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Ultrafine particle removal by residential heating, ventilating, and air-conditioning filters

Abstract This work uses an *in situ* filter test method to measure the size-resolved removal efficiency of indoor-generated ultrafine particles (approximately 7–100 nm) for six new commercially available filters installed in a recirculating heating, ventilating, and air-conditioning (HVAC) system in an unoccupied test house. The fibrous HVAC filters were previously rated by the manufacturers according to ASHRAE Standard 52.2 and ranged from shallow (2.5 cm) fiberglass panel filters (MERV 4) to deep-bed (12.7 cm) electrostatically charged synthetic media filters (MERV 16). Measured removal efficiency ranged from 0 to 10% for most ultrafine particles (UFP) sizes with the lowest rated filters (MERV 4 and 6) to 60–80% for most UFP sizes with the highest rated filter (MERV 16). The deeper bed filters generally achieved higher removal efficiencies than the panel filters, while maintaining a low pressure drop and higher airflow rate in the operating HVAC system. Assuming constant efficiency, a modeling effort using these measured values for new filters and other inputs from real buildings shows that MERV 13–16 filters could reduce the indoor proportion of outdoor UFPs (in the absence of indoor sources) by as much as a factor of 2–3 in a typical single-family residence relative to the lowest efficiency filters, depending in part on particle size.

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Key words: Particulate matter; Filtration; Central air-conditioning; Filter efficiency; MERV; Scanning mobility particle sizer.

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Practical Implications

Presented here are the first size-resolved ultrafine particle removal efficiencies for a wide range of commercially available filters measured in a real residential environment. Size-resolved ultrafine particle removal efficiencies of MERV 4 to MERV 16 residential filters increased systematically with manufacturer-reported results from ASHRAE Standard 52.2 tests, even though the 52.2 test standard does not involve measurements of ultrafine particles. Results from the experiments and modeling herein can be used to inform standards organizations and building occupants of the likely impacts of filter selection on UFP concentrations and exposures in real residential environments. Further experiments should characterize a wider variety of filters and explore the impacts of real dust loading.

Introduction

Elevated ambient concentrations of ultrafine particles (UFPs: particles <100 nm in size) are thought to play an important role in the observed adverse health effects that stem from exposures to airborne particulate matter (Hoek et al., 2010; Knol et al., 2009). UFPs deposit efficiently in both the pulmonary and alveolar regions of the lung (Chalupa et al., 2004; Hinds, 1999) and in head airways, which can also lead to translocation to the brain via the olfactory nerve (Oberdörster et al., 2004). UFPs typically have high number and surface area concentrations in urban outdoor environments (Seinfeld and Pandis, 2006); high surface areas also lead to high concentrations of other adsorbed or condensed compounds (Delfino et al., 2005; Sioutas et al., 2005). Several recent epidemiological studies have shown that elevated ambient UFP number concentrations are associated with adverse health effects, including total and cardio-respiratory mortality (Stölzel et al., 2007), hospital admissions for stroke (Andersen et al., 2010), and asthma symptoms (von Klot et al., 2002; Penttinen et al., 2001; Peters et al., 1997). Of particular importance for respiratory health are UFPs generated by vehicle traffic (Delfino et al., 2009; McConnell et al., 2006; McCreanor et al., 2007), which are typically elevated near busy roadways (Fuller et al., 2012; Westerdahl et al., 2005; Zhu et al., 2002).

Although most of the previously observed associations between particulate matter and adverse health effects have relied on measurements of outdoor particle concentrations, much of human exposure to UFPs often occurs indoors (Wallace and Ott, 2011), particularly in residences where people spend the majority of their time (Klepeis et al., 2001). UFPs have been shown to infiltrate into homes from outdoors with varying efficiencies (Rim et al., 2010; Stephens and Siegel, 2012a; Zhu et al., 2005) and are also generated by many indoor activities, including smoking, cooking on gas stoves, burning incense and candles, and toasting food (Afshari et al., 2005; Wallace, 2006; Wallace et al., 2004b).

Central forced-air heating, ventilating, and air-conditioning (HVAC) filters have been shown to be a dominant removal mechanism for particles in residential indoor environments, depending on particle size, filtration efficiency, and HVAC system runtime (MacIntosh et al., 2008, 2010; Riley et al., 2002; Thornburg et al., 2001, 2004). However, most filter test standards, including the most widely used standard in the United States, ASHRAE Standard 52.2 (ASHRAE, 2012), as well as the most widely used standard in Europe, EN779 (CEN, 2002), do not incorporate measurements of removal efficiency for UFPs. Therefore, there is a lack of knowledge of the particle removal efficiency of HVAC filters in the UFP size range.

