Air Exchange and Interzonal Flows in Residences, and the Limits of the Fully-Mixed Assumption

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Abstract: Air exchange rates (AERs) and interzonal flows are key determinants of indoor air quality (IAQ) and building energy use. This paper characterizes AERs and interzonal flows in 126 houses, and evaluates effects of these parameters on IAQ. AERs measured using weeklong tracer measurements in several seasons averaged 0.73 ± 0.76 h^{-1} (median = 0.57 h^{-1}, n=263) in the general living area, and much higher, 1.66 ± 1.50 h^{-1} (median = 1.23 h^{-1}, n=253) in bedrooms. Living area AERs were highest in winter and lowest in spring; bedroom AERs were highest in summer and lowest in spring. Bedrooms received an average of 55 ± 18% of air from elsewhere in the house; the living area received only 26 ± 20% from the bedroom. Interzonal flows did not depend on season, indoor smoking or the presence of air conditioners. A two-zone IAQ model calibrated for the field study showed large differences between pollutant levels between the living area and bedroom, and the key parameters affecting IAQ were emission rates, emission source locations, air filter use, AERs, interzonal flows, outdoor concentrations, and PM penetration factors. The study data and modeling show that the fully

mixed assumption for residences can have substantial limitations, particularly for the bedroom where people spend a substantial fraction of time.

Keywords: air exchange rate, air filters, interzonal flows, PM exposure, residences

1. Introduction

With few exceptions, previous indoor air quality (IAQ) studies have assumed that residences and other small buildings are fully mixed spaces that can be represented as a single building zone.[1-4] While this assumption facilitates analyses and may be reasonable for some purposes, it is highly idealized. The presence of gradients or differentials of pollutant concentrations, humidity levels, temperatures, and door and wall partitions in a building demonstrate the limitations of this assumption. Even when building air appears reasonably well mixed, several factors, singly or jointly, may produce such differentials that are important for exposure and other purposes like humidity control. First, the existence of localized emission sources within buildings, such as cigarette smoking or chemical use occurring in only portions of a building, is likely to produce pollutant differentials.[4,5] Second, pollutants such as particulate matter (PM) and ozone, which have relatively high deposition or removal rates, are sensitive to age-of-air and other factors that affect pollutant removal and lifetime,[6, 7] which can increase gradients in a building. Third, building zones that are either partially decoupled from the rest of the building, or that have air exchange rates (AERs) that differ from the building as a whole, may also differ in concentration, a result of varying rates of dilution, deposition or transport in the building.[2, 5] These factors may be especially relevant for pollutants that have localized sources and relatively high deposition rates, e.g., PM, for persons spending considerable time in rooms that are decoupled from the general space, e.g., children or the elderly in bedrooms, and for households containing strong and localized emission sources, e.g., cigarette smokers.

The AER is the airflow across a building envelope, and represents a key variable for understanding IAQ, building energy and ventilation. Air exchange is the primary mechanism for entry of outdoor-generated air pollutants and for removal of indoor-generated air pollutants. A minimum AER is needed to dilute and remove pollutants emitted from indoor sources, e.g., PM emissions from smoking, cooking and vacuuming. In residences, determinants of AERs include occupant behavior, e.g., window or door opening;[8, 9] characteristics of the heating, ventilation and air-conditioning (HVAC) system;[9-11] meteorological conditions, e.g., wind speed and indoor/outdoor temperature differences;[8, 9, 12] and building characteristics, e.g., tightness and number of floors.[8] Opening windows can increase the AER as much as 2 h^{-1}, and an attic fan can increase AERs by up to 1 h^{-1}. Generally, effects of temperature and wind effects are smaller,[8, 9] unless exterior doors and windows are closed.[12] Predictions of AERs in residences using empirical and mechanistic models show reasonable accuracy, e.g., a study of 31 detached homes found median absolute differences of 40 to 50%.[1]

Few studies have measured IAQ gradients and the degree of mixing in a sufficient number of buildings to characterize variation. Incomplete mixing within rooms has been demonstrated in specialized applications, e.g., filtration for control of airborne pathogens.[13] In a single-story residence, single and two-compartment models yielded good agreement with measurements, and interzonal flows depended on whether a door separating adjacent rooms was open (allowing the house to be modeled as a single

compartment) or closed (requiring two compartments).[14] In occupied buildings, mixing and air flows will vary over time as doors and windows are opened and closed, ventilation systems are turned on and off, and as outdoor meteorological conditions change. As noted, low AERs and/or little mixing can produce high pollutant concentrations if emission sources are present.

2. Objectives

The goals of this paper are to: characterize AERs and interzonal airflows in a large sample of residences; identify determinants of AERs, including seasonal and meteorological influences; and characterize interzonal transport, particularly between bedrooms and living areas (excluding the studied bedroom). Additionally, the collected data along with mechanistic models are used to understand the impact on IAQ, in particular, the sensitivity of AERs and mixing assumptions on concentrations due to indoor pollutant sources. The information presented in this paper can aid exposure assessments and inform decisions regarding the effectiveness of IAQ controls, such as smoking bans and the use of air filters.

3. Materials and methods

3.1. Recruitment, sampling schedule, and study homes

Recruitment of study homes. A total of 126 households in Detroit, Michigan were recruited as part of a study examining the effectiveness of stand-alone room air filters and air conditioners in mitigating asthma symptoms in children. Detroit contains about 715,000 people (2010), and study households were predominantly low income African American and Latino,[15] and each had a child with asthma. Households were randomized to one of three groups: (1) a "control" group receiving only community health worker (CHW) home education visits regarding the child's asthma (n=37); (2) a "standard" intervention group receiving a stand-alone HEPA filter placed in the child's bedroom and the CHW visits (n=47); or (3) an "enhanced" intervention group receiving the filter, the CHW visits, plus an air conditioner (n=42). Households entered the study on a rolling basis from March, 2009 to September, 2010, and each received a weeklong 'baseline visit' and two or three follow-up or 'seasonal' visits spaced three or four months apart. On most weeks, 6 to 10 homes were sampled. The present paper reports on a total of 346 weeklong household visits to the 126 homes.

The study was conducted using a community-based participatory research approach by the Community Action Against Asthma (CAAA) partnership. All procedures were approved by The University of Michigan Institutional Review Board. Further details on the study design and exposure assessment activities are provided elsewhere.[16]

Walkthrough and caregiver surveys. A walkthrough audit of each house was completed to collect information on its characteristics and conditions, including type of heating and cooling system, evidence of water damage, mold and number of windows, and information about the child's bedroom, sleeping and playing areas. Participants also completed surveys during baseline and seasonal visits that included questions about health status, features of their home, and indoor PM-emitting activities (e.g., frequency of cigarette smoking, cooking, and vacuuming). For a few participants, some survey or walkthrough data are missing, e.g., due to moves or refusals.

