (2) (h^{-1}). The size-resolved particle removal efficiency of the combination of the HVAC components and filter can be estimated by comparing the effective loss rates of conditions (3) and (1), as shown in Equation (3).

$$\eta_{i,ducts+filter} = \frac{V(L_3 - L_1)}{Q_{HVAC}}, \qquad [3]$$

where L_3 is the effective loss rate of particles of diameter i from condition (3) (h^{-1}). Finally, because the filter and other HVAC components are in series, as shown in Equation (4), size-resolved filter removal efficiency ($\eta_{i,filter}$) can be estimated by Equation (5).

$$\eta_{i,ducts+filter} = 1 - (1 - \eta_{i,ducts})(1 - \eta_{i,filter}), \qquad [4]$$

$$\eta_{i,filter} = 1 - \frac{1 - \eta_{i,ducts+filter}}{1 - \eta_{i,ducts}}. \qquad [5]$$

AERs are estimated in accordance with ASTM E 741, using the procedure outlined in the supplementary information (SI). The next section describes both whole-house and upstream–downstream filter test methods as applied in an unoccupied test house.

Test House Experiments

To validate the refined whole-house test method, experiments were performed in an instrumented test house, a three-bedroom two-bathroom manufactured home (described in Novoselac and Siegel [2009] and shown in Figure S1). The house has a floor area of 110 m^2, a volume of approximately 250 m^3, and contains two identical AHUs (one with ductwork installed in the crawl space and one with ductwork installed in the attic). Only the downflow unit, which was installed in a closet with no return ductwork, was used in these experiments. The unit is described in further detail in Stephens et al. (2010a). The HVAC system was operated in the fan-only mode during all of the experiments (no cooling or heating) and reasonably well-mixed conditions were achieved by the operation of several oscillating fans throughout the house.

Whole-House Particle Removal Methods

An Energy Conservatory Minneapolis Duct Blaster fan was attached to a large HEPA filter with a sheet of activated carbon placed inside and installed in a window frame in the master bedroom in order to supply filtered outdoor air to pressurize the indoor space relative to outdoors. Differential pressure measurements were made in the control room with respect to outside at 10-s intervals during the test periods using an Energy Conservatory Automated Performance Testing system (uncertainty ±1% of reading). The pressurization process ensured that particle and tracer concentrations decayed to near or below original background levels generally within 45 min.

System airflow rates were measured with an Energy Conservatory TrueFlow metering plate and a DG-700 digital manometer. Flow corrections were made based on changes in the supply plenum pressure measured during each test following the calculation procedure in the instrument manual. The flow plate has a manufacturer-reported uncertainty of ±7% of its reading, although conversations with the manufacturer suggest lower actual uncertainties for situations where repeated flows in the same system are compared; ±5% was used in previous work (Stephens et al. 2010a, 2010b) and is also used here.

To obtain an initial elevated indoor concentration of a range of particle sizes ($C_{i,in}$ at time $t = 0$), particles were generated by burning six sticks of incense for several minutes (two sticks in three locations, as shown in Figure S1), followed by shaking a used vacuum cleaner bag into the HVAC return system while operating in the absence of a filter for approximately 15 s. Incense burning emitted particles generally less than 1 μm, and shaking the vacuum cleaner bag resuspended particles generally greater than 1 μm. Because the method only requires that initial particle concentrations be elevated (the source is extinguished prior to the decay portion of the test), a consistent or standardized particle source was not required. For reference, Offermann et al. (1992) used cigarette smoke as a test aerosol, Howard-Reed et al. (2003) and Wallace et al. (2004) operated a gas stove, burned a citronella candle, and poured cat litter in the HVAC return plenum, and MacIntosh et al. (2008) utilized a fine test dust.

A TSI AeroTrak 8220 handheld optical particle counter (OPC) was installed near the central return for the downflow HVAC system at a height of approximately 1 m and set to log particle number concentrations in six particle size bins (0.3–0.5, 0.5–0.7, 0.7–1.0, 1.0–3.0, 3.0–5.0, and 5+ μm) at 1-min intervals. The particle instrument was chosen to allow comparisons with ASHRAE Standard 52.2 tests and in accordance with ASHRAE Guideline 26, which recommend OPCs because they are currently the most convenient and most commonly used instruments for these types of measurements. Once sufficiently elevated particle levels were achieved (at least twice background, but usually an order of magnitude higher, depending on particle size and the type of incense), the incense sticks were extinguished. The vacuum cleaner bag was shaken just before leaving the test house due to the rapid deposition rates of the larger particles suspended by the process. AER was measured using CO_2 as a tracer gas in accordance with ASTM E 741, as described in the SI.