Background

Several previous studies have investigated UFP removal by samples of filter media in laboratory settings (e.g., Japuntich et al., 2006; Kanaoka et al., 1987; Lee and Liu, 1981). In larger-scale laboratory investigations, Hanley et al. (1994) measured particle removal efficiency of several HVAC filters across four UFP size ranges in a full-scale laboratory test duct and Shi et al. (2011) measured the size-resolved removal efficiency of 23 commercially available HVAC filters across a larger range of UFP sizes. Although valuable, tests conducted in laboratory settings may not accurately reflect real residential environments where particle concentrations, compositions, climate conditions, face velocities, and pressure drops are likely to be different from laboratory environments.

Other recent studies have investigated UFP removal by filters in real residential or commercial buildings (e.g., Jamriska et al., 2000; Morawska et al., 2009; Rim et al., 2010; Wallace et al., 2004a), but they have been limited in the number and types of HVAC filters tested and have typically reported measurements other than actual filter removal efficiencies (e.g., indoor loss rates or indoor–outdoor UFP concentration ratios). Although previously reported values of loss rates and indoor–outdoor UFP ratios are valuable for real occupied environments, they are influenced in large part by other building characteristics, such as airflow rates through HVAC systems, deposition to ductwork and indoor surfaces, filter face velocities, and indoor air speeds.

Therefore, this work uses a modified version of a previously developed *in situ* test method (Stephens and Siegel, 2012b) to measure a more generalized parameter, size-resolved UFP removal efficiency, of a sample of six new commercially available HVAC filters installed in an unoccupied test house. The sample of six HVAC filters was chosen specifically to span a wide range of manufacturer-reported rated efficiencies according to ASHRAE Standard 52.2 test results for 0.3–10 μm particles. One additional experiment was also performed to measure the infiltration of outdoor UFPs into the same test house and all measured values were used to model the likely impact of filter selection on long-term indoor concentrations of outdoor UFPs in a single residential environment.

Experimental methods

Experimental approach

Experiments were performed January through May 2012 in an unoccupied manufactured test house located on a research campus at the University of Texas at Austin. The instrumented home was built in 2008 and has a floor area and volume of approximately 110 m^2 and 250 m^3, respectively. Tests were performed using a 100% recirculating central forced-air air-handling unit installed in an interior closet where air flows downward through ductwork installed in a crawlspace. The primary experimental methodology herein was similar to the 'whole-house' *in situ* filter test method used in Stephens and Siegel (2012b), which consists of elevating indoor concentrations of particles and a tracer gas (CO_2) and measuring the subsequent decay of both indoor UFP and CO_2 concentrations during three different HVAC operation and filter conditions: (i) with the HVAC system off, (2) with the HVAC system on without a filter installed, and (3) with the HVAC system on with a filter installed. Differences in size-resolved effective loss rates between conditions (2) and (1) provide an estimate of the impact of the HVAC system and ductwork alone on particle removal and, similarly, differences in size-resolved effective loss rates from conditions (3) and (2) provide an estimate of the impact of the installed HVAC filter on indoor loss rates. Because the HVAC system airflow rate is measured in each case and the volume of the indoor space is known, the differences in effective loss rates are used to estimate the size-resolved removal efficiency of HVAC ducts and/or filters. Last, one additional experiment was performed to measure the size-resolved penetration factor of outdoor UFPs using the same general methodology from Rim et al. (2010).

Particle instrumentation

A TSI scanning mobility particle sizer (SMPS) was used to measure particles in the ultrafine range in this work. The SMPS consisted of an electrostatic classifier (TSI Model 3080, Minneapolis, MN, USA), a water-based condensation particle counter (TSI CPC Model 3785), and a nano-differential mobility analyzer (TSI Nano DMA Model 3085). A 0.0457-cm impactor nozzle was installed on the inlet and the SMPS aerosol inlet flow rate was set to 0.6 l/min for all tests. The sheath flow rate was set to 6.0 l/min during each test (for a sheath-to-inlet flow rate ratio of 10:1), which allowed for size-resolved measurements of particles from approximately 3–107 nm in diameter. The condensation particle counter flow rate was 1 l/min. Airflows were verified with a TSI 4146 primary calibrator prior to conducting experiments. UFP raw counts were recorded during 120-s scans with a 15-s retrace period, which provided an indoor sample every 2.25 min (this was increased to 120-s scans with a 30-s retrace period for the particle infiltration experiment).