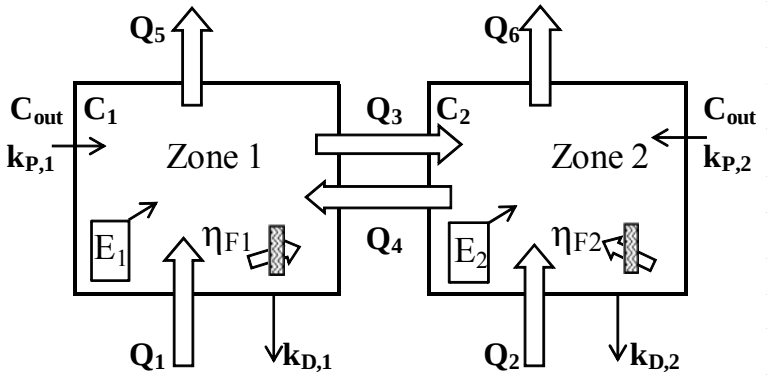
Home and household characteristics. Characteristics of the study houses have been summarized previously.[16] Volumes of the houses and bedrooms averaged 368 ± 143 m^3 (median=360 m^3, n=121) and 28 ± 12 m^3 (median=25 m^3, n=122), respectively; floor areas averaged 147 ± 58 m^2 (median=146 m^2, n=121), and the children's bedroom averaged 11 ± 5 m^2 (median=10 m^2, n=122). Most (88%) used forced air heating systems, 30% had central air conditioners, 27% had exhaust fans, and 47% used furnace filters. The average occupancy of the homes was 1.7 ± 0.8 adults and 2.4 ± 1.4 children. Over half (60%) of the households included adult smokers according to the caregiver survey, and environmental tobacco smoke was detected (by the use of tracers) in 23 homes. Nearly half (44%) of the caregivers reported using vacuum cleaners, and all of the child's sleeping area had been cleaned in the past two weeks by vacuuming, sweeping or dusting.

3.2. AER, interzonal flow, and PM measurements

Ventilation and air quality measurements were concurrently obtained in the living area and the child's bedroom of each house during baseline and each seasonal assessment. (Summer was defined as June, July and August; fall as September, October and November; winter as December, January, February, and spring as March, April and May.) AERs were estimated using the multizone constant injection method,[17,18] which allows determination of "local" AERs. The method used two different perfluorocarbon tracers (PFTs) and concentration measurements of the tracers in both zones. Two passive emitters of hexafluorobenzene (HFB) were placed in the living area, and two emitters of octafluorotoluene (OFT) in the sleeping area. Emitters were typically placed in opposite corners of rooms, releasing a PFT at a constant rate over the weeklong sampling period. PFT concentrations were measured using passive samplers at central locations in the two rooms, placed away from the emitters.[19] The passive samplers were analyzed using thermal desorption, cryofocusing and GC-MS analysis.[20] Figure 1 depicts flows Q_1 to Q_4 determined by this method; flows Q_5 and Q_6 are obtained by flow balance. Note that zone 1, called the living area in this paper, refers to all rooms other than the (study) bedroom.

Figure 1. Configuration of the fully mixed two-zone model, also, schematic of the two zone IAQ model, showing flows Q_1 to Q_6 (m^3 hr^{-1}); concentrations C_{out}, C_1 and C_2 (mg m^{-3});

emission rates E_1 and E_2 (mg h^{-1}) ; particle penetration factors $k_{P,1}$ and $k_{P,2}$ (dimensionless); deposition loss rates $k_{D,1}$ and $k_{D,2}$ (h^{-1}); and capture efficiency of filters η_{F1} and η_{F2} (dimensionless).



AERs for the house and bedroom, and flows between these zones, were determined using the measured concentrations and the volumes of the house and bedroom as follows:[21]

$$\begin{pmatrix} Q_1+Q_4 & -Q_3 \\ -Q_4 & Q_2+Q_3 \end{pmatrix} = \begin{pmatrix} C_{HFB,1} & C_{HFB,2} \\ C_{OFT,1} & C_{OFT,2} \end{pmatrix}^{-1} \times \begin{pmatrix} E_{HFB,1} & 0 \\ 0 & E_{OFT,2} \end{pmatrix} \quad (1)$$

where Q_1 and Q_2 = air flows into zone 1 and 2, respectively, from outdoors (m^3 h^{-1}); Q_3 = air flow rate from zone 1 to 2 (m^3 h^{-1}); Q_4 = air flow rate from zone 2 to 1 (m^3 h^{-1}); $C_{HFB,1}$ and $C_{OFT,1}$ = concentrations of HFB and OFT in zone 1 (mg m^{-3}); $C_{HFB,2}$ and $C_{OFT,2}$ = concentrations of HFB and OFT in zone 2 (mg m^{-3}); and $E_{HFB,1}$ and $E_{OFT,2}$ = emission rates of HFB and OFT in zones 1 and 2 (mg h^{-1}), respectively. This result assumes that outdoor PFT concentrations are zero, and that the PFTs are inert (removed only by airflows and not by settling, deposition, filtration or reaction). The AER_i (h^{-1}) in zone *i* was calculated as Q_i/V_i (i=1,2), where V_i = volume of zone i (m^3).

Interzonal flows. Interzonal flows transport pollutants between zones, e.g., cigarette smoke emitted in the living area that is brought to the bedroom. These flows are expressed as interzonal flow proportions α_{HB}, α_{BH} (dimensionless, ratios between 0 and 1):

$$\alpha_{HB} = Q_3/(Q_2+Q_3) \quad (2)$$

$$\alpha_{BH} = Q_4/(Q_1+Q_4) \quad (3)$$

where α_{HB} = fraction of the air coming into the bedroom that arises from the (remainder of the) house, and similarly, α_{BH} = fraction of house air coming from the bedroom. These proportions provide a simple way to express and compare the magnitude of interzonal flows among buildings of different sizes.

Indoor and outdoor measurements. PM concentrations in bedrooms were measured as sequential 24-hr filter samples during the sampling week collocated with the PFT samplers in each season. As detailed

elsewhere,[16] PM samples were collected at 15 L/min on 1 μm-rated PTFE filters installed in static-free polypropylene cassettes (Omega Specialty Instruments Co., Houston, TX, USA) for gravimetric analysis. The inlets on these cassettes are not designed to be size selective, and they essentially capture the total suspended particulate (TSP) fraction. In addition, particle number counts (PNCs) in 0.3 - 1.0 μm and 1 - 5 μm dia size ranges were measured continuously using an optical particle counter (GT-521, MetOne, Grants Pass, OR). PM concentrations and 0.3-1.0 μm PNCs were significantly correlated.[16] The PM data were reduced to weeklong averages.

Outdoor $PM_{2.5}$ measurements were obtained from air quality monitoring sites in Detroit selected to be representative of population exposure. These included daily data from four sites (Allen Park, Ambassador Bridge, Dearborn, Newberry School), and every third day data from five additional sites (Southwest High School, Linwood, East 7 Mile, Livonia, Wyandotte). These sites were operated by the Michigan Department of Natural Resources and the Environment using protocols that followed standard federal reference methods. Meteorological data, including wind speed, direction, temperature, humidity, and barometric pressure, were obtained from the Detroit City Airport site, located near the middle of the study area.

In addition to the PFT tracers, the same passive samplers measured two tracers of environmental tobacco smoke (ETS), i.e., 2,5-dimethyl furan and 3-ethenyl pyridine used to confirm the presence of ETS, along with about 100 other volatile organic compounds (VOCs), e.g., naphthalene, BTEX (sum of benzene, toluene, ethylbenzene and xylenes), and total volatile organic compounds (TVOC, sum of target compounds).[16, 19, 21, 22] These samplers were placed in bedrooms and living areas for a 1-week period, and analyzed using thermal desorption, gas chromatography and mass spectrometry. Temperatures and relative humidity also were monitored in both bedrooms and living rooms, and CO_2 was monitored in the bedroom using an infrared sensor. These variables were monitored continuously and reduced to 1-week averages.

