Atmospheric Environment 98 (2014) 337–346

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin

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HIGHLIGHTS

- We estimate HVAC filter removal efficiencies for $PM_{2.5}$ and UFPs of outdoor origin.
- Both UFP and $PM_{2.5}$ removal efficiency tend to increase with increasing MERV.
- Outdoor PSDs and particle density do not substantially impact $PM_{2.5}$ removal efficiencies.
- Outdoor PSDs and infiltration factors do impact UFP removal efficiencies.
- This work informs how MERV relates to outdoor $PM_{2.5}$ and UFP removal efficiency.

ARTICLE INFO

Article history:
Received 31 July 2014
Received in revised form
26 August 2014
Accepted 3 September 2014
Available online 4 September 2014

Keywords:
Aerosols
Filters
Indoor air
Modeling

ABSTRACT

This work uses 194 outdoor particle size distributions (PSDs) from the literature to estimate single-pass heating, ventilating, and air-conditioning (HVAC) filter removal efficiencies for $PM_{2.5}$ and ultrafine particles (UFPs: <100 nm) of outdoor origin. The PSDs were first fitted to tri-modal lognormal distributions and then mapped to size-resolved particle removal efficiency of a wide range of HVAC filters identified in the literature. Filters included those with a minimum efficiency reporting value (MERV) of 5, 6, 7, 8, 10, 12, 14, and 16, as well as HEPA filters. We demonstrate that although the MERV metric defined in ASHRAE Standard 52.2 does not explicitly account for UFP or $PM_{2.5}$ removal efficiency, estimates of filtration efficiency for both size fractions increased with increasing MERV. Our results also indicate that outdoor PSD characteristics and assumptions for particle density and typical size-resolved infiltration factors (in the absence of HVAC filtration) do not drastically impact estimates of HVAC filter removal efficiencies for $PM_{2.5}$. The impact of these factors is greater for UFPs; however, they are also somewhat predictable. Despite these findings, our results also suggest that MERV alone cannot always be used to predict UFP or $PM_{2.5}$ removal efficiency given the various size-resolved removal efficiencies of different makes and models, particularly for MERV 7 and MERV 12 filters. This information improves knowledge of how the MERV designation relates to $PM_{2.5}$ and UFP removal efficiency for indoor particles of outdoor origin. Results can be used to simplify indoor air quality modeling efforts and inform standards and guidelines.

1. Introduction

Epidemiology studies have consistently shown associations between increased adverse health effects and elevated outdoor fine particulate matter mass ($PM_{2.5}$) (Brook et al., 2010; Miller et al., 2007; Pope and Dockery, 2006; Pope et al., 2002) and ultrafine particle number concentrations (UFPs: particles <100 nm in size) (Penttinen et al., 2001; Stölzel et al., 2007; von Klot et al., 2002; Weichenthal et al., 2007). However, the majority of exposure to fine and ultrafine particles of outdoor origin often occurs inside buildings (Allen et al., 2004; Bhangar et al., 2011; Kearney et al., 2011; Meng et al., 2009, 2005). This is because outdoor particles can penetrate indoors (Chen and Zhao, 2011) and people in industrialized countries spend much of their time indoors (Jenkins et al., 1992; Klepeis et al., 2001). Indoor particle control technologies such as stand-alone air cleaners and particle filters installed in central heating, ventilating, and air-conditioning (HVAC) systems are being increasingly relied upon to reduce indoor concentrations of particles of both indoor and outdoor origin (Brown et al., 2014; Howard-Reed et al., 2003; MacIntosh et al., 2010, 2008; Offermann et al., 1985; Riley et al., 2002; Stephens and Siegel, 2012a, 2013; Wallace et al., 2013, 2004; Zaatari et al., 2014).

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http://dx.doi.org/10.1016/j.atmosenv.2014.09.007
1352-2310/

Although much of the health concerns with outdoor particulate matter are associated with $PM_{2.5}$ and, to a lesser extent, UFPs, common HVAC filter test standards do not explicitly account for either of these measures when evaluating particle removal efficiency (ASHRAE, 2012; CEN, 2012). Rather, they tend to characterize removal efficiency on a size-resolved basis, as is appropriate for fibrous filter media because filtration efficiency varies widely by particle size (Hinds, 1999a). For example, the most widely used particle filtration test standard in the U.S., ASHRAE Standard 52.2, classifies the single-pass particle removal efficiency of HVAC filters based on the minimum removal efficiency for three particle size bins (0.3–1, 1–3, and 3–10 μm) under various loading conditions in a laboratory test facility (ASHRAE, 2012). Minimum removal efficiency values in these three size bins are then used to assign HVAC filters a single efficiency metric called the Minimum Efficiency Reporting Value (MERV). The assignment of the MERV metric to minimum particle removal efficiencies for the three size bins in Standard 52.2 is provided in Table S1 in the SI.

Three shortcomings are apparent in ASHRAE Standard 52.2 and its resulting MERV metric. First, although particle size bins 1 and 2 evaluate removal efficiency for particle sizes within the $PM_{2.5}$ size range (0.3–1.0 and 1.0–3.0 μm, respectively), there is no explicit reference to $PM_{2.5}$ mass concentration removal efficiency. $PM_{2.5}$ mass removal efficiency will vary highly depending on particle size distribution (PSD) and particle density (El Orch et al., 2014; Hanley et al., 1994; Riley et al., 2002). Although one recent study found strong correlations between E_1 removal efficiency and indoor and outdoor origin $PM_{2.5}$ mass removal efficiency (Zaatari et al., 2014), it was limited by a small number of outdoor PSDs and $PM_{2.5}$ mass concentrations. A larger number of outdoor PSDs is important to capture because they can vary widely by location (e.g., rural, urban, and close to traffic), season (e.g., winter, spring, summer, and fall), or even time of day (e.g., morning, afternoon, and nights) (Costabile et al., 2009; Jaenicke, 1993; Kelly et al., 2011; Puustinen et al., 2007; Seinfeld and Pandis, 2006; Virtanen et al., 2006).