Upon completion of the experiments, the previously described parameter estimations were conducted using a statistical software package (Stata Version 11, College Station, TX). A nonlinear least-squares regression was performed on the time series of concentration data from each particle size bin, as well as CO_2 concentrations (for AER estimates). The analytical solution to the time-varying and size-resolved particle number concentration balances in Equation (1) were used in the regressions, using indoor concentration ($C_{i,in}(t)$) as the dependent variable and time (t) as the independent variable, and three size-resolved parameters were estimated: an initial concentration ($C_{i,in}$ at time $t = 0$), the overall particle loss rate (L_i), and the overall particle source rate ($S_i = Q_{OAS}(1 - \eta_{i,OAS})C_{i,out}/V$). If a particle source rate (S_i) was estimated to be less than or equal to zero, the filtered outdoor air supply was assumed to be contributing negligibly to indoor particle concentrations, the particle source term for that size range was set to zero, Equation (1) took the form of a simply first-order decay model, and the regression was run again with only two unknowns ($C_{i,in}$ at $t = 0$ and L_i). If the source term resulted in a positive value, estimates of all three parameters were used as is.

A total of 26 experiments were conducted during five combinations of HVAC operation and filter installations: HVAC off with no filter installed, HVAC on in the fan-only mode with no filter installed, and HVAC fan on with three different types of commercially available filters installed (all filters were 51 × 51 × 2.5 cm). The three levels of filtration efficiency, as rated by the manufacturer, were low-efficiency fiberglass panel filters (MERV <5), medium-efficiency charged synthetic pleated filters (MERV 7), and high-efficiency charged synthetic pleated filters (MERV 11). Estimates of uncertainty for individual parameters were taken as the largest of manufacturer-reported instrument uncertainty, standard deviations of means, or 95% confidence intervals from regressions, and these relative errors were added in quadrature for any parameters calculated using multiple variables.

Upstream–Downstream Removal Methods

In a separate test, upstream and downstream particle concentrations were measured for approximately 1 h at 20-s intervals with each of the three filters installed, after the filters had been used for all of the whole-house tests. Sampling lines of approximately 20–30 cm in length were used for each particle counter, positioned with approximately uniform bends to minimize differences in sampling losses. Prior to these measurements, the two OPCs were colocated at a height of approximately 1 m in the small bedroom of the test house with an oscillating mixing fan operating. Particle concentrations were elevated by burning two sticks of incense and shaking a used vacuum cleaner bag, and the door was closed. The subsequent decay of particles to background levels was monitored concurrently at 1-min intervals for a period of approximately 2 h. Using the colocation data, one OPC was calibrated relative to the other as a reference using linear regressions of the concentrations of each of the six particle bins measured with each counter, similar to the method in Wigzell et al. (2000).

RESULTS

A summary of HVAC operation and filter test conditions during validation of the refined whole-house method is shown in Table 2. Four to six replicate tests were performed at each condition. The filtered outdoor air supply maintained positive pressurization with respect to outdoors for the majority of test periods and elevated AERs to 2.3–2.6 h^{-1} on average. Although AERs were elevated relative to normal operational conditions, they were subtracted out for the filtration efficiency calculations (which utilize effective loss rates, as described in Table 1) and thus do not affect the filtration efficiency results.

Mean HVAC system airflow rates ranged from 1460 ± 73 to 1673 ± 84 $m^3\ h^{-1}$, decreasing with the rated efficiency of installed filters. The installation of new MERV <5, MERV 7, and MERV 11 filters decreased system airflow rates in the fan-only mode relative to no-filter conditions by 4%, 9%, and 13%, respectively, due to the increase in filter pressure drops with increasing filter efficiency (8, 55, and 89 Pa, respectively). Filter face velocities were estimated as the HVAC system airflow rate (Q_{HVAC}, $m^3\ h^{-1}$) divided by the apparent surface areas of the filters (51×51 cm, or approximately 0.26 m^2, ignoring the pleated area) and ranged from approximately 1.6 to 1.8 m s^{-1}. Filter face velocities were confirmed by anemometer measurements and were generally in the range of face velocities recommended in ASHRAE Standard 52.2.