Quality assurance (QA). PFT, VOC and ETS tracer measurements used duplicate samplers and showed good agreement, i.e., replicate precision averaged 11 ±12% for the PFTs, 15 ± 16% for VOCs, and 14 ± 13% for the ETS tracers. Field blanks for passive sampling tubes were deployed at each household each week, and showed negligible contamination. Emitters were weighed periodically to determine emission rates, and samplers were temperature corrected. AER measurements that were excessively large ($\geq$10 h^{-1}) or unrealistically small ($\leq$0.1 h^{-1}) probably resulted from incomplete mixing or other reasons, and thus were omitted from analyses. (As shown later, such values constituted a very small fraction of measurements.) Further description of QA is provided elsewhere.[16]

3.3. IAQ modeling

Two zone IAQ model. PM concentrations from indoor and outdoor sources were predicted using a two zone model[4] that represents the bedroom and the remainder of house (Figure 1). Each zone can have an internal emission source, which adds pollutants, and an (free-standing) air filter, which removes PM. The mass balances in the two zones are similar:

$$d(V_1C_1)/dt = Q_1C_{out}k_{P,1} + Q_4C_2 - (Q_1 + Q_4)\,C_1 - \eta_{F1}Q_{F1}C_1 - k_{D,1}V_1C_1 + E_1 \qquad (4)$$

$$d(V_2C_2)/dt = Q_2C_{out}k_{P,2} + Q_3C_1 - (Q_2 + Q_3)\,C_2 - \eta_{F2}Q_{F2}C_2 - k_{D,2}V_2C_2 + E_2 \qquad (5)$$

where C_1 and C_2 = PM concentrations in zones 1 and 2, respectively (μg m^{-3}); t = time (hr); C_{out} = outdoor PM concentration (μg m^{-3}); η_{F1} and η_{F2} = PM capture efficiency of filters, if any, in zones 1 and 2 (dimensionless); Q_{F1} and Q_{F2} = filter air flow rate (m^3 h^{-1}); $k_{D,1}$ and $k_{D,2}$ = deposition loss rate for zones 1 and 2 (h^{-1}); $k_{P,1}$ and $k_{P,2}$= particle penetration factor for zones 1 and 2 (dimensionless); E_1 and E_2= emission rates in zones 1 and 2 (mg h^{-1}) , respectively; and flows and volumes Q and V were defined earlier. PM removal by a forced air system was not considered. Most of these parameters can vary by residence, time and season.

Given known flows and emission rates, and assuming steady-state conditions, eqs. (4) and (5) can be solved for concentrations C_1 and C_2 as:

$$\begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} -(Q_1 + Q_4) - k_{D,1}V_1 - \eta_{F1}Q_{F1} & Q_4 \\ Q_3 & -(Q_2 + Q_3) - k_{D,2}V_2 - \eta_{F2}Q_{F2} \end{pmatrix}^{-1} \times \begin{pmatrix} -E_1 - Q_1C_{out}k_{P,1} \\ -E_2 - Q_2C_{out}k_{P,2} \end{pmatrix} \qquad (6)$$

Scenarios and model parameters. Several scenarios were simulated in order to predict indoor PM concentrations and to demonstrate the migration of PM between zones. (The same scenarios are used for the sensitivity analysis, described below). Scenario 1 considered an emission source (e.g., smoking) in zone 1, e.g., the living area. Scenario 2 moved the source to zone 2, e.g., the bedroom. Finally, scenario 3 considered only outdoor emission sources (no indoor sources). Cigarette smoking was the sole indoor emission source considered, and 10 cigarettes were assumed to be smoked daily, giving an average PM emission rate E_1 of 7.5 mg h^{-1} based on an emission factor of 18 mg $cigarette^{-1}$.[14, 22] This scenario is relevant for other indoor sources with equivalent PM emissions. No other emission source, other than PM infiltration from outside air, was considered. In residences, many other indoor sources other than ETS make significant contributions to PM concentrations, e.g., cooking, cleaning, grooming, dusting, vacuuming, and resuspension.

The scenarios had several variants. In scenarios 1F, 2F and 3F, a free standing filter HEPA filter was used in the bedroom, but conditions were otherwise the same. (The filter was not used in other scenario 1 to 3.) In scenarios 1-M, 1F-M, 2-M, and 2F-M, indoor emission rates were adjusted to match PM concentrations measured in the field study. For each scenario, PM concentrations in the bedroom and living area were predicted using eq. (6).

A set of nominal model parameters was selected to represent the study homes. These used the average volumes of the houses and bedrooms V_1 and V_2, and air flows Q_1, Q_2, Q_3 and Q_4 scaled to the average house volume (based on average AERs and interzonal flow proportions, and using only those homes with valid Q_1, Q_2, Q_3 and Q_4 measurements). Filter airflow rate Q_{F2} was set to an effective average value, which depended on the filter fan speed and proportion of time used. We assumed the lowest speed (400 $m^3\ h^{-1}$), weighted by the average filter usage among study participants (70%),[23] thus obtaining Q_{F2} = 280 $m^3\ h^{-1}$ (assuming continuous use of the filter). For filter efficiency, η_{F2} was set to 1.0, typical of the high efficiency (HEPA) filters used.[24] Outdoor PM concentration C_{out} was set to 11 $\mu g\ m^{-3}$, the average value among nine Detroit monitoring sites over the study period.[25, 26] Deposition velocity k_D depends on PM properties (e.g., particle size and density), air turbulence, and room characteristics (e.g., volume to surface area ratio), and values from 0 to 3.6 h^{-1} have been proposed based on theoretical and experimental values.[24, 27-29] We set $k_{D,1}$ and $k_{D,2}$ to 0.2 h^{-1}. Particle penetration rates depend on particle size and environmental conditions, and a wide range, 0.001 to 1.0, has been specified.[30-32] We assumed $k_{P,1}$ and $k_{P,2}$ to 0.5. Lastly, we matched observed results for C_2 in four cases (with and without ETS detection, and with and without the filter) by adjusting emission rates E_1 and E_2.

3.4. Data analysis

Sensitivity analysis. The influence of parameters in the two zone IAQ model is shown using sensitivity analyses for scenarios 1, 1F, 2, 2F, 3 and 3F using the nominal parameters just described (and assuming 10 cigarettes smoked daily indoors except in scenario 3). Results were expressed for each parameter i using the relative sensitivity RS_i (dimensionless):

$$RS_i = [(C_T - C_{nom})/C_{nom}]/[(X_{i,T} - X_{i,nom})/X_{i,nom}] \quad (7)$$

where C_T = PM concentration obtained for a 10% increase in parameter X_i (i.e., Q_1, Q_2, Q_3, Q_4, E_1, E_2, V_1, V_2, η_{F2} Q_{F2}, $k_{D,1}$, $k_{D,2}$, $k_{P,1}C_{out}$ and $k_{P,2}C_{out}$) over its nominal value for the scenario, $X_{i,nom}$; and C_{nom} = PM concentration for nominal values of parameter $X_{i,nom}$. Thus, RS_i represents the change in PM levels relative to a change in input X_i, while holding other parameters at nominal values.

Statistical analysis. Cumulative distributions of AERs were plotted, and tested for normality or lognormality using Anderson-Darling goodness-of-fit tests. For parameters fitting either distribution, the variability was apportioned to season/year and house effects using a variance components analysis, computed using the MIXED and NESTED procedures in SAS (v9.1.3, SAS Institute, Cary, NC, USA).[33] Key parameters were tested by intervention group using Kruskal-Wallis nonparametric tests for differences in medians, and F and Tukey's tests for means. Variables from the walk-though and caregiver surveys that might be plausibly associated with IAQ and air flow parameters were selected for analysis.