Second, ASHRAE Standard 52.2 does not evaluate UFP removal, although there is some evidence to suggest that UFP removal efficiency tends to increase with MERV (El Orch et al., 2014; Hecker and Hofacre, 2008; Stephens and Siegel, 2012b). UFPs are important to capture because the vast majority of outdoor particles actually exist in the UFP size range (Hinds, 1999b; Seinfeld and Pandis, 2006). Finally, because of the lack of removal efficiency requirements for particle size bins 1 and 2 for many MERV assignments (i.e., MERV 1-8 for E_2 and MERV 1-12 for E_1), two different filters with the same MERV can have vastly different efficiencies for particles smaller than 3 μm (and particularly so for particles smaller than 1 μm). As an example, Hecker and Hofacre (2008) reported removal efficiency of different MERV 12 filters measured in laboratory tests to range from as low as 10% to as high as 70% for ~100 nm particles.

Given these issues, there remains a need to improve knowledge of how different MERV filters perform in removing $PM_{2.5}$ and UFPs of outdoor origin. Improvements in knowledge of how MERV relates to $PM_{2.5}$ and UFP efficiency for outdoor particles can simplify indoor air quality modeling efforts and improve our ability to inform standards and guidelines. For example, there are currently draft proposals to increase filtration requirements in ASHRAE Standards 62.1 (ASHRAE, 2010) and 62.2 (ASHRAE, 2013) based on health outcomes of $PM_{2.5}$ (and possibly UFPs). Given these limitations, the objective of this paper is to provide estimates of particle removal efficiency of various HVAC filters for $PM_{2.5}$ and UFP of ambient origin. We achieved this by mapping 194 outdoor PSDs found in the literature to size-resolved particle removal efficiencies of a wide range of HVAC filters, including MERV 5, 6, 7, 8, 10, 12, 14, 16 and HEPA filters. We use the results to explore statistical distributions of outdoor-origin $PM_{2.5}$ and UFP removal efficiencies. We also test the sensitivity of our results to key assumptions such as particle density and modification by typical size-resolved infiltration factors in residences (in the absence of HVAC filtration), which alter outdoor PSDs as particles transport indoors.

2. Methods

2.1. Selecting outdoor particle size distributions (PSDs)

To make our results as generalizable as possible, we first performed a literature review to identify previous studies that reported long-term measurements of outdoor PSDs across the world. Eight key studies were identified that reported outdoor PSDs measured for a duration of at least one year, leading to a total of 194 PSDs in more than 30 locations (Asmi et al., 2011; Birmili et al., 2001; Costabile et al., 2009; Hussein et al., 2004; Sabaliauskas et al., 2012; Stanier et al., 2004; Wåhlin, 2009; Wehner and Wiedensohler, 2003). The intent of the review was to gather a wide enough variety of PSDs to explore the influence of highly varying PSD characteristics on our estimates of $PM_{2.5}$ and UFP removal efficiency by HVAC filters. A limit of one-year averages was chosen primarily to limit the number of PSDs to a reasonable amount. Most of these studies: (i) occurred in various European countries (with a few in the United States and other areas), (ii) measured particles ~10 nm–800 nm (albeit with some variation in instrumentation), and (iii) reported their results graphically in terms of particle number concentrations, or $dN/d\log D_p$, versus the log of particle size, D_p.

Tri-modal lognormal distributions were fit to each of the 194 outdoor PSDs (Hinds, 1999b; Seinfeld and Pandis, 2006). Geometric means (GMs), geometric standard deviations (GSDs), and total number concentrations for nucleation, accumulation, and coarse modes were adjusted manually using a semi-transparent graphical overlay until an adequate visual fit was achieved. Each particle size from 0.001 to 10 μm was plotted in bins of 0.001 μm, providing 10,000 discrete particle sizes that ultimately yielded 194 smooth outdoor PSDs with which to map to size-resolved HVAC filter removal efficiency. This same method for estimating tri-modal GMs, GSDs, and number concentrations has been used successfully in another recent study (El Orch et al., 2014).

2.2. Estimating outdoor UFP and $PM_{2.5}$ concentrations

The 194 PSDs were then used to estimate outdoor $PM_{2.5}$ and UFP concentrations in each location. This procedure primarily served as a check on the validity of the methodology and on the overall representativeness of these locations. Outdoor UFP number concentrations were calculated by simply adding the number concentration of particles smaller than 100 nm for each outdoor PSD. Two different scenarios of outdoor $PM_{2.5}$ mass concentrations for each outdoor PSD were estimated using two different assumptions for particle density. First, we assumed spherical particles with constant unit density (1 g/cm^3) for all particles, both for simplicity and to reflect previous assumptions in the literature (El Orch et al., 2014; Riley et al., 2002; Waring and Siegel, 2008; Zaatari et al., 2014). Second, we assumed spherical particles with density varying with diameter according to the average of that reported during two experimental campaigns in two German cities (Neusüss et al., 2002): 1.3 g/cm^3 for $D_p < 140$ nm; 1.4 g/cm^3 for 140 nm $\leq D_p <$ 420 nm; 1.5 g/cm^3 for 420 nm $\leq D_p <$ 1.2 μm; 1.6 g/cm^3 for 1.2 μm $\leq D_p <$ 3.5 μm; and 1.7 g/cm^3 for 3.5 μm $\leq D_p <$ 10 μm. Other studies have reported other size-resolved densities in outdoor aerosols (Hu et al., 2012; Pitz et al., 2008), but this second assumption serves to explore the influence of different size-resolved density assumptions

relative to the constant unit density assumption. We assumed particle density increased linearly in each size bin from 0.05 g/cm^3 lower to 0.05 g/cm^3 higher of the mean density of each bin reported in (Neusüss et al., 2002). For example, for particles smaller than 140 nm we assumed that density ranged from 1.25 g/cm^3 for 1 nm particles to 1.35 g/cm^3 for 140 nm particles with a mean density of 1.3 g/cm^3. In this way the true density estimates ranged from 1.25 g/cm^3 to 1.75 g/cm^3 for particles with diameter 1 nm to 10 μm, respectively.