Filter tests

For the filter tests, indoor particle concentrations were initially elevated during each test run by igniting three sticks of incense and allowing them to burn for several minutes in two locations (burn locations are shown in Figure S1). Once initial UFP concentrations were sufficiently elevated (at least twice background for all particle sizes, usually higher), the sticks of incense were extinguished and the house was left unoccupied for 1–2 h. Indoor UFP concentrations decayed due to removal by exfiltration and deposition to surfaces (during condition 1 tests with the HVAC system off) and by exfiltration, deposition to surfaces, and removal by the HVAC system, ducts, and filters (in conditions 2 and 3, when the HVAC system was operating). At the same time that particle concentrations were being elevated during the test periods, CO_2 was injected into each room of the house to measure the air exchange rate (AER) following the procedure described in the Supporting Information. Several oscillating fans were operated throughout the house to encourage mixing; the well-mixed assumption was previously verified in Stephens and Siegel (2012b). Airflow rates through the HVAC system were also measured during each test run using the procedure described in the Supporting Information. The same system also measured and logged the pressure drop across the filter (if installed) and the pressure in the supply plenum at the same intervals.

Six different commercially available fibrous media HVAC filters (shown in Figure 1) were tested for UFP effective loss rates, filter pressure drops, system airflow rates, and UFP removal efficiencies, which provided a total of eight test cases: Condition 1, Condition 2 and then Condition 3 repeated with six different filters.

Measurements were repeated five times with the same filter for each test case, providing a total of 40 experiments. All filters were 51 cm × 51 cm (20” × 20”). Three of the filters were 2.5-cm (1”) depth and three were 12.7-cm (5”) depth. The 2.5-cm filters were from one manufacturer and the 12.7-cm filters were from another. Each filter is referred to herein by its manufacturer-reported minimum efficiency reporting value (MERV, as defined by ASHRAE Standard 52.2). Filters marked by an asterisk (*) in Figure 1 utilized charged media.

UFP penetration test

After all filter tests were complete, one particle penetration experiment was performed in the unoccupied test house to characterize the penetration factor of the building envelope. This experiment consisted of connecting the SMPS to a solenoid switching valve that automatically switched between sampling indoors and outdoors every 2.5 min. The switch occurred at the end of each 120-s sample scan; sampling at the next location began during each 30-s retrace time to clear the sampling lines. Sampling lines were of approximately equal length for both indoor and outdoor sampling (approximately 2 m each side).

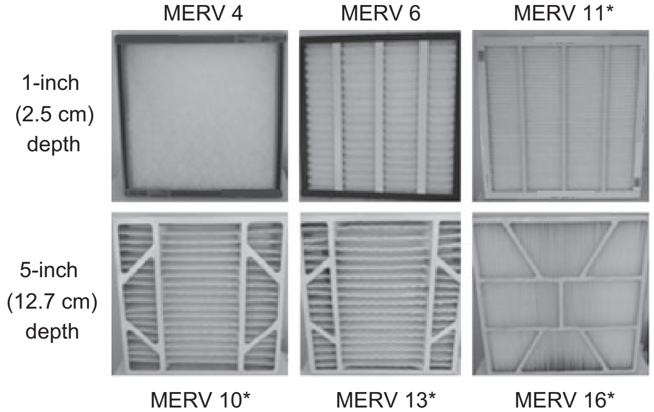

Fig. 1 Six commercially available residential test filters. The four filters marked with an asterisk (*) utilized electrostatically charged media (i.e., electret filters)

Indoor–outdoor raw particle counts were measured for approximately 4 h in the unoccupied house with the HVAC system operating without a filter installed. The house relied only on infiltration for ventilation air. AER was measured as previously described, and the time-varying concentrations of indoor and outdoor raw particle counts, the measured AER, and size-resolved loss rates from the previous tests (during the 'no filter' case) were used with a forward-marching discretization of a mass balance of each indoor particle size (absent of any indoor sources) to solve for the penetration factor of the building envelope using the methodology described in Rim et al., (2010). The penetration factor was then used along with measured loss rates and other relevant literature values to predict the likely impact of filter choice on long-term average indoor concentrations of outdoor UFPs in a single residence.

Estimation of parameters

Parameter estimation for the *in situ* filter tests used herein followed the same general procedure as Stephens and Siegel (2012a) and is outlined in full in the Supporting Information. One deviation from the previous method, other than the particle instrumentation, is that no filtered outdoor air supply was used in these experiments. Therefore, to ensure negligible infiltration of outdoor particles during tests, initial particle concentrations were elevated well above background levels and only the portion of the subsequent decay that fit a first-order decay model was used to estimate particle loss rates. This portion was visually identified for each particle size bin and test condition by plotting the particle concentration decay data on a log-scale vs. time; only the portion of the decay data that was log-linear (after several minutes of mixing) was used for the first-order decay model fit.