Whole-House Particle Loss Rates

An example of the measured particle concentration decay data and subsequent regression output is shown in Figure S2, using both traditional log-linear regressions and the aforementioned nonlinear regression strategy. The addition of a nonlinear regression including a source term in this whole-house method yielded stronger regression fits than traditional log-linear

TABLE 2
Description of HVAC filter test conditions and relevant parameters

Filter condition	HVAC operation	n	Q_{HVAC} ($\mathrm{m^3\,h^{-1}}$)	Recirculation rate, Q_{HVAC}/V ($\mathrm{h^{-1}}$)	Filter pressure drop (Pa)	$I/O\ \Delta P$ (Pa) (SD)	AER (λ) ($\mathrm{h^{-1}}$) (SD)
n/a	Off	5	n/a	n/a	n/a	2.4 (1.7)	2.32 (0.27)
No filter	Fan only	6	1673 ± 84	6.7 ± 0.3	n/a	1.7 (0.3)	2.52 (0.10)
MERV <5	Fan only	4	1608 ± 80	6.4 ± 0.3	8.1 ± 0.1	2.1 (0.1)	2.56 (0.04)
MERV 7	Fan only	6	1522 ± 76	6.1 ± 0.3	55.2 ± 1.4	0.1 (0.6)	2.56 (0.09)
MERV 11	Fan only	5	1460 ± 73	5.8 ± 0.3	89.2 ± 0.9	0.0 (0.2)	2.38 (0.05)

Note: n = number of replicate tests. Errors for Q_{HVAC} and the recirculation rate are taken from instrument uncertainty (±5%). Errors for filter pressure drop are greater than instrument uncertainty (±1%) or standard deviations across replicate tests. Errors for $I/O\ \Delta P$ and AER are standard deviations (SD) across replicate tests.

methods, suggesting imperfect filtration of outside air or imperfect positive pressurization of the test house. Size-resolved effective loss rates (β_i or $\beta_i + \eta_{i,HVAC}Q_{HVAC}/V$, excluding AER) from each filter test and HVAC operation condition estimated with this method are shown in Figure 1. Effective removal rates include the total loss term estimated from nonlinear regressions of the solution to Equation (1), minus the AER (λ).

Effective particle loss rates generally increased as both particle size and rated filter efficiency increased. Minimum loss rates occurred for 0.5–0.7 μm particles for nearly all filters. The widest ranges in deposition rates due to different rated filter removal efficiency generally occurred for 0.5–5 μm particles, as the MERV classification system in ASHRAE Standard 52.2 should reflect. The same data from Figure 1 are presented as means of replicate tests (± one standard deviation) in Table S2.

On average, high-efficiency (MERV 11) filters increased effective particle loss rates in the test house by 2.4 to 6.1 $\mathrm{h^{-1}}$ relative to background deposition rates measured with the HVAC system off. The difference increased with increasing particle size. However, for the largest and smallest particle size bins, filters did not always increase loss rates much over simply running the HVAC system without a filter. For example, medium-efficiency filters did not increase loss rates of 0.3–0.5 μm particles and increased average loss rates of particles greater than 5 μm only 15%, which suggests that primary loss mechanisms of those particle sizes may be deposition onto HVAC components and duct surfaces or exfiltration through duct leakage. These estimates of particle loss rates are likely higher than what would be expected during natural conditions, as the addition of several mixing fans will increase friction velocities and deposition rates (e.g., Lai and Nazaroff 2000), but they are elevated during all conditions and do not ultimately affect calculations of filtration efficiency.

