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Impact of placement of portable air cleaning devices in multizone residential environments

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ABSTRACT

An advantage of portable air cleaners is that they can be positioned in different parts of a building and used where air cleaning is needed. This makes them a popular choice for use in residential buildings. In typical indoor particle modeling efforts, perfect air mixing and uniform contaminant concentration distribution are assumed. However, nonuniform spatial concentrations of particles are more reflective of most environments. Using experiments to validate computational fluid dynamic and particle tracking models and applying these models in numerical based parametric analysis, this paper analyzes the overall contaminant removal in a multi-room residential building. Simulations varied (1) particle size (0.74, 3.4 and 10 μm), (2) clean air delivery rate (CADR) of the air cleaner (50 m^3/h and 500 m^3/h), and (3) position of portable air cleaner in different rooms. The results show very large variation of the overall particle removal for different positions of portable cleaning device. In extreme cases, the effective positioning of cleaning device can result in a factor of 2.5 change in overall particle removal and, consequently, strongly affect occupant exposure to particles.

1. Introduction

Portable air cleaners are popular air cleaning devices that are used in 10–30% of American homes [1,2]. There are numerous technologies used in such devices including ion generators, electrostatic precipitators, and HEPA filters. Air cleaning devices are often rated with a clean air delivery rate (CADR) which is particle-size dependent and is the product of the flow rate and efficiency. CADRs range from near zero to over 700 m^3/h depending on the model and particle size being considered. Ion generators are typically at the low end of this range, and HEPA filters and some electrostatic precipitators are at the high end of this range [3–6]. In order to put CADR in context, Miller-Leiden et al. [7] proposed the air cleaner effectiveness, H, which ranges from 0 for an air cleaner that has no impact on indoor concentrations to one for a perfectly effective air cleaner that removes all particles. H is dependent on the CADR, the volume of the space, and on other particle removal mechanisms such as deposition and exfiltration [2]. Although there are no standards for effectiveness, 0.8 is considered a minimum by some in the industry [2]. Ward et al. [8] modeled effectiveness values of 0.5–0.8 for a HEPA filter for 0.1–2 μm particles in a residence. They also report that increasing the air exchange rate decreases the effectiveness of an air cleaner. Waring et al. [6] predict effectiveness values of approximately 0.5 for ultrafine particles for an ion generator in a 50 m^3 room. The effectiveness decreased to 0.1–0.2 when the entire house is considered. Similar H values for a HEPA filter and electrostatic precipitator are predicted to be 0.8–0.9 for the room and 0.4–0.6 for the whole house.

While this earlier work has helped to characterize and evaluate different air cleaning technologies, most of the modeling investigations assume well-mixed indoor spaces. Some investigations have varied air cleaner placement within a room as well as varied the level of mixing [3] and have generally found small changes in performance. Many residential spaces are not well-mixed and instead consist of rooms that often have different concentrations of pollutants and complex airflow patterns between them. Furthermore, infiltration and exfiltration of particles are not uniformly distributed in a typical home which can also contribute to spatially varying concentrations. The goal of this paper is to assess the effect of portable air cleaner CADR and location on overall particle concentrations in a residence. The specific research objectives are to characterize the effectiveness of high- and low-CADR air cleaners in different locations in a residential building, explore the magnitude of different mechanisms for particle removal in each scenario

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(i.e., exfiltration, deposition on surfaces, removal by the air cleaner), and assess the reduction in occupant exposure to particles.

2. Methodology

In this study we used a combination of experimental measurements and computer simulations to assess particle concentrations in a residence with a portable air cleaner. Considering the challenges associated with modeling of temporal and spatial nonuniform particle distribution, the experimental measurements may seem to be a more appropriate method. However, for comparison of indoor air quality with different properties and positions of portable air cleaning devices, multiple experiments need to be conducted for the same environmental boundary conditions. These include infiltration rate and thermal boundaries in the residence. These parameters can be controlled in the laboratory environment, but for a residence in a house exposed to outdoor environment, they vary significantly due to stochastic nature of external weather conditions. Therefore, we selected computer modeling based on computational fluid dynamics (CFD) for airflow field calculation and Lagrangian particle tracking for computation of particle distribution in space. Importantly, this type of analysis enables perfect repeatability of external boundary conditions that affect infiltration and temperature field. Also, CFD combined with particle tracking enables detailed analysis of the particle distribution and fate in a multizone residence considering the effects that portable air cleaner has on nonuniform particle concentration in the space and on particle transport between rooms through the open doors.