Size-resolved indoor particle loss rates were estimated from the first-order decay period. Then, the measured AER was subtracted from each size-resolved loss rate and those 'effective' particle loss rates (L_i) were used against each other to determine the added contribution of an HVAC filter to loss rates for each particle size. The AER estimation methodology is outlined in full in the Supporting Information. The size-resolved particle removal efficiency of the non-filter HVAC system components alone (e.g., ducts, coils, and fans) was estimated by comparing the effective loss rates of Conditions (2) and (1), as shown in Equation 1.

$$\eta_{i,\text{ducts}} = \frac{V(L_{i,\text{no filter}} - L_{i,\text{background}})}{Q_{\text{HVAC,no filter}}} \tag{1}$$

where $L_{i,\text{background}}$ is the effective loss rate of particles of diameter *i* from Condition (1), $L_{i,\text{no filter}}$ is the effective loss rate of particles of diameter *i* from the HVAC on, no filter case (Condition 2), and $Q_{\text{HVAC,no filter}}$ is the HVAC system airflow rate measured during the no filter case. The size-resolved particle removal efficiency of each filter was then estimated by comparing the effective loss rates of Conditions (3) and (2), as shown in Equation 2.

$$\eta_{i,\text{filter}} = V\left(\frac{L_{i,\text{filter}}}{Q_{\text{HVAC, filter}}} - \frac{L_{i,\text{no filter}}}{Q_{\text{HVAC,no filter}}}\right) \tag{2}$$

where $L_{i,\text{filter}}$ is the effective loss rate of particles of diameter *i* from Condition (3) and $Q_{\text{HVAC,filter}}$ is the HVAC system airflow rate measured during each filter condition. Uncertainty was estimated as relative standard errors of regression outputs (for loss rates and AERs) and manufacturer-reported uncertainty (for airflow rates) all added in quadrature.

The SMPS measurements output raw particle counts for 99 particle size bins from 3.11 to 105.5 nm. Because of the large number of particle sizes spanning relatively small size ranges, a binning procedure was performed to lump several particle size bins together prior to the analysis, as described in the Supporting Information. Ultimately, raw particle counts were aggregated into 13 bins, whereby raw particle counts were summed across all diameters in each bin and assigned the geometric mean diameter between the lowest and highest size in each bin. These representative size bins ranged from 4.4 to 100 nm. Upon completion of the experiments, all parameter estimations were conducted using a statistical software package (Stata Version 11, College Station, TX, USA), following the procedures described in the Supporting Information.

Finally, for the data from the particle infiltration experiment, the discretized form of the mass balance on the indoor concentration of each particle size (Equation S1) was used to solve for the size-resolved particle penetration factor of the building envelope (*P*) using the forward-marching method in Rim et al. (2010). The AER was measured during the test and the mean value of L_i across five replicate tests during the 'no filter' test case was used, leaving only one unknown in the equation: P_i.

Results

HVAC system characteristics

Table 1 provides mean values of indoor temperature, relative humidity, filter pressure drop, and HVAC airflow rates measured across the five replicate tests during each of the eight experimental conditions in the test house. Uncertainty values of RH and airflow rates are manufacturer-reported uncertainties; uncertainty

Table 1 Heating, ventilating, and air-conditioning (HVAC) system characteristics during eight test conditions

Test condition[a]	Indoor temp. (°C)	Indoor RH (%)	Filter pressure drop (Pa)	HVAC airflow rate (m^3/h)	AER (per h)
HVAC off	22.3 (1.0)	43 ± 5	n/a	n/a	0.26 (0.08)
No filter	21.6 (2.4)	39 ± 5	n/a	1712 ± 86	0.38 (0.03)
MERV 4 (2.5 cm)	21.5 (1.1)	38 ± 5	17 (0.2)	1644 ± 82	0.40 (0.03)
MERV 6 (2.5 cm)	21.0 (0.3)	37 ± 5	51 (0.4)	1564 ± 78	0.38 (0.04)
MERV 11 (2.5 cm)	21.6 (0.4)	38 ± 5	46 (0.7)	1572 ± 79	0.44 (0.01)
MERV 10 (12.7 cm)	25.5 (1.4)	48 ± 5	17 (0.1)	1621 ± 81	0.45 (0.03)
MERV 13 (12.7 cm)	26.8 (1.5)	49 ± 5	40 (0.3)	1577 ± 79	0.52 (0.07)
MERV 16 (12.7 cm)	21.1 (1.0)	49 ± 5	25 (0.6)	1603 ± 80	0.51 (0.11)

AER, air exchange rate.

[a] MERV 4, 6, and 11 are 2.5-cm filters; MERV 10, 13, and 16 are 12.7-cm filters. Approximate European (EN 779) equivalents are as follows: MERV 4 (G2), MERV 6 (G3), MERV 11 (M6), MERV 10 (M5), MERV 13 (F7), and MERV 16 (F9/E10).

values for indoor temperature, filter pressure drop, and air exchange rate (AER) are standard deviations across the five replicates of each test condition.

