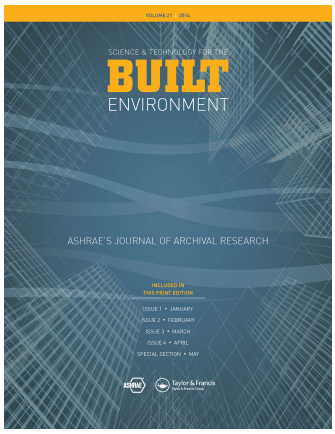

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Building design and operational choices that impact indoor exposures to outdoor particulate matter inside residences

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Building design and operational choices that impact indoor exposures to outdoor particulate matter inside residences

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Much of human exposure to particles of outdoor origin often occurs inside homes where we spend most of our time. This work (1) reviews existing literature on the important parameters governing the infiltration and persistence of particles of outdoor origin in residences, (2) re-analyzes portions of data from recent experimental investigations of submicron particle infiltration and central HVAC system operation in single-family homes, and (3) combines these data to highlight particularly stark differences in particle infiltration factors and human exposures to submicron particles of outdoor origin that are driven by building envelope design, filter choice, and HVAC system design and operation (with an additional focus on data from one low-energy home). Results reveal that envelope design and construction, HVAC filter selection, and HVAC system operation can lead to variations in infiltration factors for submicron particles ranging by a factor of 60 or more from the most protective homes to the least protective homes. Moreover, an additional experiment performed in the most protective low-energy home (when relying on infiltration for ventilation air) was also responsible for the *highest* amount of outdoor particle infiltration when tested again while using an energy recovery ventilator connected to an outdoor air supply for ventilation air, suggesting that residential mechanical ventilation systems can adversely influence outdoor particle infiltration if improperly installed.

Introduction

Elevated outdoor airborne particulate matter concentrations, including $PM_{2.5}$, PM_{10}, and ultrafine particles (UFPs, <100 nm in size), have been consistently associated with increased risks of a number of adverse health effects (e.g., Penttinen et al. 2001; Pope et al. 2002; von Klot et al. 2002; Pope and Dockery 2006; Miller et al. 2007; Stölzel et al. 2007; Weichenthal et al. 2007; Brook et al. 2010). These associations are typically made in large epidemiological studies using outdoor measurements; however, because particles can infiltrate and persist indoors (e.g., Long et al. 2001a; Thatcher et al. 2003; Zhu et al. 2005; Chen and Zhao 2011; Chen et al. 2012), where Americans spend the majority of their time (Klepeis et al. 2001), much of their exposure to particles of outdoor origin often occurs inside buildings, particularly in residences (Allen et al. 2004; Meng et al. 2005a, 2009; Bhangar et al. 2011; Kearney et al. 2011). Relying on ambient measurements alone can therefore result in exposure misclassification for a large portion of the population (Meng et al. 2005b; Baxter et al. 2010, 2013b; Hodas et al. 2013).

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Several recent studies have attempted to address this exposure misclassification by exploring variability in particle infiltration factors (F_{inf} being the indoor–outdoor [I/O] concentration ratio in the absence of indoor sources) of $PM_{2.5}$ and UFPs measured in homes (Allen et al. 2012; Hodas et al. 2012; MacNeill et al. 2012, 2014; Baxter et al. 2013a). However, knowledge of the source and removal mechanisms of particulate matter of outdoor origin inside residential buildings is not yet complete. Of particular importance is how fundamental mechanisms governing F_{inf} vary between buildings and how design and operational choices affect the magnitude of these parameters, including design and operational choices in low-energy buildings. This article expands upon a recent conference publication at ASHRAE IAQ 2013 Environmental Health in Low Energy Buildings (Stephens 2013) by (1) reviewing existing literature on the important parameters governing the infiltration and persistence of particles of outdoor origin in residences, (2) re-analyzing portions of data from recent experimental investigations of submicron particle infiltration and central HVAC system operation in single-family homes, and (3) combining these data to highlight particularly stark differences in particle infiltration factors and human exposures to submicron particles of outdoor origin that are driven by building envelope design, filter choice, and HVAC system design and operation (with an additional focus on particularly relevant data from one net-zero energy capable home). The goal of this work is to improve understanding of the exposure implications associated with these parameters for the HVAC design and engineering community.

Literature review

Indoor particulate matter: I/O ratios and key source and removal mechanisms

I/O concentration ratios of several sizes and classes of particulate matter have been measured in a wide variety of buildings worldwide. These measurements have revealed that I/O ratios of particles of a variety of sizes can vary over a large range: from ~0.02 to over 30 (Chen and Zhao 2011 and references therein). In the absence of indoor sources, measured I/O ratios (F_{inf}), which vary with particle size, have been shown to range from less than 0.1 to ~1.0 (Allen et al. 2012; Chen and Zhao 2011; and references therein). Infiltration factors may be particularly important to measure and predict accurately because some evidence suggests that particles of outdoor origin may be more detrimental to human health than many indoor-generated particles (Ebelt et al. 2005; Koenig et al. 2005), although there is also some evidence to the contrary, such as Long et al. (2001b).

