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Predictions and determinants of size-resolved particle infiltration factors in single-family homes in the U.S.

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ABSTRACT

Because people spend the majority of their time indoors and particles of outdoor origin infiltrate into buildings with varying efficiencies, human exposure to outdoor particles often occurs indoors. Relying on ambient measurements of particle concentrations alone can result in significant exposure misclassification in epidemiological studies; however, there remains a need to improve fundamental knowledge of the variation of particle infiltration across the building stock, particularly in residences. Therefore, this work develops a Monte Carlo simulation tool to predict the statistical distribution of time-averaged size-resolved indoor proportions of outdoor particles, or 'infiltration factors', for 0.001–10 μm particles across the U.S. single-family residential building stock. The model is then used to estimate the likely bounds of size-resolved infiltration factors and to identify the most important influencing factors using best available data for nationwide distributions of several model inputs, including air exchange rates, envelope penetration factors, deposition rates, and others. Results suggest that size-resolved infiltration factors vary highly across U.S. residences, which is consistent with existing experimental data. Size-resolved infiltration factors were strongly dependent on home characteristics and were predicted to vary by a factor of ~20 to more than 100 from the least protective of homes (99th percentile) compared to the most protective (1st percentile), depending on particle size. These results suggest that a wide variability in size-resolved infiltration factors among U.S. residences should be accounted for in future epidemiology studies. This work also identifies several existing data gaps that should be addressed to improve knowledge of size-resolved infiltration factors in homes.

1. Introduction

Elevated ambient concentrations of particulate matter, including $PM_{2.5}$, PM_{10}, and ultrafine particles (UFP, <0.1 μm), are consistently linked with adverse health effects [1–9]. These studies typically use ambient concentration measurements from central-site monitors. However, because Americans spend the majority of their time indoors (and most of that time at home) [10], and particles of outdoor origin can infiltrate and persist in buildings with varying efficiencies [11–17], relying on ambient measurements alone can result in significant exposure misclassification for a large portion of the population [18–21].

Several recent studies have attempted to address this exposure misclassification and elucidate the important determinants of the infiltration and persistence of outdoor particulate matter into residential indoor environments. One approach involves field measurements of indoor and outdoor particulate matter concentrations in a large number of residences, gathering information on home characteristics and occupant behaviors by questionnaires and building assessments, and using regression analyses and mass balance principles to identify predictors of indoor–outdoor ratios in the absence of indoor sources [22–27]. Another approach involves estimating indoor exposures to ambient particulate matter using mass balance models that incorporate more fundamental particle transport and control mechanisms, such as particle penetration factors through building envelopes, air exchange rates, deposition rates, removal by air-conditioning systems, and human activity patterns and behaviors [28–34].

Both approaches have shown that large variations in indoor exposures to ambient particulate matter can result from differences in both building characteristics such as envelope airtightness and

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human activities such as window opening. Accounting for these variations is an important step to improve exposure estimates for epidemiology studies. However, these same approaches are often limited in their representative sample sizes, their assumptions for important building input parameters, or in their focus on particular particle classes, sizes, or chemical constituents. Therefore, this work attempts to improve upon existing modeling approaches by developing a Monte Carlo simulation tool for predicting the statistical distribution of time-averaged size-resolved indoor concentrations of outdoor particulate matter across the U.S. single-family residential building stock. The tool utilizes a time-averaged size-resolved particle number balance on 0.001–10 μm particles in a well-mixed indoor environment and is integrated with best available data on influential building-related input parameters to predict time-averaged indoor proportions of outdoor particles in U.S. residences.

Results are intended to demonstrate the likely statistical bounds and distributions of heterogeneity in size-resolved indoor–outdoor particle relationships (in the absence of indoor sources) across the building stock and to provide a model framework for others to use in future exposure and epidemiology studies as new input data are acquired. Results from these simulations are also used to explore the ability of the model to use outdoor particle size distributions to predict the likely distributions of time-averaged indoor concentrations of particular classes of particulate matter encountered across the building stock, including ultrafine particle number concentrations and $PM_{2.5}$ mass concentrations. Finally, this work also highlights the importance of particular building characteristics as determinants of particle infiltration factors, which serves to identify data gaps in the existing literature and inform future field studies on ongoing measurement needs.

2. Methods

Our simulations utilize a time-averaged, well-mixed number balance to predict the proportion of outdoor particles 0.001–10 μm in diameter found inside residences due to a combination of infiltration and window opening (i.e., natural ventilation) for outdoor air exchange. Similar number or mass balance approaches have been used in other studies [35–40], but this approach differs by incorporating best available data for important building factors and likely statistical distributions of window opening behaviors, central forced-air HVAC system ownership, and HVAC filter ownership into a large Monte Carlo simulation. The model framework and relevant input parameters are described in the next sections.