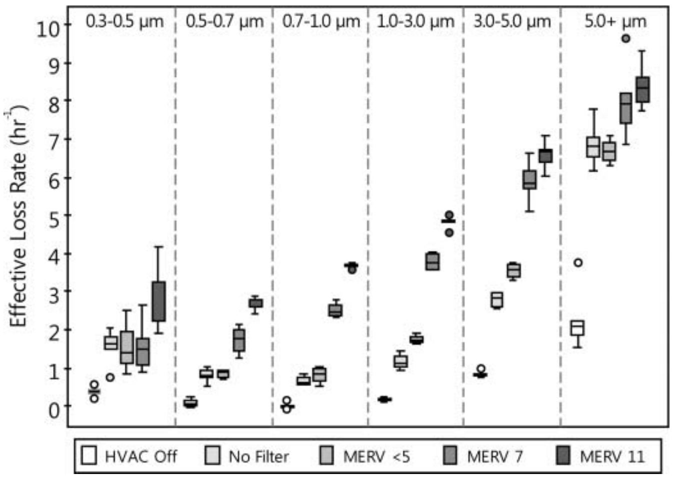

FIG. 1. Size-resolved effective particle loss rates measured in the test house during replicate tests at five filter conditions: background with HVAC off, HVAC on with no filter, and HVAC on with MERV <5, MERV 7, and MERV 11 filters. Loss rates are divided into six particle size bins as indicated by the dashed vertical lines. Boxes represent 25th, 50th, and 75th percentiles, whiskers represent 5th and 95th percentiles, and circles represent outlier values.

Upstream–Downstream Tests

Results from particle removal efficiency tests as measured directly upstream and downstream of each of the three filters are shown in Figure S3. Relative standard deviations of the means across all particle bins ranged from 2% to 14%, from 2% to 18%, and from 4% to 8% for low-, medium-, and high-efficiency filter tests, respectively. The large ranges of efficiency values measured highlight the large uncertainties involved in the relatively simple upstream–downstream method when performed in a real environment. These levels of uncertainties are similar to those for lab tests reported by Hanley et al. (1994), which revealed variations in measured efficiency of up to 15% (absolute) for some particle sizes between triplicate tests repeated with identical filter conditions.

Comparison of Methods of Estimating Filter Efficiency

Estimations of particle removal efficiency for each of the three test filters determined by the two field methods applied in the test house were compared with those measured in two laboratory settings: (1) as reported by the filter manufacturer (taken from their product literature) and (2) as measured by an independent test lab. After the rounds of testing in the test house, the three filters were shipped to an independent testing facility to