2.3. Selecting representative size-resolved HVAC filter removal efficiencies

Size-resolved particle removal efficiencies from 0.001 to 10 μm were then gathered for generally representative HVAC filters, including MERV 6, 7, 8, 10, 12, 14, 16 and HEPA filters. These data were based on the measured single-pass size-resolved removal efficiencies for 0.03 μm–10 μm particles reported in Hecker and Hofacre (2008), which were also extended to accommodate particles smaller than 0.03 μm by extrapolation from their reported curve fits. This report contained the most extensive size-resolved filtration efficiency measurements for MERV designations of which we are aware. Several best fit curves for size-resolved removal efficiency versus particle diameter were used to estimate removal efficiency for most of the filters (shown in Table S2 in the SI). In addition, a curve fit for MERV 10 was manually adjusted to accommodate particles smaller than 0.03 μm. Removal efficiencies for MERV 5 filters were modeled following procedures outlined in Kowalski et al. (1999). Additionally, because reported removal efficiencies of both MERV 7 and MERV 12 filters in Hecker and Hofacre (2008) varied so drastically between different makes and models (particularly for particles smaller than 0.3 μm), two curves were used for each. This provided both 'high' and 'low' efficiency versions of MERV 7 and MERV 12 designations.

2.4. Estimating UFP and $PM_{2.5}$ removal efficiency of HVAC filters

The particle removal efficiency of the various MERV filters for outdoor UFPs and $PM_{2.5}$ were estimated using Eqs. (1) and (2), respectively.

$$\eta_{UFP} = 1 - \frac{\sum_{i=1}^{100} N_i \times \left(1 - \eta_i\right)}{\sum_{i=1}^{100} N_i} \quad (1)$$

$$\eta_{PM2.5} = 1 - \frac{\sum_{i=1}^{2500} N_i \times \rho_i \times \frac{\pi d_i^3}{6} \times \left(1 - \eta_i\right)}{\sum_{i=1}^{2500} N_i \times \rho_i \times \frac{\pi d_i^3}{6}} \quad (2)$$

where η_{UFP} = estimated UFP removal efficiency of a filter (−); $\eta_{PM2.5}$ = estimated $PM_{2.5}$ removal efficiency of a filter; d_i = diameter of particles of size i (cm); N_i = number of concentration of particles with diameter d_i (#/cm^3); η_i = removal efficiency of filter for particles with diameter d_i (−); and ρ_i = density of particles with diameter of d_i (g/cm^3). These estimates assume that HVAC filters are used to filter 100% outdoor air (Zaatari et al., 2014) and that the same face velocities achieved in laboratory tests leading to the reported size-resolved efficiency values are achieved. The sensitivity of our results to the 100% outdoor air (OA) assumption is tested following procedures described in the next section.

2.5. Modifications to UFP and $PM_{2.5}$ removal efficiency after infiltration

Additionally, a similar procedure to Section 2.4 was used to estimate UFP and $PM_{2.5}$ removal efficiency of the various MERV filters assuming that outdoor PSDs have been modified by transport losses during penetration through a typical residential building envelope (Chao et al., 2003; Chen and Zhao, 2011; Liu and Nazaroff, 2001, 2003; Long et al., 2001; Rim et al., 2010; Thatcher et al., 2003; Zhu et al., 2005) and by deposition losses once indoors (Chao et al., 2003; He et al., 2005; Lai and Nazaroff, 2000; Thatcher, 2002; Wallace et al., 2004). This was accomplished by estimating size-resolved infiltration factors, or the indoor proportion of outdoor particles, in the absence of HVAC filtration, using Eq. (3).

$$F_{inf,i} = \frac{\lambda P_i}{\lambda + k_{dep,i}} \quad (3)$$

where $F_{inf,i}$ = size-resolved infiltration factor (−); λ = infiltration air exchange rate (1/hr); P_i = envelope penetration factor of particles of size i (−); and $k_{dep,i}$ = indoor deposition loss rate for particles of size i in the absence of HVAC filtration (1/hr). Unfortunately, we are not aware of any investigations that have measured size-resolved envelope penetration factors, indoor deposition rates, or infiltration factors for the full range of particle sizes of interest (0.001–10 μm). However, we used approximations of typical infiltration air exchange rates and size-resolved penetration factors and indoor deposition rates from previous studies reported in El Orch et al. (2014) to estimate typical size-resolved infiltration factors in the absence of HVAC filtration. More specifically, we used an estimate of the geometric mean infiltration air exchange rate in U.S. residences from Figure 1a in their paper (data from Persily et al., 2010), size-resolved penetration factors from their Figure 3a, and size-resolved deposition rates in the absence of HVAC filtration from their Figure 3b as inputs in Eq. (3) (these inputs are shown in Fig. S1a)–c) in the SI). Although not necessarily representative of the entire building stock, these values provide a decent estimate of the typical shape and magnitude of size-resolved penetration factors and deposition rates, as well as infiltration air exchange rates, in U.S. residences. We should note that the size-resolved infiltration factor used is similar in shape and magnitude to measurements at one home in Long et al. (2001) (shown in their Figure 5b).

Each of the 194 outdoor PSDs was then modified to a hypothetical "infiltrated indoor PSD" for particles of outdoor origin by multiplying PSDs by this size-resolved infiltration factor for each particle size. Finally, a modified version of outdoor-infiltrated UFP and $PM_{2.5}$ removal efficiencies was estimated using Eqs. (1) and (2) with the new modified, or infiltrated, PSDs.

3. Results and discussion

3.1. Outdoor PSDs

Full summary tables of the references used, their measurement locations and durations, time period of averaging, and tri-modal distribution fit parameters (GM, GSD, and number concentrations) of all 194 collected distributions are provided in the SI (Tables S3 and S4). Table 1 shows a brief summary of the eight studies used herein. The majority of the outdoor PSDs came from two large studies (Asmi et al., 2011; Hussein et al., 2004), while the combination of all 194 PSDs includes a wide variety of locations ranging from remote rural sites to highly trafficked urban environments. The 194 PSDs also varied widely by season and time of day over which long-term averages were taken.

Table 1
Summary of long-term outdoor PSDs used herein.