Spearman correlation coefficients were used to examine associations between AERs, house and occupant characteristics.

4. Results and discussion

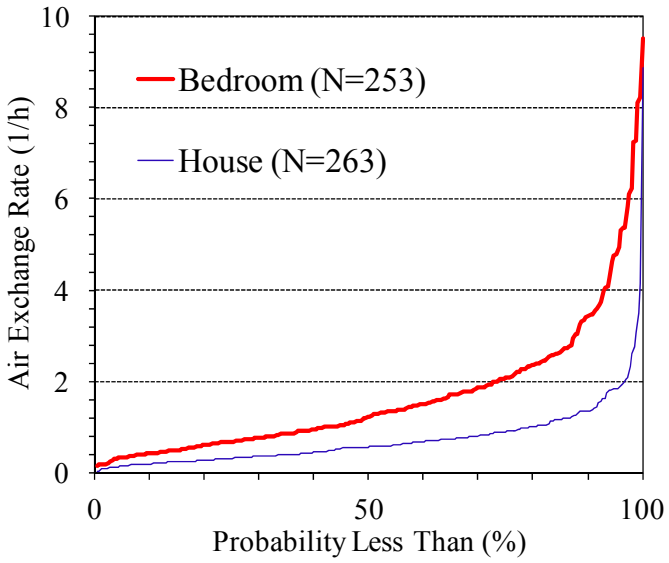
4.1. AERs in residences and bedrooms

In houses, AERs averaged 0.73 ± 0.76 h^{-1} (median = 0.57 h^{-1}, n=263) and the interquartile range (IQR) was 0.32 to 0.90 h^{-1}. The distribution of AERs, shown in Figure 2, show that most values fell in a narrow range, e.g., only 10% of measurements were below 0.2 h^{-1} and 1% exceeded 4 h^{-1}, and measurements were lognormally distributed (p=0.32, Anderson-Darling test). The house AERs exclude flows between two zones, i.e., only outside air entering the zone is considered. AERs in the control group (median = 0.56 h^{-1}, n=74), standard intervention group (0.60, n=101) and enhanced intervention group (median = 0.54, n=88) did not differ statistically (p=0.75, Kruskal-Wallis test).

In bedrooms, AERs averaged 1.7 ± 1.5 h^{-1} (median = 1.2 h^{-1}, n=253) and the IQR was 0.68 to 2.07 h^{-1}. Overall, bedroom AERs were approximately twice that seen for the house, suggesting that windows were frequently open (at least in the summer) or that the bedrooms were relatively "leaky." Most of the sampled bedrooms were small (volume of only 28 ± 12 m^3), and all had at least one (and sometimes several) operable windows and exterior walls. The large exterior wall-to-volume ratio in these bedrooms may increase air infiltration due the driving forces of the wind and stack (indoor-outdoor temperature differences) effects, as compared to the house as a whole, and yield higher AER. The distribution of AERs, also shown in Figure 2, was neither normal nor lognormal, thus the variance proportions analysis was not conducted. Bedroom AERs in bedrooms did not differ by group (p=0.40; median levels in control, standard, and enhanced intervention groups were 1.31 h^{-1} [n=69], 1.33 [n=99], and 1.03 [n=85], respectively). AERs in bedrooms and houses were weakly, but significantly correlated (Spearman r=0.21, p=0.001).

Because AERs did not differ by intervention group, these data were combined for subsequent analyses. Standard and enhanced interventions were merged and are denoted as the 'with filter' group; the control group is called 'without filter' group. Four observations were excluded as outliers (3 bedroom AERs ≥10 h^{-1} and 1 bedroom AER ≤0.1 h^{-1}), representing only 1.6% of the collected data.

Figure 2. Cumulative distributions of AERs in houses and bedrooms.



AERs differed by season (Table 1). House AERs were lowest in spring and highest in winter, with an overall variation of about 53% based on median seasonal values. Increased AERs are expected in winter due to greater indoor/outdoor temperature differences and higher wind speeds.[12] Based on the variance proportions analysis, temporal variation (year and season) explained 74% of the total variation, and house-to-house variation explained the remainder, 26%, showing a strong need for seasonal measurements. Homes with filters showed smaller and marginally significant seasonal changes. The reason(s) for differences between the groups with and without filter is not clear. While not statistically significant, homes with filters were slightly smaller (volume = 362 ± 146 m^3 versus 371 ± 124 m^3) and younger (average age was 54 versus 61 years, though ages were known for only 39 of the homes) than homes without filters. Occupants in homes receiving filters were instructed to try to keep bedroom doors closed or partially closed (to maximize the filter's effect), but compliance with this instruction was likely low.

Table 1. Air exchange rates in the house and child's bedrooms by season

Outcome	Season	Without filter				With filter				All groups			
		N	Average	SD	Median	N	Average	SD	Median	N	Average	SD	Median
AER_H (h^{-1})	Spring	21	0.46	0.24	0.37	58	0.61	0.62	0.41	79	0.57	0.55	0.40
	Summer	33	0.91	1.53	0.46	49	0.69	0.45	0.60	82	0.78	1.03	0.58
	Fall	8	0.78	0.50	0.60	44	0.78	0.65	0.60	52	0.78	0.63	0.60
	Winter	12	0.97	0.61	0.79	38	0.84	0.64	0.72	50	0.88	0.63	0.74
	All	74	0.78	1.08	0.55	189	0.72	0.60	0.57	263	0.73	0.76	0.57
	p-value[a]		0.060				**0.037**				**0.002**		
AER_B (h^{-1})	Spring	20	1.41	1.05	0.96	56	1.19	0.81	1.05	76	1.25	0.87	1.00
	Summer	29	1.88	1.84	1.34	46	2.27	2.16	1.74	75	2.12	2.03	1.50
	Fall	8	2.18	1.92	1.30	45	1.50	1.27	1.14	53	1.60	1.39	1.23
	Winter	12	1.67	1.02	1.43	37	1.65	1.29	1.30	49	1.65	1.22	1.30
	All	69	1.74	1.52	1.31	184	1.63	1.49	1.18	253	1.66	1.50	1.23
	p-value[a]		0.822				**0.048**				**0.049**		

[a] p-value from Kruskal-Wallis test for differences among homes by seasons.

In bedrooms, AERs also varied by season, and again the lowest values occurred in spring. However, the highest AERs in bedrooms occurred in summer (excluding the small number of homes tested without filters), probably reflecting the use of air conditioners, opened windows, or fans to cool the bedrooms. Thus, compared to AERs in houses, AERs in the bedrooms are higher and show different seasonal trends. As discussed below, these are important and striking results that are not well recognized in the literature.