Filters were tested across generally similar indoor environmental conditions, with indoor temperatures typically ranging 21–26°C and RH ranging 37–49%. The operation of the HVAC fan increased AERs relative to the HVAC off case, presumably due to the combined effects of supply duct leakage and envelope depressurization. However, AER is subtracted from each total particle loss rate to determine an 'effective' loss rate attributed to surface deposition and any installed filtration; therefore, variations in AER do not impact the overall results.

The installation of 2.5 cm (1") MERV 4, MERV 6, and MERV 11 filters introduced a filter pressure drop of 17, 51, and 46 Pa, respectively, which led to decreases in airflow rates relative to the no filter condition of 4%, 9%, and 8%, respectively. Interestingly, the MERV 11 filter had a slightly lower pressure drop and higher airflow rate than the MERV 6 filter, which is consistent with previous measurements of medium- and high-efficiency filter pressure drops (Stephens et al., 2010). The extended filter bed depths of the 12.7-cm (5") filters were effective in maintaining a relatively low pressure drop; in fact, the highest rated efficiency filter in this sample (MERV 16) actually had a lower pressure drop (and higher airflow rate) than two 2.5-cm filters (MERV 6 and MERV 11) and one other 12.7-cm filter (MERV 13). Overall, the deeper MERV 10, MERV 13, and MERV 16 filters resulted in airflow rates that were 5%, 8%, and 6% lower than operating the HVAC system without a filter, respectively.

UFP generation and loss rates

Figure S2 shows mean (±s.d.) values of the initial indoor particle concentration measured across all 40 experiments (i.e., $C_{i,in}$ at time $t = 0$ for each experiment), which provides an idea of the typical ultrafine particle size distribution resulting from incense burning. Initial particle concentrations measured during incense burning were very low for the smallest geometric mean particle size (< 5 nm) likely due to a combination of low emission rates, instrument detection limits, and/or a short SMPS retrace times of 15 s. High uncertainties resulted for this particle size; therefore, the smallest particle size is excluded from the rest of the analysis.

Table S1 provides estimates of size-resolved effective loss rates (L_i, total particle loss rates minus AER) for each of the eight test conditions. Figure 2 shows the same results graphically, but excludes the 'no filter' condition for clarity (loss rates for the no filter condition were very similar to the MERV 4 condition for most particle sizes).Values represent the mean and compounded uncertainty (standard deviations in quadrature with measurement uncertainty) of estimates resulting from the five replicate tests for each particle size and test condition.

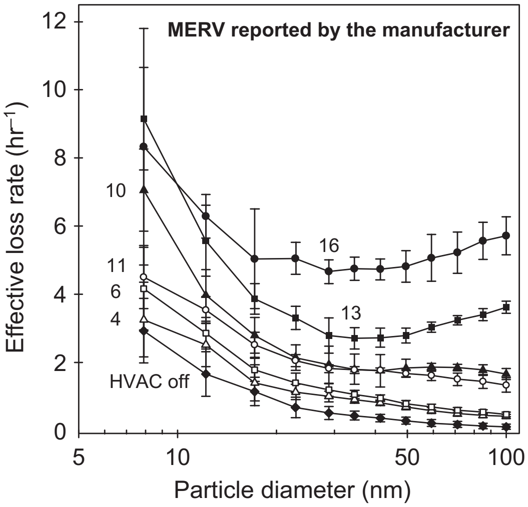

Fig. 2 Mean (±compounded uncertainty) size-resolved 'effective' particle loss rates measured across five replicates of seven of the eight test conditions, including the heating, ventilating, and air-conditioning off condition and the six filter conditions (the no filter case is excluded for clarity). Air exchange rate is subtracted from each total loss rate to yield the 'effective' loss rate

Effective particle loss rates generally increased with rated filter condition. For example, effective loss rates of 12.2-nm particles (the 10.2- to 14.6-nm bin) increased from 1.66 ± 0.66 per h with the HVAC system off to 2.51 ± 0.65 per h with a MERV 4 filter installed and to 6.28 ± 0.69 per h with a MERV 16 filter installed. The trend was similar for most particle sizes. Relative uncertainties were generally highest for test cases with lower effective loss rates (and lower manufacturer-reported MERV). For example, the HVAC off condition had a mean relative uncertainty of approximately 43% across the 12 particle size bins; the MERV 13 condition had a mean relative uncertainty of only approximately 10% across all particle sizes. Relative uncertainty was also generally higher for smaller particle sizes, likely due to a combination low indoor concentrations, low counting efficiencies, and higher loss rates that led to shorter durations of valid data.