Figure 1 presents a simplified schematic of the fate and transport of particles of outdoor origin inside a typical single-family residence with a 100% recirculating central HVAC system, absent any indoor sources and ignoring other potential indoor fate and transport mechanisms (e.g., particle resuspension, coagulation, or phase changes). In the absence of indoor sources, occupants are exposed to particulate matter of outdoor origin only after penetrating the building envelope via air exchange and overcoming any indoor losses due to deposition to surfaces (Thatcher and Layton 1995; Thatcher 2002; He et al. 2005), filters installed in operating central HVAC systems (Offermann et al. 1992; Hanley et al. 1994; Howard-Reed et al. 2003; Wallace et al. 2004), exfiltration by air exchange (Abt et al. 2000) or dedicated exhaust fans (Singer et al. 2011), and standalone air filtration (Offermann et al. 1985), which is not depicted in Figure 1 but is treated similarly to HVAC removal.

Considering the simplified indoor volume of the space in Figure 1 to be a well-mixed reactor in the absence of indoor sources, the dynamic indoor concentration of airborne particles of outdoor origin (C_{in}) is described in Equation 1.

$$\frac{dC_{in}}{dt} = P\lambda C_{out} - \lambda C_{in} - kC_{in} - f\frac{\eta_{HVAC}Q_{HVAC}}{V}C_{in}, \quad (1)$$

where t is time (h), P is the penetration factor of the building envelope for the particle size in question (dimensionless, ranging from 0 to 1), λ is the air exchange rate (AER; h^{-1}), C_{out} is the outdoor particle concentration (# m^{-3} or $\mu g\ m^{-3}$), k is the first-order indoor particle deposition loss rate coefficient (h^{-1}), η_{HVAC} is the particle removal efficiency of the HVAC system and filter combined (or similarly, a standalone portable air cleaner; dimensionless, ranging from 0 to 1), Q_{HVAC} is the airflow rate through the HVAC system and filter ($m^3\ h^{-1}$), V is the volume of the building (m^3), and f is the fractional operation time of the HVAC system (dimensionless, ranging from 0 to 1). Additionally, Q_{HVAC}/V is described as the recirculation rate (λ_{HVAC}, h^{-1}), with the same units as the AER (λ). The time-averaged I/O particle concentration ratio, or infiltration factor, is described in Equation 2:

$$\frac{C_{in}}{C_{out}} = F_{\inf} = \frac{P\lambda}{\lambda + k + f\frac{\eta_{HVAC}Q_{HVAC}}{V}} = \frac{P\lambda}{\lambda + k + f\eta_{HVAC}\lambda_{HVAC}}, \quad (2)$$

where all parameters represent mean values taken over the averaging period.

Characterizing these individual particle source and removal mechanisms in actual buildings can be quite challenging. The current state of knowledge of typical values of these influential parameters in residences (as well as some similar small commercial buildings) is summarized in the next sections. These parameters include general characteristics, such as HVAC system airflow rates (Q_{HVAC}), recirculation rates (λ_{HVAC}), operation times (f), and AERs (λ), as well as particle size-resolved characteristics, such as indoor particle loss rates (k) and particle penetration factors (P).

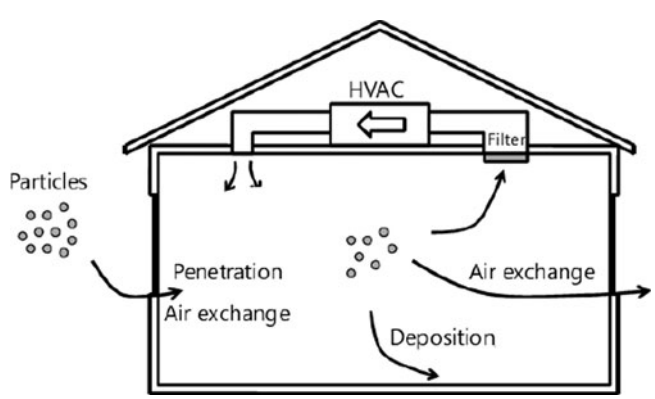

Fig. 1. Simplified model of the fate and transport of particles in buildings in the absence of indoor sources.

Airflow rates and recirculation rates (Q_{HVAC} and λ_{HVAC})

HVAC equipment manufacturers typically recommend that airflow rates in single-family residences systems be between 169 and 193 $m^3\ h^{-1}$/kW of nominal capacity (350–400 cfm/ton), although a wide range of airflow rates have been measured in field installations, from less than 100 $m^3\ h^{-1}$/kW to greater than 230 $m^3\ h^{-1}$/kW (Parker et al. 1997; Proctor 1997; Stephens et al. 2011). Low airflow rates can have significant impacts on comfort and energy use by reducing cooling capacities, altering sensible heat ratios, and causing systems to operate longer. Additionally, the recirculation rate is an important parameter in determining the effectiveness of in-duct particle removal technologies because the product of filter efficiency, recirculation rate, and fractional operation time can be compared directly to other loss mechanisms, including air exchange and indoor deposition rates. Recirculation rates can also be used to calculate clean air delivery rates (CADRs), which are widely used to characterize air cleaner performance (e.g., Offermann et al. 1985; MacIntosh et al. 2008; Waring et al. 2008). Typical recirculation rates in central HVAC

systems range from 4 to 8 h^{-1} when operating, not accounting for average system operational fractions (Stephens et al. 2011).