2.1. Model framework

The long-term, time-averaged number balance on indoor particles of diameter *i* of outdoor origin in a well-mixed space used for each modeled home is shown in Equation (1).

$$F_{i,\text{inf}} = \frac{C_{i,\text{in}}}{C_{i,\text{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\text{dep}} + \lambda_{\text{HVAC}} f_{\text{HVAC}} \eta_{i,\text{HVAC}}} \tag{1}$$

where $F_{i,\text{inf}}$ = time-averaged size-resolved infiltration factor (–); $C_{i,\text{in}}$ = time-averaged size-resolved indoor concentration of particles of diameter i (#/cm^3); $C_{i,\text{out}}$ = time-averaged size-resolved outdoor concentration of particles of diameter i (#/cm^3); P_i = time-averaged size-resolved envelope penetration factor (–); λ = time-averaged air exchange rate (AER, 1/h); $k_{i,\text{dep}}$ = time-averaged size-resolved particle deposition rate (1/h); λ_{HVAC} = recirculation rate through a central forced-air HVAC system, if applicable (1/h); f_{HVAC} = time-averaged fractional operation time of the HVAC system, if applicable (–); and $\eta_{i,\text{HVAC}}$ = size-resolved particle removal efficiency of a filter installed in the HVAC system, if applicable (–).

Terms in the numerator account for outdoor sources alone and terms in the denominator account for a number of removal mechanisms, including air exchange, surface deposition, and HVAC filtration. Input parameters that are defined on a time-averaged basis take into account both fundamental building characteristics applicable for periods when doors and windows are closed (referred to as 'closed-window' values), as well as adjusted values of those same characteristics during periods when the building is influenced by human interaction (primarily by altering values during periods of open windows, which will increase air exchange rates, penetration factors, and deposition rates).

Each modeled home is uniquely described first by estimating its time-averaged air exchange rate (λ) using Equation (2), which accounts for estimates of both closed-window and open-window air exchange rates.

$$\lambda = \lambda_{\text{closed windows}}\left(1 - f_{\text{open windows}}\right) + \lambda_{\text{open windows}} f_{\text{open windows}} \tag{2}$$

where $\lambda_{\text{closedwindows}}$ = the air exchange rate in a home with doors and windows closed (1/h); $\lambda_{\text{openwindows}}$ = the average air exchange rate during periods of open windows (1/h); and $f_{\text{openwindows}}$ = the fraction of time windows are open (–). The fractional time of open windows ($f_{\text{openwindows}}$) was adjusted to account for window opening only during times of mild weather, as shown in Equation (3). This same approach has been used in other recent work [31].

$$f_{\text{openwindows}} = f_{\text{mild}} f_{\text{openwindows,mild}} \tag{3}$$

where f_{mild} = the fraction of time mild weather is experienced and $f_{\text{openwindows, mild}}$ = the fraction of time windows are open during mild weather. $\lambda_{\text{openwindows}}$ is based on $\lambda_{\text{closedwindows}}$ for each home but is adjusted for the probability that windows are open either a low or high amount ($\phi_{\text{openwindows,low}}$ or $\phi_{\text{openwindows,high}}$) using a constant air exchange rate multiplier for each opening condition ($m_{\text{openwindows,low}}$ or $m_{\text{openwindows,high}}$) as shown in Equation (4). The selection of AER multipliers is described in a later section.

$$\lambda_{\text{openwindows}} = \lambda_{\text{closedwindows}}\left(\phi_{\text{openwindows,low}} m_{\text{openwindows,low}} + \phi_{\text{openwindows,high}} m_{\text{openwindows,high}}\right) \tag{4}$$

Similar to the process for estimating time-averaged air exchange rates, time-averaged size-resolved envelope penetration factors are then estimated based on size-resolved penetration factors during closed-window periods combined with the fraction of time windows are open and penetration factors are higher, as shown in Equation (5).

$$P_i = P_{i,\text{closedwindows}}\left(1 - f_{\text{openwindows}}\right) + P_{i,\text{openwindows}} f_{\text{openwindows}} \tag{5}$$

where $P_{i,\text{closedwindows}}$ = the closed-window size-resolved envelope penetration factor in a home (–) and $P_{i,\text{openwindows}}$ = the average size-resolved penetration factor during periods with windows open (–). Values for $P_{i,\text{openwindows}}$ are estimated by taking into account separate values for low and high window opening conditions as well as the probability of each opening condition, as shown in Equation (6).