On average, the no filter condition increased effective UFP loss rates by 0.3–0.6 per h relative to the HVAC off condition for most particle sizes. Similarly, the MERV 4 and MERV 6 filters increased effective loss rates by 0.3–0.5 and 0.3–0.7 per h for most particle sizes, respectively, and the MERV 10 and 11 filters increased effective loss rates by 1.2–1.4 and 1.3–1.7 per h for most sizes. Finally, the MERV 13 and MERV 16 filter increased effective loss rates by 2.2–3.5 per h and 4.3–5.4 per h for most particle sizes, respectively, which is a substantial increase over lower-efficiency filters both herein and in other studies (Rim et al., 2010; Wallace et al., 2004a). Overall, UFP effective loss rates with the filters in this study increased systematically with manufacturer-rated filter efficiency, even though those rated efficiency values from ASHRAE Standard 52.2 are not actually based on UFP removal.

UFP removal efficiency

Figure 3 shows mean and associated uncertainty values of size-resolved UFP removal efficiency measured during the six filter test conditions. These values are also included in tabular form in the Supporting Information (Table S2).

Ultrafine particles removal efficiency of the MERV 4 filter was not statistically different from zero for most particle sizes and the MERV 6 filter resulted in removal efficiencies <10% for almost all sizes. The MERV 11 (2.5 cm) and MERV 10 (12.7 cm) filters resulted in similar UFP removal efficiencies of 15–20% for most particle sizes, although the deeper bed MERV 10 filter resulted in greater removal efficiencies for the smallest particle sizes. The MERV 13 filter resulted in UFP removal efficiencies of 30–50% for most particle sizes; removal efficiency of the smallest size bin was approximately 90%, albeit with large uncertainty. Finally, the MERV 16 filter resulted in UFP removal efficiencies of 60–80% for most particle sizes. Note that the filters that utilized electrostatically charged media (MERV 10, 11, 13, and 16) all experienced minimum removal efficiencies around 20–30 nm, which is generally consistent with other studies on electret filter media (e.g., Kanaoka et al., 1987; Li et al., 2012). Overall, results herein again suggest that substantial increases in UFP removal can be achieved by installing higher rated efficiency filters, even if those filters are not specifically rated for UFP removal in laboratory testing.

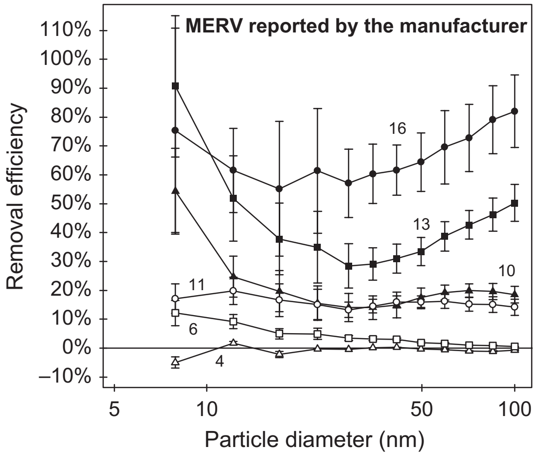

Fig. 3 Size-resolved particle removal efficiency for six test filters. Note that MERV 4, 6, and 11 are 2.5-cm (1”) filters and MERV 10, 13, and 16 are 12.7-cm (5”) filters. The smallest geometric mean particle size (4.4 nm) is excluded because of very large uncertainties associated with the measurements

UFP infiltration and modeling filter impacts on indoor concentrations of outdoor UFPs

Results from the particle penetration experiment performed in the test house are shown in Figure 4a. Size-resolved particle penetration factors ranged from approximately 0.40–0.55 for particles <30 nm and increased to 0.55–0.80- for 30–100-nm particles. The AER during this test was approximately 0.63 per h. These values of P_i were somewhat higher than those measured in Rim et al. (2010) for a different test house, who reported values of P_i from approximately 0.20–0.55 for most particle sizes smaller than 100 nm, potentially because of different building envelope leakage characteristics (e.g., Liu and Nazaroff, 2001; Stephens and Siegel, 2012a).

The measured size-resolved particle penetration factors (P_i) from Figure 4a were then used to estimate the impacts of HVAC filter choice on long-term average size-resolved indoor proportions of outdoor UFPs in this particular single-family detached home relying on infiltration for ventilation air and with a 100% recirculating HVAC system. The indoor proportion of outdoor UFPs represents the average indoor/outdoor concentration ratios ($C_{i,\mathrm{in}}/C_{i,\mathrm{out}}$) that would exist in the absence of any indoor sources. Indoor proportions of outdoor UFPs were estimated for each particle size using the well-mixed mass balance in Equation 3.

$$\frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + L_{i,\mathrm{background}} + (L_{i,\mathrm{filter}} - L_{i,\mathrm{background}}) f_{\mathrm{HVAC}}} \quad (3)$$

where P_i = penetration factor of particles of diameter i (dimensionless, from Figure 4a), $L_{i,\mathrm{background}}$ = the size-resolved particle loss rate with the HVAC system off (per h), $L_{i,\mathrm{filter}}$ = the additional size-resolved particle loss rate due to the HVAC ducts and filter combined for each filter condition (per h), and f_{HVAC} = fractional operation time of the cycling HVAC system, which typically operates only in response to indoor and outdoor climate conditions in residences. Note that background (HVAC off) particle loss rates may be overestimated due to the operation of mixing fans, but this exercise can still provide a valuable understanding of the impact of filtration on indoor concentrations of outdoor UFPs. Additionally, this analysis assumes that particle removal efficiency does not change with dust loading in time; this assumption should be explored in further analyses because electrostatically charged fibrous media filters (e.g., MERV 10–16 in this study) have been shown to have substantially reduced removal efficiency for some particle sizes after loading with some particle types (Hanley et al., 1994, 1999; Lehtimäki et al., 2002).