Fractional HVAC operation times (f)

While airflow rates and recirculation rates through HVAC systems are important, central residential HVAC systems in the United States typically only cycle on to meet the heating or cooling load of a building, and the frequency of system operation affects both energy and indoor air quality (IAQ). However, there is a lack of information in the literature about how often systems operate to meet heating and cooling loads in real environments. Previous IAQ investigations have traditionally either assumed values for fractional operation times (Thornburg et al. 2001; Klepeis and Nazaroff 2006; Waring and Siegel 2008) or estimated them from building energy models (MacIntosh et al. 2010). James et al. (1997) reported average fractional operation times of only 8%–14% for correctly sized air-conditioning systems in Florida homes in the summer. Thornburg et al. (2004) reported mean (±SD) HVAC system operational fractions of only 6% ± 5% in homes in North Carolina and 21% ± 11% in homes in Florida. It was not clear whether these low values of fractional operation times were adequate in duration to meaningfully decrease indoor particle concentrations. More recently, Stephens et al. (2011) reported mean hourly operational fractions ranging from 10.7% to 55.3% in homes and small commercial buildings in Texas during the cooling season, with an overall mean of 20.6%.

AER (λ)

Residential buildings in the United States are seldom mechanically ventilated and typically rely on infiltration of outdoor air through unintentional openings and cracks in the building envelope to provide air exchange, although this is changing with increasing adoption of ASHRAE Standard 62.2 and its requirements for mechanical ventilation systems (ASHRAE 2013). Regardless, AERs, or the rate at which indoor air is replaced by outdoor air, have competing effects on energy consumption and IAQ. High AERs introduce more unconditioned outdoor air that may require more energy to heat or cool a space, but if outdoor air is clean relative to indoor air, greater amounts of outdoor air can dilute indoor pollutant concentrations. Conversely, lower AERs diminish the importance of outdoor pollutants but increase the importance of indoor sources as dilution times are increased.

AERs have been measured in thousands of buildings worldwide and have been shown to vary widely across buildings as well as temporally within individual buildings. Murray and Burmaster (1995) reported a geometric mean (GM) AER of 0.52 h^{-1} measured across nearly 3000 homes in the United States. Wallace et al. (2002) measured AERs in a single occupied townhouse for 1 year and demonstrated that AERs were impacted by window openings, exhaust fan operation, I/O temperature differences, and wind speed and direction. More recently, Offermann (2009) reported a median AER of 0.26 h^{-1} in 108 new homes in California, and Persily et al. (2010) estimated the national average AER (resulting from infiltration) for single-family homes in the United States to be 0.44 h^{-1}, increasing with age of construction.

Indoor particle loss rates excluding AER ($k + fQ_{HVAC}\eta_{HVAC}/V$)

Indoor particle loss rates (excluding AERs) vary widely by particle size and are impacted primarily by building characteristics (e.g., surface areas, surface roughness, and indoor airspeeds) and HVAC operation, including ductwork and filters (Lai and Nazaroff, 2000; Lai, 2002; Riley et al., 2002; Thatcher, 2002; He et al., 2005; Wallace et al., 2013). For example, Howard-Reed et al. (2003) measured particle loss rates inside a townhouse with the central HVAC system off and found average deposition rates to range from 0.3 h^{-1} for 0.3–0.5 μm particles to 5 h^{-1} for particles greater than 10 μm. Operating a central recirculating HVAC system, even without a filter installed, doubled deposition rates for particles less than 5 μm in diameter, suggesting that deposition to ductwork is a significant removal mechanism, which later laboratory work confirmed (Sippola and Nazaroff, 2004). Similarly, Wallace et al. (2004) measured deposition rates of a wider range of particle sizes in the same house and found that the use of the central HVAC fan both without a filter installed and with a standard low-efficiency furnace filter installed increased deposition rates relative to conditions with the HVAC system off by 0.1–0.5 h^{-1}. Installing a higher-efficiency filter increased indoor loss rates by up to 2 h^{-1} for most particle sizes (except those in the 0.1–0.5 μm size range, which are not substantially reduced by any removal forces, e.g., Brownian motion, gravitational settling, impaction, or interception). Most recently, Wallace et al. (2013) reported that combined deposition rates + filtration removal rates (if a filter was present) for $PM_{2.5}$ ranged from ~0 to ~7.3 h^{-1} (median of ~0.7 h^{-1}) and ranged from ~0 to ~8.6 h^{-1} (median of ~0.9 h^{-1}) for UFPs across 74 homes in Edmonton, Canada.

Although it is clear that HVAC systems, ducts, and particularly filters can have a substantial impact on particle removal rates in indoor environments, central HVAC filters are typically only tested in laboratory settings (Hanley et al. 1994; ASHRAE 2007). ASHRAE Standard 52.2 is the most widely used filter test methodology in the United States. The standard requires filters to be tested over a range of simulated dust loading conditions in a test duct in a laboratory. 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). However, 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. For example, Standard 52.2 relies on dry, spherical KCl particles for which the characteristics (e.g., density, shape, and composition) may not reflect typical outdoor-infiltrated aerosols. Additionally, airflow and pressure drop relationships

are more complex in residential systems with permanent split capacitor (PSC) blowers, which can yield face velocities that are different from test conditions.