Comparison to the literature. The house AERs measured in the present study are comparable to those reported in several recent studies. In the Detroit Exposure and Aerosol Research Study (DEARS), median AERs in 120 households in Detroit ranged from 0.7 to 1.4 h^{-1}, depending on season.[34] In another southeast Michigan study, but in the more suburban and affluent communities of Ann Arbor and Ypsilanti, AERs measured using methods similar to those in the present study were lower, averaging 0.43 ± 0.37 h^{-1} (n=15).[35] Homes in nearby Windsor, Ontario, Canada were "tighter" than the Detroit homes, with a geometric mean AER in winter of 0.32 h^{-1} (range from 0.26 to 0.40 h^{-1}; n=32), and only 0.19 h^{-1} (0.15 to 0.24 h^{-1}; n=42) in summer.[36] In the Relationship among Indoor Outdoor and Personal Air (RIOPA) study, which measured approximately 100 residences each in Elizabeth, NJ, Houston, TX and Los Angeles, CA, the median AER was 0.71 h^{-1} (n=506), and AERs differed by city (0.87, 0.88 and 0.47 h^{-1}, respectively), as well as by season.[37] A analysis using the 1997 U.S. Department of Energy Residential Energy Consumption Survey and 140 single-family houses in 19 cities estimated a median AER of 0.44 h^{-1} with a range from 0.26 to 0.58 h^{-1}, and AERs depended on house age, climate, and city/region.[38]

AERs in bedrooms. There are very few reports of AERs measured in bedrooms, and none in the US to our knowledge. In Europe, low AERs have been found in bedrooms, for example, the geometric mean AER in children's bedrooms in Odense, Denmark was 0.46 ± 2.09 h^{-1} (n=500);[39] and the mean AER in

children's bedrooms of single family homes in Sweden ranged from 0.31 to 0.47 h^{-1} (n=390), and depended on the ventilation system, construction period, foundation type, and number of floors.[40] Notably, northern European residences typically have very low AERs, e.g., AERs in the single-family houses in the Swedish study just noted averaged 0.36 h^{-1} (n=333).[40] Due to the substantial differences in building air tightness, ventilation, climate and other factors, AERs in the US and Europe are not expected to be comparable. Nonetheless, it is interesting to note that bedrooms in the Detroit homes have much higher AERs than the remainder of the house and thus likely to be rather drafty in winter. In contrast, the European studies show similar AERs in houses and bedrooms.

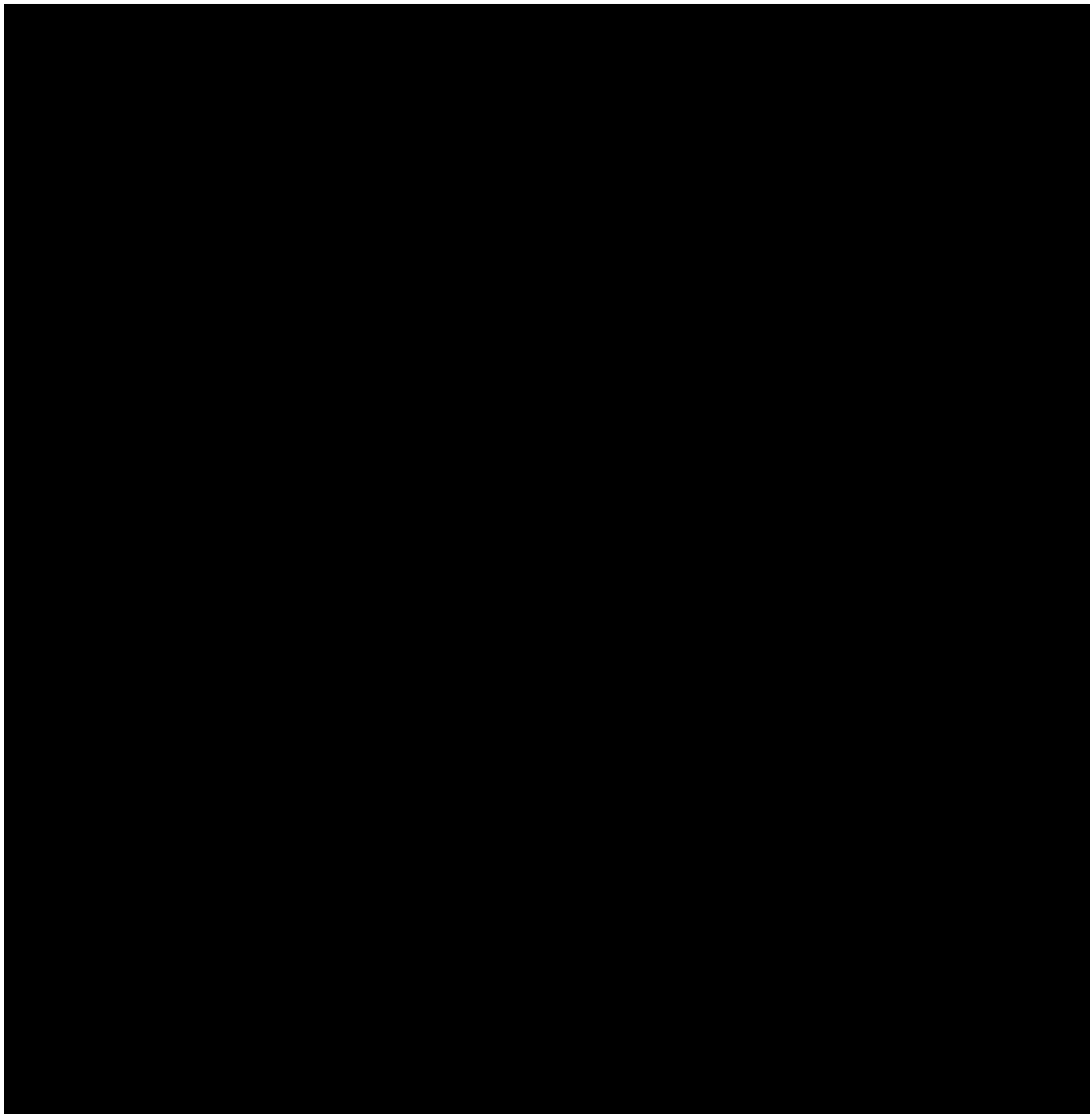
Temporal variability. Temporal variability of AERs has been shown in many studies. For example, AERs varied on both daily and seasonal bases in four nonsmoking households in Boston, MA monitored for one or two 6-day periods in winter and summer.[41] Strong winter/summer differences were shown in Windsor, Ontario homes, as noted earlier.[36] In the three RIOPA cities, AERs in Houston were lower in the summer cooling season (median = 0.37 h^{-1}) compared to winter (0.63 h^{-1}), higher in Los Angeles in summer (1.13 h^{-1}) than in winter (0.61 h^{-1}), and relatively low in spring and similar in heating and cooling seasons in Elizabeth.[37] Based on measurements in many US homes (n=2,844) from 1982-1987, AERs averaged 0.41 ± 0.58 h^{-1} in fall and 1.50 ± 1.53 h^{-1} in summer.[42]

Factors associated with AERs. House and occupant characteristics associated with AERs are shown in Table 2. House AERs were negatively and significantly associated with house size (area and number of bedrooms), the presence of a central air conditioner, indoor CO_2 and VOC concentrations, and the presence of cigarette smokers. AERs were positively associated with recent sweeping and dusting, and indoor PM concentrations. Similar results were found for bedroom AERs with the addition of negative correlations with outdoor wind speed, the number of adults/children in the home, and the presence of dogs/cats. Daily average wind speeds during the sampling period ranged from 1.8 to 5.1 m/s, and wind speed was negatively but not statistically significantly correlated to the house AERs. The lack of significant associations with the meteorological variables may be caused by the weeklong AER measurements, which average over shorter-term fluctuations in these variables, as well as wind and sun sheltering, which diminishes the agreement with airport meteorological data.