One AER was used in all model cases for simplicity: the mean AER from all experiments in the test house with the HVAC system on (λ = 0.41 per h). The mean size-resolved particle loss rates with the HVAC system off (mean values of $L_{i,\mathrm{background}}$ from Figure 2) were used to model a baseline I/O UFP ratio without a filter installed. Each of the six filter test cases (MERV 4–16) were then modeled using the additional size-resolved particle loss rates attributed to the filter and duct system combined, where $L_{i,\mathrm{filter\ +\ ducts}}$ is the difference between the total effective loss rates from each filter condition in Figure 2 and $L_{i,\mathrm{background}}$. Finally, each value of $L_{i,\mathrm{filter\ +\ ducts}}$ was multiplied by the median fractional operation time (*f*) of 17 residential and light-commercial HVAC systems reported in Stephens et al. (2011) for the six filter cases ($f = 0$ for the baseline HVAC off case). This value (f = 20.6% of the time) accounts for long-term averages in HVAC system cycling operation during the long cooling season in a range of typical low-rise buildings in Austin, Texas USA (measurements were made from March to late October in Stephens et al., 2011). Therefore, the estimates of the indoor proportion of outdoor UFPs shown in Figure 4b reflect the combined impacts of particle infiltration through the building envelope, air exchange, and the long-term operation of the HVAC system with six different filters installed in a typical single-family residential building (albeit with several unlikely assumptions, including no change in filter removal with dust loading in time and no variations in AER or P_i).

Using this model, long-term operation of this building without the HVAC system operating would lead to an average indoor proportion of outdoor UFPs of 0.05–0.63, increasing with particle size. Long-term operation of the building with a cycling HVAC system with a low-efficiency MERV 4–6 filter installed would reduce indoor concentrations of outdoor UFPs by approximately 9–12% relative to that which would occur with the HVAC system off, on average across all particle sizes (I/O UFP ratios would range from 0.05 to 0.57, generally increasing with particle size). Increasing to MERV 10–11 filters would likely reduce the average indoor proportion of outdoor UFPs by 24–28% on average across all particle sizes relative to HVAC off (I/O UFP ratios would range from 0.04 to 0.43, increasing again with particle size). Finally, increasing

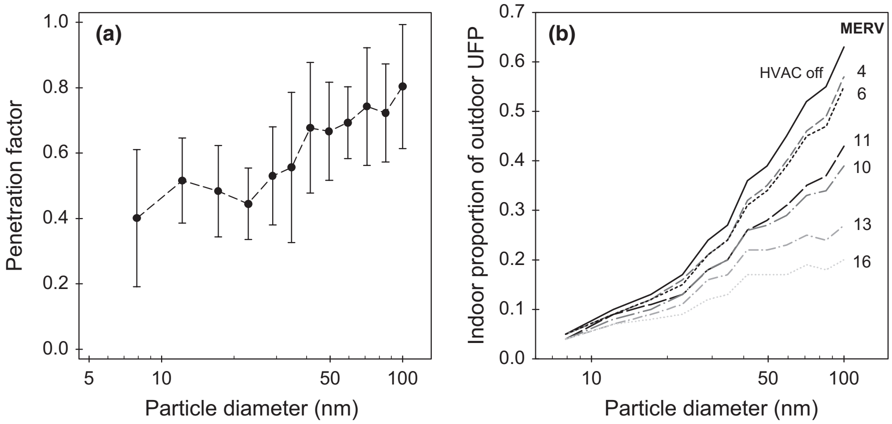

Fig. 4 (a) Size-resolved ultrafine particles (UFP) penetration factors measured in the test house. Error bars include relative standard errors of P_i and L_i from regression outputs added in quadrature. (b) Modeled size-resolved indoor proportions of outdoor UFPs in the test house using size-resolved penetration factors (P_i) from (a). Model calculations are made using the mean air exchange rate from Table 1 (λ = 0.41/h), the mean effective loss rates from Figure 2, and the median fractional heating, ventilating, and air-conditioning operation time (f = 0.206) from 17 residential and light-commercial air-conditioning systems in Stephens et al. (2011)

to a MERV 13 or MERV 16 filter would decrease the average indoor proportion of outdoor UFPs by 40% and 51% relative to those without the HVAC system operating, respectively (I/O UFP ratios would range from 0.04 to 0.27 and 0.04 to 0.20, respectively, again increasing with particle size). These estimates provide insight into how HVAC filtration may influence human exposure to UFPs of outdoor origin inside residences.