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) or (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; Stephens and Siegel 2012b, 2013). The first field method involves measuring filter efficiency by comparing upstream and downstream concentrations and 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. The second field method, which involves measuring the differences in overall particle loss rates in an environment with and without a filter installed, is also 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 CADRs or filter removal efficiencies (if the airflow rate through the HVAC system is known).

Particle penetration factors (P)

In buildings that rely on infiltration for ventilation air, which represent the majority of residential buildings in the United States, outdoor particles can transport indoors via leaks within the building envelope when windows are closed. The process is dependent on several factors, including the geometry of openings, I/O pressure differences, the amount of airflow through openings, AERs, and particle size (e.g., Liu and Nazaroff 2001, 2003; Rim et al. 2010). Previous investigations of the penetration of outdoor airborne particulate matter have generally occurred in four forms, including (1) modeling efforts (Liu and Nazaroff 2001); (2) laboratory measurements of building envelope structures (Mosley et al. 2001; Liu and Nazaroff 2003); (3) measurement of infiltration factors during periods free of indoor sources (e.g., Fogh et al. 1997; Abt et al. 2000; Bennett and Koutrakis 2006; McAuley et al. 2010; Bhangar et al. 2011), which are sometimes coupled with models to estimate penetration factors from measured data (e.g., Ozkaynak et al. 1996; Long et al. 2001a; Vette et al. 2001; Lunden et al. 2003; Williams et al. 2003; Zhu et al. 2005); and (4) specific particle penetration methods designed to isolate both indoor loss rates and penetration factors (Thatcher and Layton 1995; Chao et al. 2003; Thatcher et al. 2003; Rim et al. 2010; Stephens and Siegel 2012b).

Of those that measured I/O concentrations ratios during periods free of indoor sources and later estimated penetration factors from the data, Long et al. (2001a) reported that the penetration factor of 0.02–10-μm particles in nine homes ranged from ~0.2 to >0.9 and depended on particle size, season, and home characteristics. Vette et al. (2001) reported that penetration factors ranged from ~0.5 to 0.9 for 0.01–2.5-μm particles at a single occupied residence using nighttime data assumed to be collected during source-free periods. Williams et al. (2003) analyzed I/O particulate matter data ($PM_{2.5}$ mass) from 37 residences and reported a mean (±SD) penetration factor of 0.72 ± 0.21 across all homes but with considerable variability across individual homes (ranging from 0.11 to 1.0). Zhu et al. (2005) reported relatively constant penetration factors of ~0.5 for 0.02–0.2-μm particles at four apartments with declining average penetration factors for smaller particles, down to <0.2 for particles smaller than 0.01 μm. Open windows can have a large influence on these estimates of penetration factors, but this work focuses on envelope properties alone to isolate the influence of particle transport only through infiltration.

Specific particle penetration tests (i.e., those that performed targeted experiments to explicitly quantify indoor loss rates and envelope penetration factors using time-varying measurements) have been conducted in a very limited number of homes worldwide (Chen and Zhao 2011). Thatcher and Layton (1995) measured penetration factors of approximately 1.0 for all particle sizes investigated (0.3–25+ μm) in one home. Chao et al. (2003) estimated mean (±SD) penetration factors in six high-rise apartments to be ~0.6 ± 0.3 for 20–1000 nm particles, ~0.7 ± 0.2 for 0.5–2.5-μm particles, and ~0.5 ± 0.3 for 2.6–10-μm particles. Thatcher et al. (2003) measured penetration factors in two homes ranging from ~1 for 0.1-μm particles to ~0.3 for 10-μm particles; importantly, particles of all sizes penetrated more efficiently into the leakier of the two homes (envelope air leakage was measured by standardized fan pressurization tests). Rim et al. (2010) measured penetration factors of UFPs at an unoccupied test house during two conditions: (1) closed windows and (2) with a window open approximately 7.5 cm. The penetration factor increased from ~0.2 for 0.01-μm particles to an asymptote of ~0.6 for 0.03–0.1-μm particles with closed windows and ranged from 0.6 to 0.8 across all particle sizes with the window open.

Most recently, Stephens and Siegel (2012a) refined a particle penetration test method, applied it in an unoccupied manufactured test house and 18 single-family homes in Austin, TX, and explored correlations between measured particle penetration parameters and building characteristics, including results from blower door tests. The mean (±SD) measured penetration factor of submicron particles (20–1000 nm, not size resolved) was 0.47 ± 0.15 in 19 residences that relied on infiltration for ventilation air, ranging from 0.17 ± 0.03 to 0.72 ± 0.08. Particle penetration factors (P) and outdoor particle source terms ($P \times$ AER) were both significantly and positively correlated with results from blower door air leakage tests. Outdoor particle source terms were also significantly and negatively correlated with the year of construction. These results suggested that occupants of leakier and older homes are exposed to higher indoor concentrations of outdoor submicron particles than those in tighter and newer homes, and that simple air leakage tests or knowledge of the year of construction may be able to provide an approximate prediction of outdoor particle infiltration into single-family residences. Additionally, experimental results from just one of the homes in Stephens and Siegel (2012a) measured during periods when

an energy recovery ventilator (ERV) was operating offers particularly helpful insights into the impacts of building design and operational choices that influence indoor exposures to outdoor particulate matter, particularly in low-energy homes.