The relationships seen with AERs are generally consistent with expectations. For example, CO_2 is an indicator of occupancy and ventilation, and CO_2 levels generally increase with low AERs. Similarly, concentrations of VOCs and other pollutants with indoor emission sources will increase at low AERs. Individuals may open windows and doors when sweeping and dusting, which will increase AERs; these activities are also likely to entrain dust and thus increase PM concentrations. As noted earlier, wind speed and indoor-outdoor temperature differentials are important determinants of AERs.[9, 12] The Detroit data did not include variables reflecting opened windows and doors, which has been associated with AERs in houses in Ohio,[12] California and Virginia,[8] Redwood City and Watsonville, CA,[43] Columbus, OH,[12]

Odense, Denmark,[39] and Boston, MA.[41] Lastly, we show lower AERs in homes with central air conditioning (particularly in summer), which likely reflects closed windows.[44]

Table 2. Association between AERs and house and building/occupant characteristics. Spearman correlation coefficients used for continuous variables, and Kruskal-Wallis tests for categorical variables. Statistically significant associations ($p<0.05$) in bold. PNC = particle number count; CSA = child's sleep area (e.g., bedroom); *C=continuous variable; I = indicator variable; M = multilevel categorical variable.



4.2. Interzonal flows

A seasonal analysis of interzonal flows between the house and bedroom, including proportions α_{HB} and α_{BH}, is shown in Table 3. Overall, 55 ± 18% of the air entering the bedroom came from the house; the balance directly entered the bedroom from outdoors. For the house's main living area, an average of 26 ± 20% of air entered from the child's bedroom; most air entered directly from outdoors. While some variation in these proportions was seen by season, intervention group and the presence of central air conditioning and smokers, differences were not statistically significant.

Table 3. Proportion of interzonal flows in the house and bedroom by season and intervention group.

Outcome	Season	Without filter				With filter				All groups			
		N	Average	SD	Median	N	Average	SD	Median	N	Average	SD	Median
α_{HB}	Spring	20	0.55	0.18	0.60	55	0.53	0.16	0.53	75	0.54	0.17	0.54
	Summer	23	0.57	0.21	0.58	38	0.51	0.19	0.53	61	0.53	0.20	0.53
	Fall	7	0.46	0.25	0.52	42	0.60	0.18	0.62	49	0.58	0.20	0.61
	Winter	11	0.55	0.21	0.58	38	0.54	0.18	0.53	49	0.54	0.18	0.55
	All	61	0.55	0.20	0.58	173	0.55	0.18	0.54	234	0.55	0.18	0.55
	p-value[b]		0.804				0.189				0.525		
α_{BH}	Spring	20	0.30	0.19	0.30	55	0.23	0.17	0.20	75	0.25	0.17	0.22
	Summer	23	0.38	0.28	0.31	38	0.27	0.24	0.21	61	0.31	0.26	0.26
	Fall	7	0.24	0.26	0.24	42	0.24	0.17	0.20	49	0.24	0.18	0.20
	Winter	11	0.21	0.17	0.16	38	0.25	0.15	0.24	49	0.24	0.15	0.22
	All	61	0.31	0.23	0.27	173	0.25	0.18	0.20	234	0.26	0.20	0.22
	p-value[b]		0.249				0.942				0.753		

Bedroom AERs were negatively correlated with α_{HB} (r = -0.36, p <0.001) and α_{BH} (r = -0.30, p <0.001), indicating that tighter homes (low house and bedroom AERs) had relatively more air exchanged between zones. In homes with forced air central air conditioning and heating systems, for example, windows are normally closed and air circulates rapidly throughout the house. Conversely, homes with higher AERs tend to have flows that are decoupled between zones, e.g., local exchange may occur as windows are opened in multiple rooms.

As noted, few measurements of airflows within residences or other buildings are available.[4, 5, 14] Several modeling exercises have been completed. A two zone model for a single-story house in California, which gave reasonable fit between predicted and observed CO concentrations, showed interzonal air flow ratios of 0.976 (α_{BA}, proportion of room A's intake air coming from room B) and 0.614

(α_{AB}, proportion of room B's intake air from room A) after smoking a cigar for 15 min in the kitchen (emission rate of 60 mg/min).[14] This house is not representative of Detroit homes, e.g., AERs were very high (4.0 and 4.6 h^{-1} for the kitchen and living room, respectively), and the two zones had similar volumes (34 and 36 m^3). An aerosol dynamics model using experimental data in a two zone test facility showed interzonal flows from 0.6 to 154 $m^3\ h^{-1}$ for a non-smoking room (31 m^3) to a smoking room (36 m^3), and reverse flows from 1.1 to 163 $m^3\ h^{-1}$, depending on the sealing between rooms, ventilation and filtration system.[4] Again, room volumes and configurations are not comparable to our study. Thus, this is believed to be the first report of interzonal airflows within North American residences. (We have previously reported on flows between attached garages and residences, along with several others.[35]

4.3. Scenario analyses

Model parameters. Table 4 shows statistics of the measured parameters used by the two-zone model. As noted, interzonal flows (Q_3, Q_4) were positively correlated with outdoor airflows (Q_1, Q_2) and house volume, and interzonal flow Q_4 was negatively correlated with bedroom volume and positively correlated with outdoor pollutant concentrations (data not shown).

Table 4. Statistics of house and filter airflows, house and bedroom volumes, and outdoor PM concentrations for the Detroit homes, including number of observations (N), average, standard deviation (SD), median, 25th, 75th and 90th percentile values.

Parameter	Unit	N	Average	SD	25th	Median	75th	90th
Q_1	$m^3\ h^{-1}$	234	242	272	109	179	287	446
Q_2	$m^3\ h^{-1}$	234	43	39	17	31	52	87
Q_3	$m^3\ h^{-1}$	234	57	76	23	41	71	102
Q_4	$m^3\ h^{-1}$	234	84	138	27	54	96	166
Q_{F2}	$m^3\ h^{-1}$	156	456	223	282	499	661	722
V_1	m^3	234	360	137	261	359	434	495
V_2	m^3	234	28	11	22	25	29	36
C_{out}	$\mu g\ m^{-3}$	179	11	4	8	10	14	17

The nominal parameters derived for modeling purposes, intended to be representative of the field data, were as follows. House and bedroom volumes V_1 and V_2 were set to study averages, 360 and 28 m^3, respectively. Airflows Q_1, Q_2, Q_3 and Q_4, scaled to the mean house volume, were 263, 50, 60 and 94 $m^3\ h^{-}$

^{1}, respectively. As described earlier, Q_{F2} was set to 280 m^3 h^{-1}, and C_{out} to 11 µg m^{-3}, $k_{D,1}$ and $k_{D,2}$ to 0.2 h^{-1}, and $k_{P,1}$ and $k_{P,2}$ to 0.5.