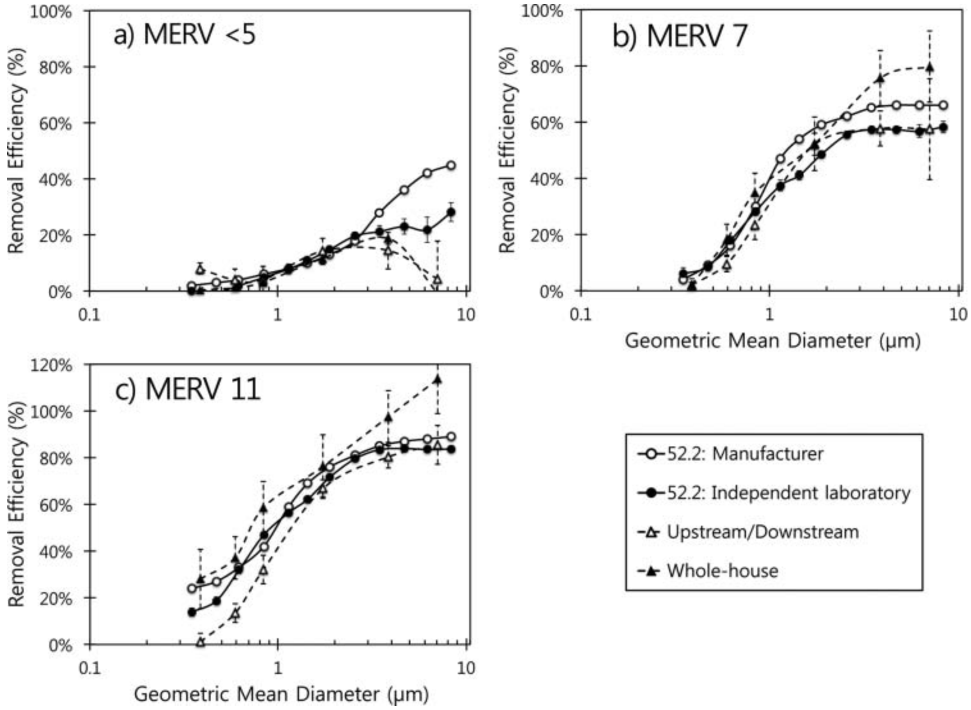

FIG. 2. Comparison of size-resolved particle removal efficiency of three filters [(a) MERV <5, (b) MERV 7, and (c) MERV 11] tested by four methods: ASHRAE 52.2 test results reported by the manufacturer, results from the initial loading stage of ASHRAE 52.2 lab tests on the filters after being used in the test house, results from upstream–downstream measurements in the test house, and results calculated from the whole-house methods in the test house. Removal efficiency is plotted versus the geometric mean diameter for each particle size bin (12 bins for the 52.2 tests and 6 bins for the test house measurements). Note that the vertical scale on Figure 2c extends to 120%.

have an ASHRAE Standard 52.2 test performed. A comparison of the four methods (two *in situ* and two in lab settings) is shown in Figure 2. Values for particle removal efficiency are plotted against the geometric mean diameter of each particle size bin (6 bins from the OPC in the *in situ* tests and 12 bins from OPCs in the lab tests). Uncertainty for field tests is reported as previously discussed and uncertainty from the independent laboratory tests was reported as the 95% confidence interval for each particle size bin. No uncertainty was included in the manufacturer-reported data.

In general, removal efficiencies between all methods agreed well for many particle sizes and filter combinations, and uncertainties for the whole-house method were generally larger than the upstream–downstream method, but not for all particle sizes and filter conditions. Mean absolute uncertainties across all particle size bins and across the three filters were approximately 2% for the independent lab tests, 6% for the upstream–downstream method, and 7% for the whole-house method. Mean uncertainties were relatively constant (±1%) across all filters for the independent lab and upstream–downstream tests, while uncertainties in the whole-house method generally increased as rated filter efficiency increased.

For larger particles (>3 μm), both *in situ* methods resulted in lower estimated removal efficiencies for the MERV <5 filter than were measured in lab tests. The whole-house method overestimated removal efficiencies for MERV 7 and MERV 11 filters relative to the other three tests, even exceeding 100% in one case (an efficiency greater than 100% is theoretically impossible, but we suspect that the discrepancy stems from inadequate mixing of the largest particle sizes, which were removed within only a few minutes with the MERV 11 filter installed). In general, the upstream–downstream method agreed well with MERV 7 and MERV 11 lab tests; however, removal efficiencies of particles <1 μm measured by the upstream–downstream method with a MERV 11 filter installed were lower than the three other test methods. Manufacturer-reported removal efficiencies from lab tests were consistently equal to or greater than those reported by the independent test lab, which might be indicative of a bias, as manufacturers can perform multiple ASHRAE Standard 52.2 tests for a filter and will typically report their best results.

DISCUSSION

Both upstream–downstream and whole-house methods show promise for characterizing the *in situ* particle removal efficiency of HVAC filters in real environments. In many ways, a whole-house test method is preferred because of its ability to characterize the net effects of HVAC systems on particle concentrations in real environments, and our refined whole-house method differs from others in several important ways. The supply of HEPA- and activated-carbon-filtered outdoor air shortened the test duration relative to previous investigations, and we ensured that the tests were performed in a reasonably well-mixed environment. Overall average spatial differences in particle concentrations were near an arbitrary acceptable range of 10% generally used in the literature (Klepeis 1999), as described in the SI.

We also measured system airflow rates using a more accurate method than other studies. Offermann et al. (1992) estimated system airflow rates for each filter condition indirectly by measuring the pressure rise across the fan and referencing the manufacturer's fan calibration curve. This method likely suffers from poor accuracy, as installed conditions often do not accurately reflect rated conditions. Howard-Reed et al. (2003) and Wallace et al. (2004) measured duct air velocities using a hot-wire anemometer and converted the values to a volumetric airflow rate by multiplying by the area of the ductwork. Although this method is valid, it is time consuming and they estimated the experimental uncertainty to be approximately 20% or more. MacIntosh et al. (2008) simply assumed that airflow rates remained constant with each filter, an unlikely assumption for the range of filters tested and the types of systems in most residential and light-commercial systems (Stephens et al. 2010a, 2010b). The flow plate device that we used has been shown to be more accurate than previous methods and is relatively quick to use (Francisco and Palmiter 2003).