Re-analysis of Texas field study data and modeling exposure implications

Experimental results from Stephens and Siegel (2012a) were revisited and combined with other recent data for the purposes of this work to highlight particularly stark differences in particle infiltration factors and human exposures to particulate matter that are driven by building envelope design, filter choice, and HVAC system design and operation (with an additional focus on particularly relevant data from one low-energy home). Additional summaries of measured penetration factors, AERs, and indoor loss rates beyond what was presented in the original article are first provided. Subsequently, results from that study are combined with results from several others to provide an estimate of the range of impacts that the aforementioned building design and operational choices can have on indoor exposures to submicron particles of outdoor origin. Finally, a case study of one of the sample homes from Stephens and Siegel (2012a)—a new, net-zero energy capable model home—is used to highlight the impact of building design and operation on the infiltration and persistence of outdoor particulate matter, particularly in regards to the use of a mechanical outdoor air supply (OAS) connected to an operating ERV unit.

Outdoor particle infiltration rates

Figure 2 shows submicron particle penetration factors (P) measured in each of the 19 homes relying on infiltration for ventilation air in Stephens and Siegel (2012a) plotted versus AERs measured during the typically 2–4-h test procedure. AERs ranged from 0.13 to 0.95 h^{-1} (with a mean of 0.39 h^{-1}), and estimates of penetration factors ranged from 0.17 to 0.72 (with a mean of 0.47). Penetration factors and AERs were correlated (Spearman's rho = 0.54, $p < 0.02$) in these homes, suggesting that during the test periods, homes with lower AERs also typically filtered more particles from outdoor air than homes with higher AERs. Importantly, several of these homes align within two distinct regimes of outdoor particle infiltration rates or combinations of both P and AER. In the bottom left corner of Figure 2, eight homes were classified as having both low AERs and low penetration factors for submicron particles (i.e., P and AER were both below their respective median values in this sample of homes). Conversely, in the top right corner of Figure 2, four homes were classified as having both high AERs and high penetration factors (i.e., P and AER were both above their median values in this sample). The remaining homes were grouped within these bounds, with most having higher penetration factors and lower AERs, albeit with two homes having lower penetration factors with higher AERs. However, it should be noted that AERs are not only a function of envelope airtightness but of infiltration driving

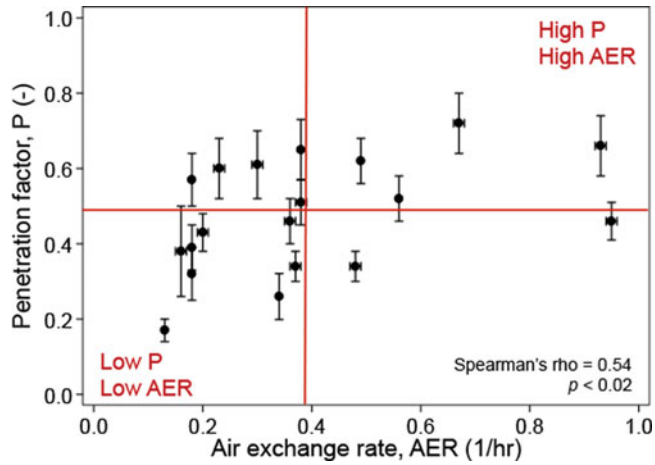

Fig. 2. Penetration factors (P) for submicron particles and AERs measured in the 19 single-family homes relying on natural infiltration for ventilation air in Stephens and Siegel (2012a).

forces, such as indoor/outdoor temperature differences, wind speeds and directions, leakage sites, and site shielding, which were not explored in detail herein.

Interestingly, because both particle penetration factors and AERs were correlated, the product of the two ($P \times$ AER, or the outdoor particle source term in Equation 2) varied even more widely among only these 19 homes than P and AER did individually. Figure 3 shows outdoor particle source terms with a lognormal distribution fit to the data. Values of outdoor particle infiltration rates ($P \times$ AER) ranged from as little as 0.02 h^{-1} in the tightest, newest home to as much as 0.62 h^{-1} in one of the leakiest and oldest homes in the relatively small sample of residences. The data also fit a lognormal distribution relatively well, with a GM of 0.16 h^{-1} (geometric standard deviation [GSD] = 2.33). Although most of the homes had somewhat similar outdoor particle source terms (from 0.1 to 0.2 h^{-1}), the tails of the distribution were quite long, and outdoor particle source terms varied by a factor of ~30 from the most protective home to the least protective home. These data suggest that building envelope characteristics can have a large impact on indoor exposures to outdoor particles.