Scenario results. Table 5 shows PM concentrations predicted for all scenarios, along with average concentrations measured in bedrooms, both with and without filters, and with and without the detection of ETS. (As mentioned, PM measurements in the living area were unavailable.) Observed concentrations were considerably elevated if smokers were present, and greatly lowered with the filter.[16, 23]

In scenario 1 (emission sources in the living area), the nominal emission rate (10 cigarettes day^{-1}) yielded PM concentrations of 24 and 15 µg m^{-3} in the living area and bedroom, respectively; concentrations in the bedroom dropped greatly, to only 4 µg m^{-3}, when the HEPA filter was used (scenario 1F). This nominal case closely matched the field study results in predicting a 73% reduction of PM levels in the bedroom due to the filter, as compared to the 69 to 80% measured.[16] However, predicted PM concentrations were low compared to measurements. Observed concentrations were matched by adjusting the emission rate. When ETS was detected in the homes, this required 33.5 cigarettes day^{-1} if the filter was not present (to attain 39 µg m^{-3} in the bedroom), and 85 cigarettes day^{-1} with a filter (to attain 25 µg m^{-3}). Especially the latter cigarette consumption rate seems unreasonably high, and these two scenarios produced correspondingly high PM predictions in the living area (71 and 172 µg m^{-3}). Most likely, some smoking and other PM emissions occur in or near the bedroom (e.g., dust from bedding, resuspension, and exfoliated skin), which was not modeled in this scenario (emissions were assumed to occur in only the living area). When ETS was not present, PM emission rates equivalent to 21.5 and 37.5 cigarette day^{-1} matched concentrations measured in the bedrooms without and with the filter, respectively (27 and 12 µg m^{-3}). Like the results just discussed, the scenario does not consider other sources.

Table 5. Average concentrations observed in homes and results of scenario analyses, including adjustment of emission rates to match observed concentrations. C_1 and C_2 are concentrations in living room (LA) and bedrooms (BR), respectively.

Case or Scenario	Condition	Emission Rate		No Filter		With Filter (F)	
				C_1 (LA)	C_2 (BR)	C_1 (LA)	C_2 (BR)
		(cig/day)	($mg\ h^{-1}$)	($\mu g\ m^{-3}$)	($\mu g\ m^{-3}$)	($\mu g\ m^{-3}$)	($\mu g\ m^{-3}$)
Observed	Houses with ETS	-	-	-	39	-	25
	Houses without ETS	-	-	-	27	-	12
Scenario 1 Source in Living Area	Nominal rate	10.0	7.5	24	15	22	4
	Match to ETS without filter	33.5	25.1	71	**39**	64	10
	Match to ETS with filter	85.0	63.8	172	92	157	**25**
	Match to non-ETS without filter	21.5	16.1	47	**27**	43	7
	Match to non-ETS with filter	37.5	28.1	78	43	72	**12**
Scenario 2 Source in Bedroom	Nominal rate	10.0	7.5	20	78	8	21
	Match to ETS without filter	4.7	3.5	12	**39**	6	10
	Match to ETS with filter	12.0	9.0	24	93	9	**25**
	Match to non-ETS without filter	3.0	2.3	9	**27**	5	7
	Match to non-ETS with filter	5.5	-	13	45	6	**12**
Scenario 3	No indoor sources	-	-	4	5	4	1

Scenario 2, where indoor emissions occur in only the bedroom, yielded considerably different results. For this case, the nominal emission rate (10 cigarettes day^{-1}) without a filter produces 78 and 20 $\mu g\ m^{-3}$ in the bedroom and living area, respectively, and 21 and 8 $\mu g\ m^{-3}$ with the filter. The bedroom concentration can become quite elevated due to this room's small volume (despite its relatively rapid AER), and the relatively small fraction of air from the bedroom to the rest of the house limits concentrations in other living areas. Again, the HEPA filter provides good control of PM in the bedroom, reducing concentrations by 74%, and also in the rest of the house (which was not seen in scenario 1). Matching observed concentrations with ETS detection required 4.7 cigarettes day^{-1} without the filter, and 12 cigarettes day^{-1} with the filter. When ETS was not detected, emission rates equivalent to 3 and 5.5 cigarette day^{-1} matched concentrations observed without and with the filter, respectively. Compared to smoking in the living area (scenario 1), much lower emission rates in the bedroom are needed match observed concentrations.

Without indoor emission sources, scenario 3 shows that infiltration of outdoor PM gives living area and bedroom concentrations that are similar and low, 4 and 5 $\mu g\ m^{-3}$, respectively, without the filter. The

bedroom concentration is minimal (1 μg m^{-3}) with the filter (scenario 3F). The $PM_{2.5}$ infiltration factors in scenario 3 were 0.36 and 0.45 in the living area and bedroom, respectively (i.e., indoor/outdoor concentration, or [4 μg m^3]/[11 μg m^3] in the living area). The $PM_{2.5}$ infiltration factor measured in other Detroit homes in DEARS was 0.70 ± 0.33, which included homes with and without indoor sources.[34] Since indoor sources increase infiltration factors, and given the limitations of the two zone IAQ model and the use of several literature values in this study (i.e., no model fitting), the modeled infiltration factors are reasonable.

The actual emission rates, air flows and other factors affecting PM levels in the study homes almost certainly differed from the modeled scenarios, thus explaining some of the results and apparent discrepancies in Table 5. In particular, the specific emission rates and source locations are unknown, emissions likely occur in both spaces simultaneously, most model parameters will vary in time, literature values of some parameters may not apply, and the considerable variation in house configurations may be simulated only approximately using mean or representative values. Further, some differences were noted in house parameters where ETS was detected, e.g., the volumes of these houses and bedrooms (V_1 = 329 ± 132 m^3; V_2 = 24 ± 5 m^3; n=49) were significantly smaller than those without ETS detection (V_1 = 368 ± 138 m^3, V_2 = 29 ± 12 m^3; n=185, p=0.026; p=0.014, Mann-Whitney test). (No other differences were noted.) These and other factors can help explain why different emission rates are needed with and without the filter to match observed levels.

Notably, most of the modeled scenarios show strong gradients of PM concentrations in the house. For strong emission sources in (only) the living area, concentrations in the bedroom are lower than those in the living area by 43 to 47% without a filter, and by 83 to 84% with a filter (scenarios 1 and 1F). For strong emission sources in (only) the bedroom, concentrations in the bedroom are higher by 65 to 74% without the filter, and by 31 to 65% with the filter (scenarios 2 and 2F). These differences occur as a result of limited exchange to the remainder of the house and the strong emission source that boosts levels well above that due to the penetration of (contaminated) outdoor air. In all scenarios, the HEPA filter substantially lowers concentrations in the bedroom. Moreover, the filter substantially lowers living area concentrations if emissions occur primarily in the bedroom (scenario 2F). Without indoor sources, levels in the bedroom slightly exceed those in the living area, a result of relatively greater penetration and exchange rates in the bedroom. Thus, the high AERs in bedrooms can be important for exposure estimation purposes given the substantial fraction of time people spend in bedrooms. Of course, all results depend on the choice of model parameters, which is analyzed next.

4.4. Sensitivity analyses

The relative sensitivity (RS) of each model parameter for six scenarios is shown in Table 6. As expected, high sensitivity (RS=0.54 to 0.94) is shown for indoor emission rates E_1 and E_2, and, for example, doubling E_1 will increase concentrations by about 82% in the living area and 69% in the bedroom. In this case, results do not depend whether or not a filter is present. PM levels in the bedroom (C_2) were sensitive to air filter use (RS = -0.68), as noted earlier.

Table 6. Relative sensitivity of model parameters on predicted concentrations in living area (LR) and bedroom (BR) for six scenarios (scenario number in parentheses).
Absolute values greater than 0.40 are shown in bold.