Ref.	Measurement duration	No. of PSDs	No. of cities	Location	Location type	Season	Time period
(1)	2006–11	8	1	Canada	Urban	Winter Summer	0:00–5:00 6:00–11:00 12:00–17:00 18:00–23:00
(2)	2001–02	2	2	USA	Urban Rural	N/A	N/A
(3)	1997–03	64	2	Finland	Urban	All	3:00–4:00 9:00–10:00 11:00–12:00 20:00–21:00
(4)	2002–07	6	1	Denmark	Close to traffic	N/A	N/A
(5)	2005–06	3	3	Germany	Urban Rural Close to traffic	N/A	N/A
(6)	1997–01	2	1	Germany	Urban	Winter Summer	N/A
(7)	2008–09	95	24	All Europe	Urban Rural Remote rural	All	N/A
(8)	1996–97	14	1	Germany	Rural	Spring Summer Winter	10:00–12:00 12:00–14:00 14:00–16:00 16:00–18:00 18:00–20:00 20:00–22:00

(1) Sabaliauskas et al., 2012; (2) Stanier et al., 2004; (3) Hussein et al., 2004; (4) Wåhlin, 2009; (5) Costabile et al., 2009; (6) Wehner and Wiedensohler, 2003; (7) Asmi et al., 2011; (8) Birmili et al., 2001.

Smooth fits of all 194 long-term average outdoor PSDs from 0.001 to 10 μm are shown graphically in Fig. 1. The individual PSDs are not labeled for graphical clarity. Most distributions have a peak number concentration between 8 and 40 nm, as is typical for most outdoor environments (Seinfeld and Pandis, 2006). It was important to capture this wide range of outdoor environments in order to explore the sensitivity of estimates of UFP and $PM_{2.5}$ removal efficiency by HVAC filters to a wide array of PSDs, including those of different shapes, GMs, GSDs, and magnitudes of number concentrations.

Fig. 2(a) and (b) show mass concentration distributions of the same 194 outdoor PSDs ($dM/d\log D_p$ versus $\log D_p$) assuming spherical particles with (a) constant density (1 g/cm^3) and (b) varying density with particle diameter, ranging from 1.25 to 1.75 g/cm^3, respectively. The mass distributions peak between 0.2 and 2 μm for all outdoor scenarios, consistent with literature on many outdoor environments. However, we should note that because most (if not all) of the studies reported herein utilized instrumentation that only measured submicron particles, there may be some missing mass concentrations in the 1–10 μm size range that remain unaccounted for (number concentrations are not meaningfully affected). However, the shapes and magnitudes of the curves suggest that $PM_{2.5}$ mass can still be estimated reasonably although the mass of the largest particles may not be captured.

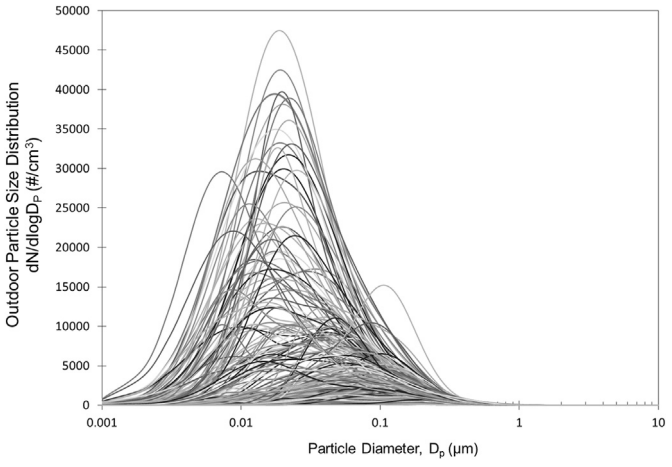

Fig. 1. Long-term average outdoor PSDs for all 194 locations.

3.2. Outdoor UFP and $PM_{2.5}$ concentrations

Estimates of UFP and $PM_{2.5}$ concentrations for the 31 locations based on the 194 outdoor PSDs described in Table 1 (and Tables S3 and S4 in the SI) are shown in Figs. 3 and 4, respectively. For locations with multiple long-term averages made over different periods of time (i.e., weekdays versus weekends or morning versus night), the bars represent mean values and the error bars represent plus and minus one standard deviation. Estimates of long-term average UFP concentrations varied from ~50 to ~37,000 #/cm^3, with a mean and standard deviation of ~8500 #/cm^3 and ~9100 #/cm^3, respectively. This range is well in line with UFP and submicron number concentrations measured in other urban environments (Fuller et al., 2013; Kearney et al., 2011; Stölzel et al., 2007; Wheeler et al., 2011), suggesting that the 194 PSDs used herein are reasonably representative of a large number of outdoor environments ranging from remote rural areas with low UFP concentrations (i.e., remote habitat in Norway) to larger urban environments with higher UFP concentrations (i.e., Copenhagen), and that the method of graphically fitting tri-modal distributions is reasonable.

Similarly, estimates of long-term average $PM_{2.5}$ mass concentrations (shown in Fig. 4) varied from ~0.2 μg/m^3 to ~33.3 μg/m^3 and ~0.3 μg/m^3 to ~49.8 μg/m^3 assuming constant density and varied density, respectively, with mean (s.d.) values 8.0 (6.5) μg/m^3 assuming constant density and 11.4 (9.5) μg/m^3 assuming varied density. These values are also well in line with measurements from a large range of outdoor environments measured in multiple countries over the last 10–15 years (Gehrig and Buchmann, 2003;

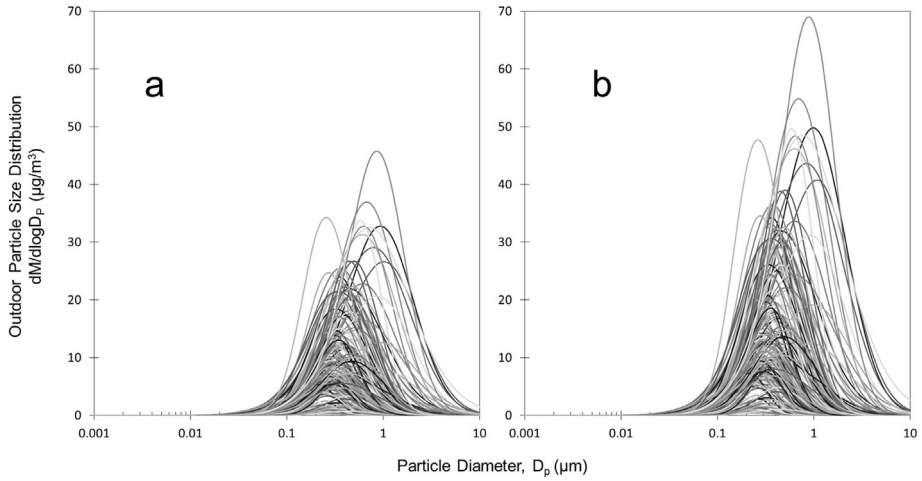

Fig. 2. Long-term average outdoor particle mass distributions for all 194 locations assuming (a) constant unit density and (b) density varies with particle size.