It is important to accurately obtain estimates of system airflow rates because, as shown in Equation (1), particle removal by HVAC systems is a function of both efficiency and airflow. System airflow rates are particularly important for investigating filters throughout their life span because filters have been shown to decrease airflow rates in most residential and light-commercial systems as they load with dust in time (Stephens et al. 2010b). If, for example, the airflow rate through a filter decreases by 10% due to the added pressure drop from dust loading after several months of operation, but filter efficiency increases by 10%, the net change would be negligible. Dust loading has been shown to affect particle removal efficiency in both directions, typically decreasing with increased dust loading of charged media filters and increasing with increased dust loading of mechanical filters (Hanley et al. 1994, 1999; Raynor and Chae 2003). Thus, we recommend that both the whole-house and upstream–downstream methods be used in real environments to characterize changes in filter efficiency due to actual dust loading, in conjunction with changes in airflow rates that may occur.

Finally, our method generally achieved greater statistical accuracy relative to other whole-house methods by using nonlinear regressions and attempting to create a well-mixed environment. Propagated errors for the whole-house method of estimating removal efficiency ranged from $<1\%$ to 15%, which are similar to those reported by lab tests in Hanley et al. (1994).

A whole-house *in situ* test method is generally preferred because of the ability to characterize multiple particle interactions, including deposition to ductwork, sources and losses due to duct leakage airflow, and the effect of filter bypass. Particle deposition to ventilation ducts has been shown to be a significant removal mechanism, especially for particles larger than 1 μm (Sippola and Nazaroff 2003, 2004). Wallace et al. (2004) reported average increases in loss rates relative to background due to the operation of a central HVAC fan without a filter of 20%–40% for particles less than 1 μm and 40%–70% increases for 1–3 μm particles, likely caused by deposition to ductwork, as well as the effects of increased turbulence on deposition to interior surfaces. By contrast, the operation of the HVAC fan without a filter in our experiments increased whole-house loss rates by at least a factor of 3 for all particle sizes measured. Again, it should be noted that the particle loss rates reported herein are likely elevated relative to normal operating conditions due to higher AERs and the addition of several mixing fans throughout the house, but estimates of filter efficiency are still valid because they rely only on the difference of measured loss rates. Additionally, supply duct leakage was approximately 15% of system airflow rates (as measured according to ASTM E 1554 [2007]); thus, increased loss rates with the HVAC system operating were likely to be due to the combined effects of enhanced mixing, deposition to ductwork, and exfiltration through duct leakage. These tests could be repeated after duct sealing retrofits in order to determine the importance of both duct deposition and exfiltration through duct leaks as particle loss mechanisms.

Finally, and often most importantly, residential and light-commercial HVAC systems generally operate only in response to heating or cooling loads. Modeling efforts have predicted that removal by HVAC filters is likely a significant removal mechanism only if HVAC systems are operating, while deposition to indoor surfaces is likely more important if HVAC systems are not operating (Thornburg et al. 2001; Waring and Siegel 2008). Typical fractional operation times of residential and light-commercial air-conditioning systems have ranged from 6% to 60%, depending on building and system characteristics, climate, and time of day (James et al. 1997; Thornburg et al. 2004; Stephens et al. 2011). Thus, both HVAC operational characteristics and filter selection are important factors in determining particle fates in these environments (MacIntosh et al. 2010) and should be measured in any field study of central HVAC filtration.

CONCLUSIONS

This work compared four methods of evaluating HVAC filters for particle removal efficiency: two field methods and two laboratory methods. A refined *in situ* whole-house test method for determining the particle removal efficiency of HVAC filters was developed and validated with three types of filters in an unoccupied test house. Results agreed reasonably well for most particle sizes with *in situ* upstream and downstream measurements and with laboratory tests as reported by the manufacturer and as tested by an independent lab. The whole-house method tended to yield higher removal efficiencies for larger particles relative to the upstream–downstream method, especially for higher rated filters, which may be attributed to inadequate mixing of the largest particles. The opposite effect was observed for smaller particles with the same higher-efficiency filters. Regardless, the refined whole-house method can provide a complete picture of particle interactions in a real environment, and both field methods should be used to further investigate the effects of duct leakage, filter bypass airflow, and system operation times on particle removal efficiency in real environments. In addition, more advanced particle instrumentation should be used to more accurately determine the applicability for more particle sizes, including ultrafine particles.

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