Para-meter	Units	Emissions in Living Area				Emissions in Bedroom				No Indoor Emissions			
		No Filter (1)		W/Filter (1F)		No Filter (2)		W/Filter (2F)		No Filter (3)		W/Filter (3F)	
		LA	BR	LA	BR	LA	BR	LA	BR	LA	BR	LA	BR
E_1	$\mu g\ h^{-1}$	**0.82**	**0.69**	**0.83**	**0.69**	-	-	-	-	-	-	-	-
E_2	$\mu g\ h^{-1}$	-	-	-	-	**0.78**	**0.94**	**0.54**	**0.94**	-	-	-	-
Q_1	$m^3\ h^{-1}$	**-0.50**	**-0.42**	**-0.45**	-0.37	**-0.47**	-0.06	-0.18	-0.01	0.16	0.08	0.30	0.13
Q_2	$m^3\ h^{-1}$	-0.04	-0.29	0.00	0.05	-0.36	**-0.43**	-0.05	-0.09	0.02	0.08	0.03	**0.44**
Q_3	$m^3\ h^{-1}$	0.05	0.35	0.03	**0.69**	-0.35	**-0.41**	-0.06	-0.10	-0.01	-0.03	0.02	0.30
Q_4	$m^3\ h^{-1}$	-0.09	-0.08	-0.18	-0.15	**0.69**	0.09	0.36	0.02	0.01	0.01	-0.15	-0.06
$C_{out}k_{P,1}$	$\mu g\ m^{-3}$	0.16	0.13	0.16	0.13	0.19	0.03	**0.44**	0.03	**0.87**	**0.42**	**0.96**	**0.42**
$C_{out}k_{P,2}$	$\mu g\ m^{-3}$	0.02	0.18	0.01	0.18	0.03	0.03	0.02	0.03	0.13	**0.58**	0.04	**0.58**
$k_{D,1}$	h^{-1}	-0.19	-0.16	-0.17	-0.14	-0.19	-0.03	-0.17	-0.01	-0.19	-0.09	-0.17	-0.08
$k_{D,2}$	h^{-1}	-0.01	-0.05	0.00	-0.01	-0.05	-0.05	-0.01	-0.01	-0.01	-0.05	0.00	-0.01
V_1	m^3	-0.19	-0.16	-0.17	-0.14	-0.19	-0.03	-0.17	-0.01	-0.19	-0.09	-0.17	-0.08
V_2	m^3	-0.01	-0.05	0.00	-0.01	-0.05	-0.05	-0.01	-0.01	-0.01	-0.06	0.00	-0.02
$\eta_{F2}Q_{F2}$	$m^3\ h^{-1}$	-	-	-0.03	**-0.68**	-	-	-0.39	**-0.68**	-	-	-0.05	**-0.68**

In Scenario 1, PM concentrations in the bedroom were sensitive to interzonal flow Q_3 (living area to bedroom), especially if a filter was present (RS = 0.69 and 0.35, with and without filter, respectively). PM concentrations were relatively unaffected by deposition rate ($k_{D,2}$) and bedroom volume (V_2). In Scenario 3 where outdoor pollutants were the only PM source, outdoor airflows Q_1 and Q_2 were key variables, especially in the bedroom with filter use, and particle penetration factor $k_{P,1}$ and outdoor PM concentration C_{out} became among the most sensitive parameters (especially in the living area). The

influence of $k_{P,2}$ and C_{out} was considerably lower, a result of the much larger volume of the living area compared to the bedroom.

As noted, the importance of interzonal flows Q_3 and Q_4 depended on the scenario. Low interzonal flows will impede transfers between zones, however, exposure to ETS will likely occur throughout a house even if smoking is restricted to one room.[45] While some degree of isolation and lower ETS exposure can be attained by closing doors and opening windows in the room containing smokers,[14] the typical house design and HVAC configuration in the US can quickly deliver pollutants throughout a house.[2] Thus, isolation is incomplete and this strategy has limited effectiveness. The simple two zone models allow easy evaluation of such strategies.

The key result from sensitivity analyses is identification of those model parameters that strongly affect results. Results of the two zone model show that among the many parameters, emission rates, air flows and air filter use significantly affect pollutant levels, and thus it is important to obtain the most accurate data for these parameters to accurately model concentrations and exposures in homes. These results also demonstrate that with strong and localized sources like cigarettes, or with the use of a free-standing air filter, the assumption that the house is fully-mixed will not yield accurate results for either the smoker in the main living area or an individual in a bedroom.

5. Strengths and limitations

This is believed to be the first report of air flows between bedrooms and general living areas in North American homes, and one of the few reports quantifying AERs in bedrooms. (The few European studies that have measured these parameters have only limited applicability to US and Canadian homes.) AERs and interzonal flows are critical parameters for understanding the effect of localized pollutant sources and pollutant control strategies, such as the degree of isolation that might be accomplished by restricting smoking to a particular area. For exposure purposes, bedrooms are important given the amount of time individuals spend sleeping at home. The reported AERs and air flow data were collected from a large sample of occupied houses and reflect seasonal factors, and the influence of house and other characteristics were identified. The sensitivity analysis modeled a variety of emission scenarios, each with and without a PM filter. This resulting information is useful to understand the levels and variation of exposure that might result, which is especially important in exposure and risk assessment applications of vulnerable populations such as children with asthma who may be exposed to ETS. In fact, our concern regarding such exposures was the basis for selecting the study homes, and the results show that a substantial fraction of children with asthma are exposed to ETS at home.

The study has limitations with respect to information on PM emissions and occupant activities that might affect AERs and PM levels, e.g., amount and location of smoking, filter use patterns, and opening of windows and doors. PM concentrations in the living area of homes and outside homes were not

measured, and the time- and space-averaged value used in the modeling does not reflect the variation expected. Literature values of PM penetration rates also may not apply. The measurements and models are based on steady-state assumptions, and short term fluctuations will be missed. The study homes were mostly single family homes that were smaller and older than US averages, and some results appear unlikely to represent conditions for other building types and climatic regimes. Additionally, the reported parameters and model results may not reflect actual conditions if the governing parameters dramatically change over the day or week. The modeling considered only two zones (more may be needed) and, as noted earlier, neither considered PM removal by forced air systems nor the many PM sources found indoors other than ETS (or an equivalent source) isolated to a single zone. Any measurement bias between the two PM methods (central-site and home-indoors) can increase the uncertainty. The use of averaged parameters in the sensitivity analysis also has limitations, e.g., the results may not reflect conditions that diverge greatly from the nominal case used. Finally, the sensitivity analysis does not incorporate the correlation among the parameters, although this is not expected to alter results.

6. Conclusions

This paper presents results and analyses of a large survey in Detroit, Michigan investigating air exchange rates (AERs) and interzonal flows, two important factors relevant to indoor air quality (IAQ), as well as energy and comfort. In the houses' living area, air exchange rates (AERs) averaged 0.73 ± 0.76 h^{-1} (median = 0.57 h^{-1}, n=263). In the child's bedroom in each house, AERs were substantially higher, averaging 1.66 ± 1.50 h^{-1} (median = 1.23 h^{-1}, n=253). Seasonal trends of the house and bedroom AERs differed. AERs were either positively or negatively correlated with house size, the presence of a central air conditioner and smokers, indoor CO_2, VOC and PM concentrations. Interzonal air flows were measured, and their proportion of the total flow tended to increase as AERs decreased. Scenario and sensitivity analyses using a two zone simulation model identified the key factors affecting pollution levels, which included the emission source strength, location, presence of an operating air filter, AERs and interzonal air flows; secondary factors were PM penetration factors, deposition rates and house and room volumes. The fully-mixed assumption applied only for homes without localized indoor emission sources or that did not use room air filters; otherwise, we conclude that spatial gradients of concentrations of pollutants like PM can be significant in residences. The results in this paper can inform the development of strategies designed to improve air quality, and can be used to estimate concentrations and exposures needed for epidemiology and risk assessment purposes.

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