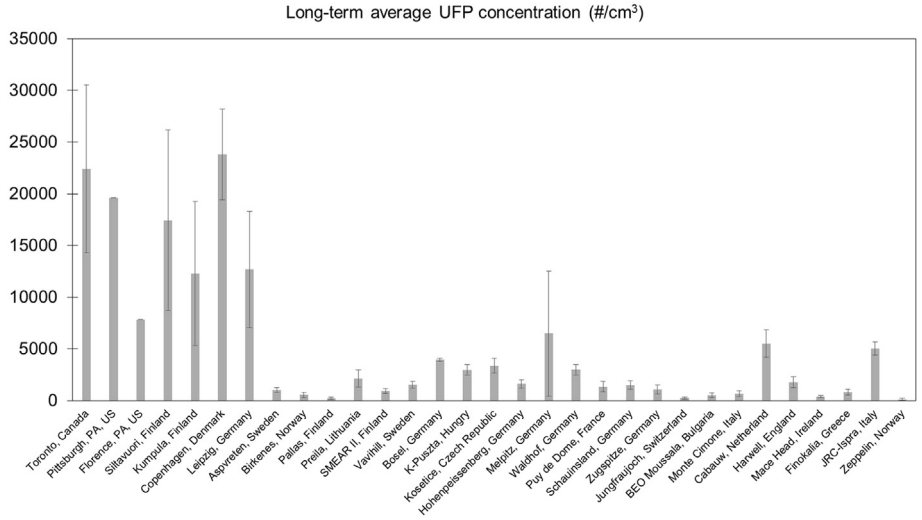

Fig. 3. Long-term average UFP concentrations estimated using PSDs from each city. For cities with multiple long-term measurements, bars represent mean values and error bars represent ± one standard deviation.

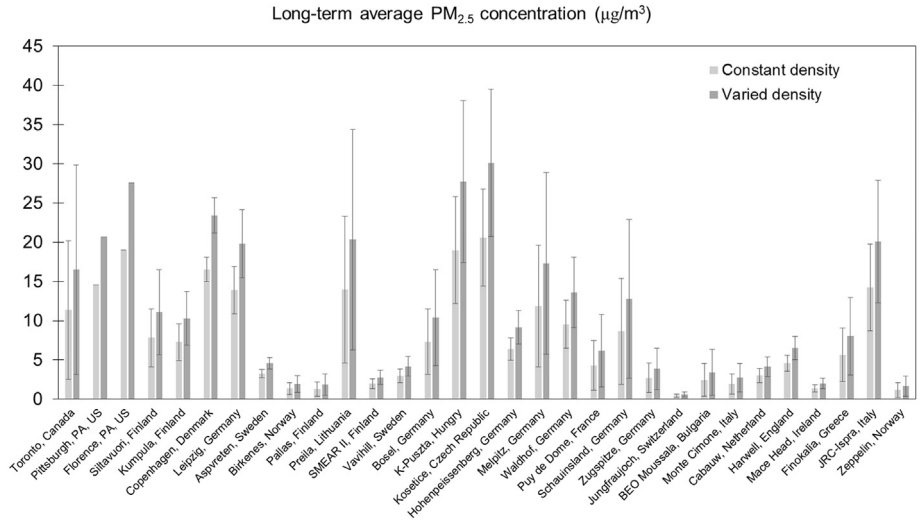

Fig. 4. Long-term average $PM_{2.5}$ concentrations estimated using PSDs from each city. Estimates include two different assumptions for particle density: constant density and varying density with particle size. For cities with multiple long-term measurements, bars represent mean values and error bars represent ± one standard deviation.

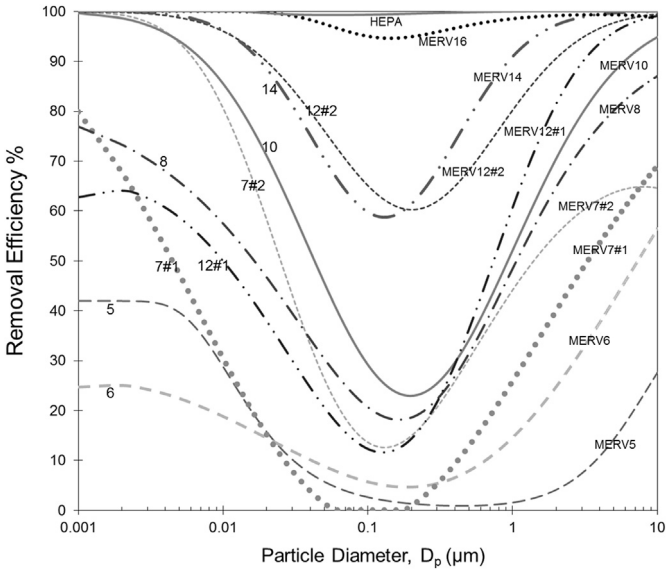

Fig. 5. Size-resolved removal efficiency of various MERV filters used herein.

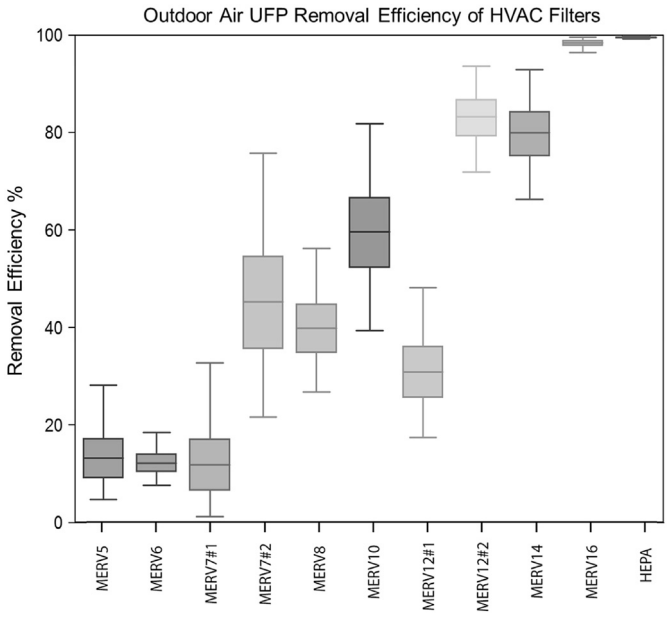

Fig. 6. Estimated distribution of UFP removal efficiency for 11 representative HVAC filters and 194 outdoor PSDs, assuming filtration of 100% OA.