Indoor particle loss rates (excluding AER)

Figure 4 shows indoor particle loss rates that were measured in homes in Stephens and Siegel (2012a). These values combine both particle deposition rate coefficients (k) and HVAC system and filter removal rates ($Q_{HVAC}\eta_{HVAC}/V$), with HVAC systems operating 100% of the time during the test periods (f = 100%), and exclude AER to isolate the impacts of filtration and other indoor characteristics apart from envelope airtightness. Figure 4a shows mean (±SD) total particle loss rates measured in the homes split by three distinct ranges of HVAC filtration that were identified in the homes (from MERV <5 to MERV 11 or higher). Filters were identified visually in each home and MERV classifications were either reported by the manufacturers or identified visually based on knowledge of

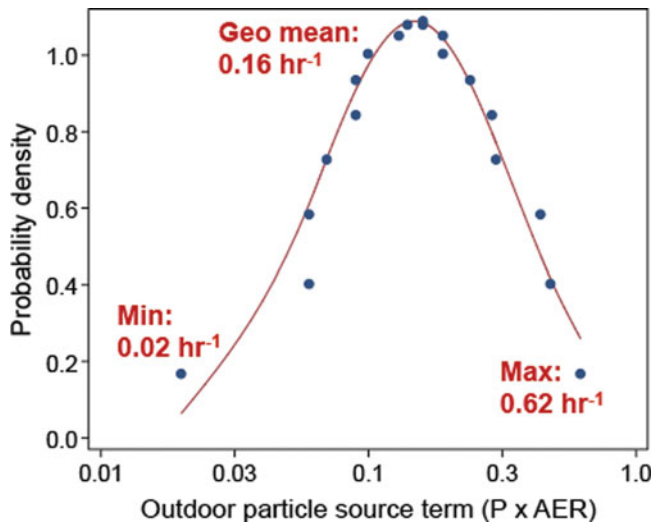

Fig. 3. Probability density function of outdoor submicron particle infiltration rates ($P \times$ AER) in homes measured in Stephens and Siegel (2012a), which were lognormally distributed with GM = 0.16 h^{-1} and GSD = 2.33.

typical residential HVAC filtration products.Figure 4b shows the same particle loss rates fit with a lognormal distribution.

Values of indoor particle loss rates excluding AER (i.e., $k + Q_{HVAC}\eta_{HVAC}/V$) ranged from as little as 0.31 h^{-1} in a home with a very low-efficiency filter installed (MERV <5) to as much as 3.24 h^{-1} in a home with a relatively high-efficiency filter installed (MERV 12). The data also fit a lognormal distribution relatively well, with a GM of ~1.0 h^{-1} and a broad distribution (GSD = 1.85). These data suggest that indoor particle loss rates with the HVAC system operating varied by a factor of ~10 from the most protective to the least protective home in this sense, which is a large variation in a relatively small sample of homes. These data also suggest that simple knowledge of the type of HVAC filtration used in a home may be sufficient to further group indoor particle loss rates in a home and that filter choice can have a large impact on indoor exposures to particles of outdoor origin.

HVAC system runtimes

Although long-term HVAC system runtimes were not measured in all of the homes in Figure 4, a few of the homes were used in a previous study of both residential and very similar small commercial buildings (many of which were homes converted to offices) in Austin, TX. These systems were monitored as part of ASHRAE Research Project 1299 (Stephens et al. 2010a, 2010b). Measurements included power draws of air handling unit fans and outdoor compressor units at 10-sec intervals once per month in each building during the long cooling season in Austin, TX. These data were used to construct profiles of hourly HVAC operation, which were then summarized and reported in Stephens et al. (2011). Mean hourly HVAC operation fractions from each building in this study are shown in Figure 5.

Even in the long cooling season in Austin, TX, the median of the long-term average fractional HVAC system operational times of these systems was only ~21%, although this value ranged from as little as 10.7% to as high as 55.3%, depending on a wide range of factors including thermostat set-points, occupancy density and schedules, HVAC system performance, building envelope details, duct leakage fractions, and other parameters. If central HVAC filters are relied upon to remove particles from recirculated air, these data suggest that even within this small sample of fewer than 20 buildings in a climate that has high cooling energy requirements, HVAC system operational fractions can easily vary by a factor of ~5 from the highest frequency operation to the lowest frequency operation. The variation would likely be larger across a wider number of homes.

Implications for human exposure to submicron particles

These ranges of recently measured parameters were combined to highlight particularly stark differences in particle

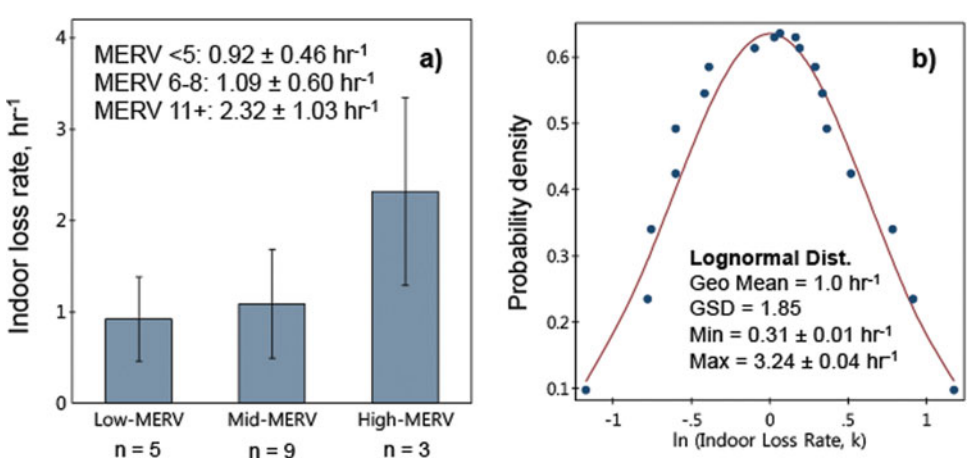

Fig. 4. Summary of indoor submicron particle loss rates (excluding AER) measured in Stephens and Siegel (2012a). a. Split by identified MERV classification of HVAC filters installed in the homes. b. Lognormal distribution of loss rates was observed, ranging approximately one order of magnitude from minimum to maximum with GM = 1.0 h^{-1} and GSD = 1.85.