Discussion

With this sample of six commercially available filters, it appears that MERV 4–6, MERV 10–11, MERV 13, and MERV 16 filters of the types tested herein can generally be classified into four distinct regimes with UFP removal efficiencies for most particle sizes of approximately 0–10%, 15–20%, 30–50%, and 60–80%, respectively. To achieve substantial removal of UFPs in real residential environments (i.e., >50% removal efficiency and modeled indoor proportions of outdoor UFPs of less than approximately 0.25 for most particle sizes), much higher efficiency filters than are typically used in homes are likely required (e.g., MERV 13 or MERV 16). Additionally, these particular deeper bed filters appear to achieve dual benefits of higher UFP removal efficiency with lower pressure drop, and thus should result in higher airflow rates in most residential HVAC systems. These gains may be practically difficult to achieve in existing buildings as most HVAC systems would require some level of retrofitting to allow for installation of deeper bed filters.

These findings are particularly important as the majority of residential occupants still use traditional low-efficiency fibrous filters (Burroughs and Kinzer, 1998), and there is a wide variety of filters commercially available for use in residences. Additionally, technical standards organizations and green building rating systems continue to debate the use of higher efficiency filtration in homes. For example, ASHRAE Standard 62.2, ‘Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings,’ currently requires a minimum of MERV 6 to be installed to provide ‘acceptable indoor air quality’ in residences. Results herein show that MERV 6 filters are unlikely to control indoor ultrafine particles in any significant way. Additionally, a prerequisite for certification by the U.S. Green Building Council’s LEED® for Homes Rating System is the installation of at least MERV 8 filters. Additional credits can be obtained by installing MERV $\geq$ 10 filters (for 1 point) and MERV $\geq$ 13 filters (for 2 points). HVAC filtration therefore represents nearly 10% of the total Indoor Environmental Quality (EQ) credits available in LEED® for Homes (2 of 21 possible points). Using this small sample of HVAC filters, the LEED® for Homes Rating System would require filters that provide likely 0–20% removal efficiency for UFPs as a prerequisite and filters that provide approximately 15–20% and 30–50% removal efficiency for most particle sizes for one and two additional EQ credits, respectively, which suggests that these credits are aligned in a logical manner with respect to UFP removal. However, additional credits may need to be added to reward even higher levels of filtration that achieve >50% removal of most UFP sizes.

One important limitation to the values measured herein is that all filters were installed as new from the manufacturer. In real residential environments, dust loading will alter the actual particle removal efficiency over time; the direction and magnitude of changes is a function of system runtimes, indoor particle size distributions and concentrations, and the level of degradation of any electrostatic charge applied to the filter media. Dust loading is also particularly important in terms of pressure drop; although the highest efficiency deeper bed filters in this study had initially low pressure drops during our measurements, it is not clear how much pressure drop will increase with dust loading in time. If the deeper filters can maintain lower pressure drops (and thus higher airflow rates in most residential HVAC systems) for a longer period of time than their traditional counterparts, perhaps the use of these filters with higher capital costs could be justified from perspectives of both costs and UFP particle removal. Finally, the measured values herein are limited only to the particular filters used in this study. Results may not necessarily be generalized to all other commercially available residential filtration products.

Conclusions

A variation of a previously developed *in situ* filter test method was used to measure the size-resolved ultrafine particle (UFP) removal efficiency of six commercially available HVAC filters in an unoccupied test house. UFP removal efficiency generally increased with manufacturer-reported efficiency (MERV, as reported by ASHRAE Standard 52.2) for most particle sizes, even though the rated metrics do not specifically take into account UFP removal. These results also suggest that MERV 4–6, MERV 10–11, MERV 13, and MERV 16 filters can likely be classified into four distinct regimes in terms of ultrafine particle removal efficiency; that is, UFP removal efficiency for most particle sizes was 0–10%, 15–20%, 30–50%, and 60–80% for MERV 4–6, MERV 10–11, MERV 13, and MERV 16 filters, respectively. To achieve substantial removal of ultrafine particles by central HVAC filters in residential environments (i.e., >50% efficiency), much higher efficiency filters than are typically used in homes are likely required. A modeling effort using the measured values showed that MERV 13 and MERV 16 filters could reduce the indoor proportion of outdoor UFPs to less than approximately 0.25 for most particle sizes in a typical single-family residence.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:
Data S1. Ultrafine particle removal by residential HVAC filters.

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