Hoek et al., 2002; Stölzel et al., 2007; US EPA, 2009; Wheeler et al., 2011). It is not clear which density assumption is more appropriate, given the lack of density measurements available in the literature; however, the use of the varying density assumption primarily serves to explore the sensitivity of our estimates of filter efficiency in the next sections.

3.3. HVAC filter removal efficiency for UFP and $PM_{2.5}$ of outdoor origin (100% OA)

Fig. 5 shows the resultant size-resolved removal efficiencies for each representative HVAC filter for particle sizes 0.001–10 μm.

Fig. 6 shows estimates of outdoor-origin UFP removal efficiency for the 11 representative HVAC filters used herein, estimated using Eq. (1) for all 194 outdoor PSDs and the size-resolved efficiencies in Fig. 5. These estimates assume outdoor particles are being removed directly by filters (i.e., an HVAC system would be operating with 100% outdoor air).

Estimates of 100% OA UFP removal efficiency for MERV 5, 6 and 7 (#1) filters were similar to each other and relatively tightly grouped, with a median efficiency of ~12–13% and ranges from ~1% to ~33% depending on MERV and PSD combination. MERV 7 (#2) and MERV 8 revealed similar estimates of 100% OA UFP removal efficiency, with median values around ~40–45% and ranges from ~22% to ~76% depending on PSD. The median efficiency for MERV 7 (#2) was actually higher than the median MERV 8. MERV 10 had a median 100% OA UFP removal efficiency of ~60% and range from 40% to 82%. MERV 12 (#1) actually had estimates of UFP removal efficiency below MERV 7 (#2), 8, and 10, while MERV 12 (#2) had UFP removal efficiencies very close to that of MERV 14. Finally, 100% OA UFP removal efficiencies for MERV 16 and HEPA were tightly grouped near 98% and >99%, respectively. These data combined suggest that although higher UFP efficiencies generally occurred with higher MERV filters, MERV alone cannot always be used to distinguish HVAC filters on their outdoor UFP removal efficiency (particularly for MERV 7 and 12). These data also suggest that outdoor PSD characteristics can influence UFP removal efficiency, although ranges of values can still be used to assign reasonable UFP efficiencies to various MERV filters.

Similarly, Fig. 7 shows estimates of 100% OA $PM_{2.5}$ removal efficiency for the 11 representative HVAC filters used herein, estimated using Eq. (2) for all 194 outdoor PSDs and the size-resolved efficiencies in Fig. 5. Fig. 7(a) assumes constant unit density and Fig. 7(b) assumes density varies with particle size.

Estimates of 100% OA $PM_{2.5}$ removal efficiency of all MERV designations were similar for both assumptions for particle density. Estimates of removal efficiency of MERV 5 for outdoor $PM_{2.5}$ was low, with a median efficiency of ~1% in both density scenarios. MERV 6 and MERV 7 (#2) revealed similar estimates of outdoor $PM_{2.5}$ with median values around ~7–8% and ranges from ~2% to ~21% depending on MERV and PSD combination. Median estimates of 100% OA $PM_{2.5}$ removal efficiencies for MERV 7(#2), MERV 8, MERV 10, and MERV 12(#1) were similar, ranging from ~24% to ~31% with ranges from 17% to 51%. Between these four MERV classified filters, MERV 10 actually had the highest median value (albeit only slightly); MERV 8 and MERV 12(#1) were very similar. Outdoor $PM_{2.5}$ removal efficiencies for MERV 12 (#2) were similar to MERV 14 (median of ~66% and ~71%, respectively). Finally, 100% OA $PM_{2.5}$ removal efficiencies for MERV 16 and HEPA were grouped near 96% and >99%, respectively.

These estimates of $PM_{2.5}$ removal efficiency are generally in line with limited data from other studies, including MERV 8 and 14 in commercial rooftop units (Zaatari et al., 2014). However, our estimates of outdoor $PM_{2.5}$ removal efficiency were lower for MERV 7, MERV 8, and MERV 12 (#1) than estimates used in a recent modeling study (Brown et al., 2014); conversely, our MERV 12 (#2) estimates for $PM_{2.5}$ removal efficiency were similar to the MERV 12 used in (Brown et al., 2014), while our MERV 16 estimates were significantly higher than their MERV 16 assumptions. Overall, these data suggest that outdoor PSD characteristics have a smaller effect on estimates of $PM_{2.5}$ filtration efficiency than for estimates of UFP efficiency. Additionally, although higher $PM_{2.5}$ efficiencies generally occurred with higher MERV, MERV alone cannot always be used to distinguish HVAC filters on their outdoor $PM_{2.5}$ removal efficiency, particularly for MERV 7 and MERV 12 (similar to the UFP findings).

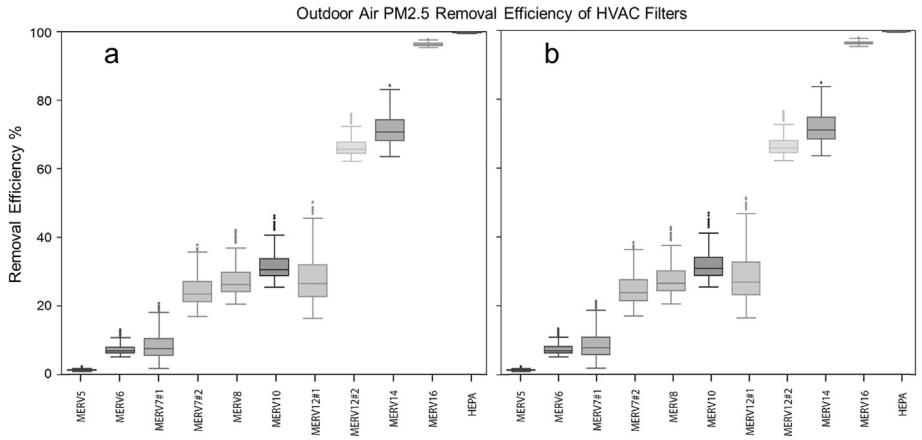

Fig. 7. Estimated distribution of $PM_{2.5}$ removal efficiency for 11 representative HVAC filters and 194 outdoor PSDs, assuming 100% OA: (a) assumes constant unit density and (b) assumes density varies with particle size.