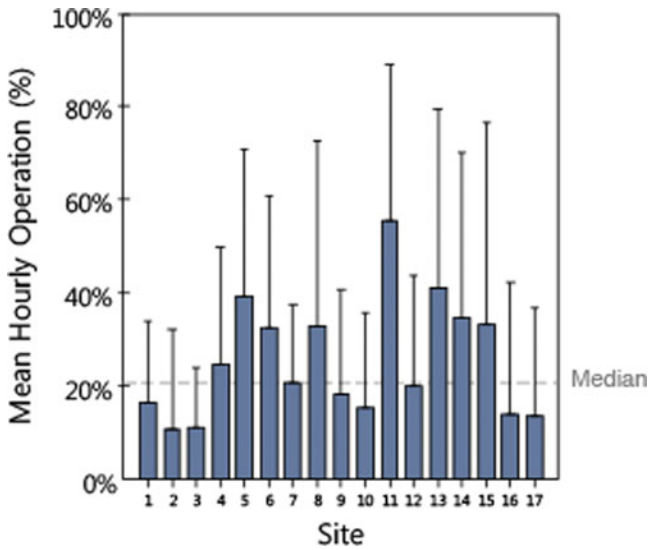

Fig. 5. Mean hourly HVAC operation times of 17 residential and light commercial buildings during the long cooling season in Austin, TX. Sites 1–8 are residences, and sites 9–17 are small commercial buildings (many of which were converted residences).

Table 1. Hypothetical homes ranging from most to least protective for indoor concentrations of outdoor submicron particles.

	Lower bound, most protective	Median	Upper bound, least protective
Outdoor particle source term, $P \times$ AER (1/h)	0.02	0.16	0.62
AER (1/h)	0.13	0.39	0.95
Indoor loss rate, $k + \eta Q/V$ (1/h)	3.24	1.00	0.31
Fractional HVAC operation, f	55.3%	21.0%	10.7%
I/O submicron PM ratio (F_{inf})	0.01	0.27	0.63

infiltration factors (and thus human exposures, given constant time–activity patterns across homes) to submicron particles of outdoor origin that are driven by the combination of building envelope design and construction, filter choice, and HVAC system operation. Three hypothetical homes were constructed: (1) a lower bound exposure, or "most protective," home; (2) a typical "median-exposure" home; and (3) an upper bound exposure, or "least protective," home. The most protective, lower exposure home is a home that would have the lowest outdoor particle source term ($P \times$ AER) from the aforementioned study (Stephens and Siegel 2012a), combined with the highest total indoor loss rate ($k + \eta Q/V$) and highest fractional HVAC operation time (f) summarized in previous sections (i.e., a tight home with a high-efficiency filter and an HVAC system that operates much of the time). Conversely, the least protective high-exposure home would have the outdoor particle infiltration rate, the lowest indoor particle loss rate, and the lowest fractional HVAC operation time (i.e., a leaky home with a low-efficiency filter and an HVAC system that does not operate very often). Finally, the median-exposure home would have the median values of each parameter. Estimates of the long-term average submicron particle infiltration factor (F_{inf}) for these three hypothetical homes are made using Equation 2 and shown in Table 1.

Using this simple analysis, the most protective home would likely have a submicron particle infiltration factor (F_{inf}) of approximately 0.01 (indoor concentrations are only 1% of outdoor concentrations). Conversely, the least protective home would likely have a submicron particle infiltration factor of approximately 0.63, or about 60 times higher than the least protective home. The median home would likely have a long-term F_{inf} of approximately 0.27 (about half that of the least protective home and ~25 times higher than the most protective home). While there may be large uncertainties in these estimates limited to the number of homes from which data are drawn and likely variations in deposition rates and system runtimes across different homes in different climates, they are still instructive for demonstrating the large variations in indoor concentrations of outdoor particles that can be found inside residences.

These ranges of estimates for submicron infiltration factors are reasonably in line with other recent field measurements. For example, Kearney et al. (2011) measured values of F_{inf} for submicron particles in more than 40 homes in Windsor, Ontario, ranging from ~0.03 to ~0.9 with a median of ~0.19–0.27, depending on season and estimation method. Similarly, Bhangar et al. (2011) estimated values of F_{inf} for submicron particles from ~0.1 to ~0.5 in seven homes in California. A more complex size-resolved modeling effort has also recently been conducted (a major limitation of Stephens and Siegel [2012a] was the lack of size-resolved measurements), which has yielded similar bounds in ultrafine and submicron particle infiltration factors (El Orch et al. 2014). Taken together, these results demonstrate the impacts that the combined effects of building envelope penetration factor, AERs, indoor loss rates, HVAC filter selection, and HVAC system design and operation can have on indoor exposures to particles of outdoor origin.