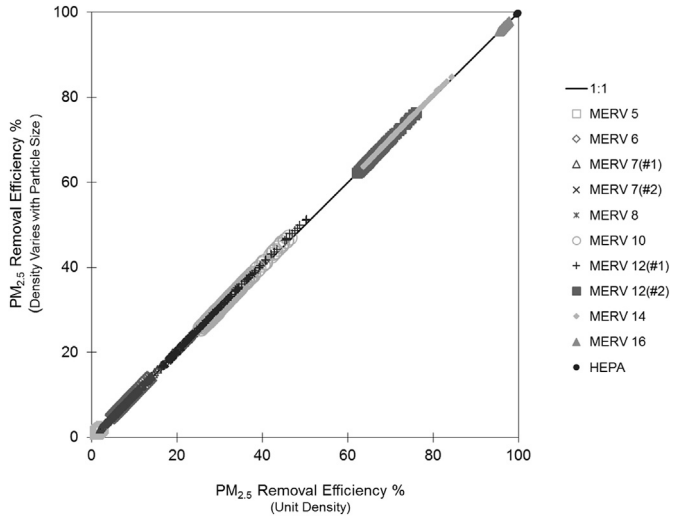

Fig. 8. Relationship between estimates of 100% OA $PM_{2.5}$ removal efficiency of HVAC filters assuming constant unit density and varying density.

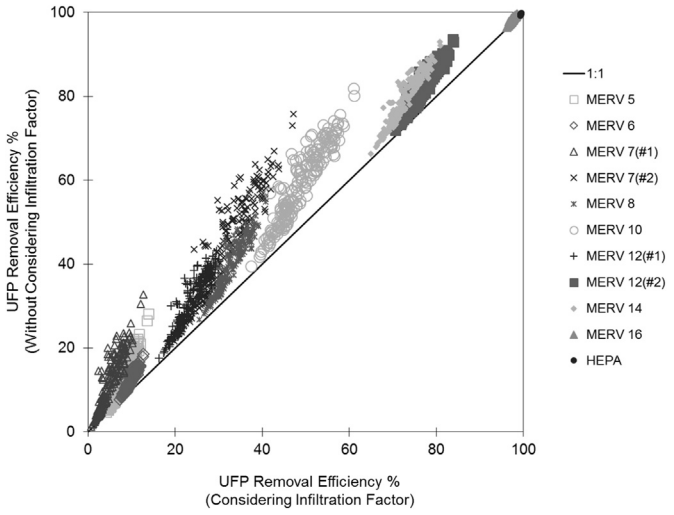

Fig. 9. Relationship between estimates of UFP removal efficiency of HVAC filters for 100% OA and after considering the effects of envelope penetration and indoor deposition losses.

3.4. Sensitivity to assumptions for particle density

Fig. 8 shows the estimates of 100% OA $PM_{2.5}$ removal efficiency of the 11 HVAC filters assuming constant unit density plotted versus $PM_{2.5}$ removal efficiency estimated using a varying density assumption. All estimates fall within 1% of the 1:1 line and suggest that the two different assumptions for particle density do not impact the resulting estimates of outdoor $PM_{2.5}$ removal efficiency for these HVAC filters and the 194 PSDs considered here.

3.5. Modification by infiltration factor

Another important assumption to test is that of filtration of 100% outdoor air. In residences that rely on infiltration for air exchange (which represent most homes in the U.S.), outdoor particles will deposit as outdoor air infiltrates through cracks and gaps in the building envelope, leaving a smaller portion available to penetrate and persist indoors. Moreover, indoor deposition rates will further reduce the portion available to persist indoors, even in the absence of HVAC filtration. Fig. 9 shows estimates of 100% OA UFP removal efficiency values from Fig. 6 plotted versus revised estimates of UFP removal efficiency assuming that each of the 194 outdoor PSDs was modified during outdoor–indoor transport to account for the mean size-resolved infiltration factors in Figure S1c in the SI.

Estimates of UFP removal efficiency when considering the effects of envelope penetration and deposition were consistently lower than the original outdoor-only UFP removal efficiencies for the 194 PSDs used herein (distribution statistics are summarized in Table 2). Differences were often as large as 20% lower removal efficiency (on absolute terms), with mean differences of ~6% and minimum and maximum differences of ~0% and ~29%, respectively, depending on outdoor PSD characteristics. In general, the most extreme deviations were associated with PSDs with the smallest peak diameters (e.g., <10 nm) and the smallest deviations were associated with PSDs with the largest peak diameters (e.g., >80 nm). The modified infiltrated UFP removal efficiency estimates were not sensitive to assumptions for infiltration air exchange rate because the shape of the PSD does not vary. However, they are sensitive to the shape of size-resolved infiltration factors.

These results suggest that estimates of UFP removal efficiency are somewhat dependent on accurate knowledge of both outdoor PSDs and size-resolved infiltration factors. However, because size-resolved measurements are costly to make, these data suggest

Table 2
Summary of distributions of UFP and $PM_{2.5}$ removal efficiency for 194 outdoor PSDs and 11 representative HVAC filters, both considering 100% OA and modification by typical residential infiltration factors.