A cautionary tale: Net-zero energy home

Finally, Figure 6 further demonstrates the influence that HVAC system design and operation can have on indoor exposures to outdoor particles. In one home measured and reported in Stephens and Siegel (2012a), particle penetration factors, AERs, and indoor loss rates were measured twice: once while relying only on infiltration for ventilation air, as already reported, and once with an ERV unit operating (data not yet shown). This very airtight home actually had the lowest P and lowest AER measured while relying on infiltration alone; thus, it had the most protective envelope in the study. However, Figure 6 shows the ratio of indoor particle concentrations to outdoor particle concentrations measured during the test periods

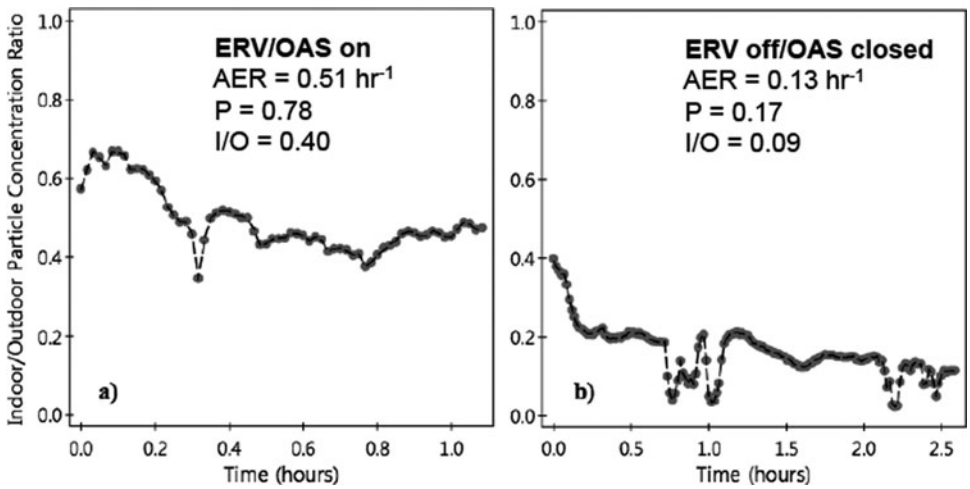

Fig. 6. I/O submicron particle concentration ratio measured at 1-min intervals in a new net-zero energy capable home. a. During operation with an ERV unit providing dedicated OAS. b. With the ERV + OAS unit unplugged and blocked.

for both days of testing in this home, along with a mathematical model using the estimated parameters of indoor loss rates and particle penetration factors to fit those concentration ratios. Figure 6a shows data for the day of testing with the ERV unit operating normally, intentionally supplying outdoor air to the indoor space through a dedicated outdoor air supply (OAS) duct installed in the return plenum. Figure 6b shows data from the day of testing with the ERV unit unplugged and the OAS duct opening in the return plenum taped to prevent outdoor air delivery (this is the most protective infiltration condition).

With the ERV and OAS operating normally, the AER was approximately 0.51 h^{-1}. Because of the dedicated OAS, the outdoor submicron particle penetration factor was approximately 0.78, which actually became the highest measured value in this sample of homes. Upon closer inspection, it was found that the OAS duct opened into the return plenum *downstream* of the HVAC filter (which was installed at one of the interior return grilles). Thus the ERV and OAS ductwork provided no more than ~22% ± 9% of filtration efficiency of outdoor particles. Manufacturer's literature for the ERV mentions the use of a pre-filter in the unit, which obviously has relatively low removal efficiency for submicron particles.

As previously shown, when the OAS was intentionally taped in the return plenum and the ERV was unplugged from the electrical outlet, the AER was only 0.13 h^{-1} and the resulting penetration factor was only 0.17 (a 61% reduction from the day of testing with an ERV operating). For both days of testing, the HVAC filter and indoor loss rates were similar, with total indoor particle loss rates of 0.61 h^{-1} on day 1 and 0.55 h^{-1} on day 2. The resulting time-averaged submicron particle infiltration factors for the 2 days were approximately 0.40 and 0.09. Thus, occupants would be exposed to over four times as much outdoor particulate matter while inside this otherwise very tight home with the OAS + ERV unit operating compared to when it is not supplying essentially unfiltered outdoor air. These results suggest that caution should be used when designing and installing residential mechanical ventilation systems, as they too can have a large impact on indoor exposures to outdoor particles if improperly installed.

Conclusions

Recent measurements of outdoor particle infiltration and persistence in homes has revealed that a few key building design and operational choices can have a substantial impact on indoor exposures to outdoor particles. These parameters include building envelope design and construction, HVAC filter selection, and HVAC system operation. However, results from this work are limited to a relatively small sample of buildings, and more experimental work should be conducted in a larger number and variety of homes to accurately measure these parameters for other particle sizes and constituents known to have adverse health implications. These fundamental drivers of infiltration factors are important to capture accurately across a wider number of homes and operational conditions to improve the ability to accurately predict exposures for epidemiology studies and to inform the general public on effective measures to reduce their indoor exposures to outdoor particulate matter. This work also suggests the need for guidelines and commissioning for the installation of residential ventilation systems to avoid inadvertent increases in human exposure to outdoor air pollution due to improper or inadequate installation of these systems.

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