MERV	100% OA						Modification by typical residential infiltration factors					
	UFP removal efficiency			$PM_{2.5}$ removal efficiency			UFP removal efficiency			$PM_{2.5}$ removal efficiency		
	GM	GSD	Log-normal	GM	GSD	Log-normal	GM	GSD	Log-normal	GM	GSD	Log-normal
5	12.3%	1.5	N	1.4%	1.1	N	7.6%	1.3	N	1.3%	1.1	N
6	12.1%	1.2	N	7.2%	1.2	N	9.7%	1.1	N	6.9%	1.2	N
7 (#1)	10.0%	1.9	N	7.6%	1.6	Y	4.4%	1.7	N	7.3%	1.5	Y
7 (#2)	43.6%	1.3	N	24.1%	1.2	Y	31.4%	1.2	N	23.6%	1.2	Y
8	39.3%	1.2	N	27.1%	1.2	N	32.5%	1.1	N	26.4%	1.1	N
10	58.6%	1.2	N	31.5%	1.1	N	48.6%	1.1	N	30.5%	1.1	N
12 (#1)	30.1%	1.2	N	27.2%	1.3	Y	23.2%	1.1	N	26.6%	1.2	Y
12 (#2)	82.7%	1.1	N	66.4%	1.0	N	77.3%	1.0	N	65.6%	1.0	N
14	79.3%	1.1	N	71.4%	1.1	N	72.7%	1.0	N	71.0%	1.1	N
16	98.3%	1.0	N	96.3%	1.0	N	97.5%	1.0	N	96.3%	1.0	N
HEPA	99.5%	1.0	N	99.7%	1.0	Y[a]	99.4%	1.0	N	99.7%	1.0	Y[a]

[a] Estimates were normally distributed.

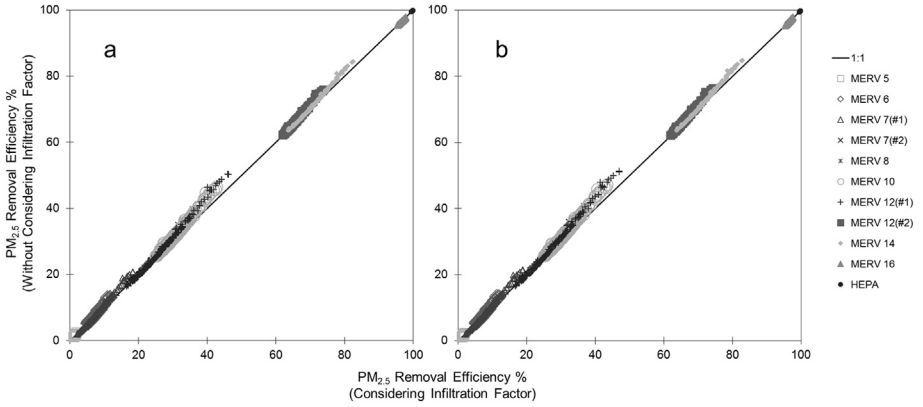

Fig. 10. Relationship between $PM_{2.5}$ removal efficiency of HVAC filters using the 100%OA assumption and after considering the effect of size-resolved infiltration factors: (a) assumes constant unit density and (b) assumes varying density.

that minor modifications to statistical distributions of 100% OA UFP removal efficiency estimates can still provide a reasonable estimate of outdoor-infiltration UFP removal efficiencies for HVAC filters. For example, estimates of outdoor-infiltrated UFP removal efficiency of MERV 5, 6 and 7 (#1) filters had GMs ranging ~4–8% (Table 2). MERV 7 (#2) and MERV 8 had similar estimates of outdoor-infiltrated UFP removal efficiency, with GMs of ~31–33%. MERV 10 had a median outdoor-infiltrated UFP removal efficiency of ~49%. MERV 12 (#1) again had a GM outdoor-infiltrated UFP removal efficiency (~23%) below MERV 7 (#2) (~31%), 8 (~33%), and 10 (49%), while MERV 12 (#2) had a GM outdoor-infiltrated UFP removal efficiency slightly greater than that of MERV 14 (~77% vs. ~73%). Finally, outdoor-infiltrated UFP removal efficiencies for MERV 16 and HEPA were ~98% and >99%, respectively.

Fig. 10 shows similar estimates of $PM_{2.5}$ removal efficiencies for each of the 194 PSDs and 11 HVAC filters using the 100% OA assumption compared to estimates made after considering size-resolved infiltration factors in the absence of HVAC filtration. This procedure again assumes (a) constant unit density and (b) varying density. Interestingly, infiltration factors had only minor effects on estimates of $PM_{2.5}$ removal efficiency, likely because most of the outdoor $PM_{2.5}$ mass occurs in larger, tighter particle size ranges where the assumed infiltration factors do not vary much with particle size.

Table 2 shows the GMs and GSDs of estimates of both 100% OA and outdoor-infiltrated UFP and $PM_{2.5}$ removal efficiencies for the 11 HVAC filters across all 194 PSDs. Each filtration efficiency distribution was tested for normality and log-normality using Skewness/Kurtosis tests with p-values of 0.05. The removal efficiencies that were normally or log-normally distributed across the 194 PSDs are marked in Table 2. Only $PM_{2.5}$ removal efficiencies of HEPA filters (both density scenarios) were normally distributed and several others were log-normally distributed. Most others did not fit a particular single-mode distribution shape but GMs and GSDs are still provided for reference. Percentiles of the removal efficiency estimates are also shown in Table S5 in the SI.

4. Conclusion

In this work we fit 194 outdoor tri-modal particle size distributions (PSDs) from locations across the world and used those PSDs to estimate outdoor-origin UFP and $PM_{2.5}$ removal efficiencies for 11 generally representative HVAC filters using information from existing literature. We demonstrate that although the MERV metric does not explicitly account for UFP or $PM_{2.5}$ removal efficiency, both tend to increase in efficiency with increasing MERV. The geometric mean (GM) estimates of UFP removal efficiency ranged from ~5 to 12% for MERV <7 (depending on the assumption of 100% OA or modification by infiltration factors) to over 99% for HEPA filters. Similarly, the GM estimates of $PM_{2.5}$ removal efficiency ranged from ~1 to 8% for MERV <7 to over 99% for HEPA filters. We also demonstrate that outdoor PSD characteristics and assumptions for particle density and size-resolved infiltration factors do not drastically impact estimates of HVAC filter removal efficiencies for

$PM_{2.5}$, although the impacts are larger for UFPs. However, knowledge of MERV alone cannot always be used to predict UFP or $PM_{2.5}$ removal efficiency, as different makes and models can have very different UFP and $PM_{2.5}$ removal efficiencies depending on their actual size-resolved removal efficiencies.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2014.09.007.

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