Accuracy of computer simulation depends on many modeling parameters, and in this study experimental data were used for adjustment of several simulation parameters and for validation of overall accuracy of applied numerical models. A previously developed set of particle dynamics tests in a room-sized environmental chamber [9] was used to select basic numerical parameters including turbulence model, computation grid size, particle turbulence diffusion parameters, particle deposition calculations, time step for particle tracking and particle source properties. To test these models, additional validation experiments were conducted in a full-scale multizone home. By measuring airflows parameters and spatial and temporal particle concentration for well defined boundary conditions, validation data were collected. The next section provides details about the models and the full-scale experimental validation.

3. Modeling of particle distribution in the residence with a portable air cleaner

To analyze the portable air cleaner effectiveness positioned at various locations in a residential building, we selected two common types of portable air cleaners with considerably different CADRs: AC a is an ion generator with a high efficiency (100%) for all particle sizes but a low flow rate and CADR of 50 m^3/h; AC b is a HEPA filter with a similarly high efficiency (100%) but with a much higher flow rate and CADR of 500 m^3/h. The performance of these two cleaners is analyzed in each of the three characteristic locations in the house. We considered different particle sizes (0.74, 3.2 and 10 μm) to take into account the effect of particle properties and different likely sources. A total of 21 simulations were completed (2 air cleaners × 3 room locations × 3 particle sizes = 18 + 3 baseline simulations with no air cleaner).

For the analysis we used the UTest house, shown schematically in Fig. 1. This three-bedroom and two-bath manufactured home is located in Austin, TX, and has a floor area of 110 m^2 and a volume of 250 m^3. The heating ventilation and air-conditioning (HVAC) systems in the home were turned off for all simulations and measurements. In the simulations, infiltration through the cracks and openings in the facades provided 0.5 air changes per hour. The wind direction determined the position of infiltration and exfiltration spots on the building envelope (Fig. 1b). In the computational model the two windward facades were positively pressurized, which generated infiltration through the cracks. In the model these cracks were distributed around the windows in Rooms 2 and 3 (Fig. 1b). The negative pressure on the two leeward sides generated exfiltration from Bathroom 1, Rooms 1, 2 and 4 (Fig. 1b). The flow between the rooms generated inter-room air and particle mixing. The internal wall-surface temperatures were 4 °C higher than external wall-surface temperatures, which created realistic buoyancy driven flow in the house [10]. This flow created air and particle mixing through the doors between the rooms. Beside buoyancy, this flow was also affected by air infiltration and by operation of the air cleaner.

In order to assess air cleaner performance with a variety of sources, including a burst of particles caused by human activity such as cooking [11,12] or vacuuming [13], we considered two sources. The infiltration of outdoor air provided steady source of outdoor particles, and an initial burst injection of particles in the kitchen area of Room 2 (Internal particle source in Fig. 1b) provided an instantaneous increase of particle concentration. This burst of internal particles generated nine times higher concentration in this area of the house than in the rest of the house. Due to this kitchen particle source, at the initial time step, the average concentration in the house was 1.4 times higher than concentration of particles penetrating into the house through the cracks. After the burst emission of particles in the kitchen area, the portable air cleaner was energized and particle concentrations in various rooms were calculated over a 2 h period. Also, the number of exfiltrated, deposited and filtered particles was recorded in order to better understand the fate of particles in each scenario.

To analyze the portable air cleaner effectiveness we studied concentration fields in the house with and without air cleaners. In the case when the portable cleaner was present, it was positioned: (1) in Room 2, the central largest space that had the highest initial concentration because of the kitchen source, (2) in Room 3 that was, considering general airflow, upstream from this central space and, (3) in Room 1 that was downstream from the central space.

The CFD parameters used included: 197,080 grid points with cells size from 0.05 to 0.12 m and a k–ε RNG turbulence model in the Reynolds-averaged Navier–Stokes Equations. As convergence criteria residuals of mass, momentum, and temperature were used in combination with an overall energy balance. For particle tracking an initial concentration of 206,000 particles was used in each simulation. The initial particle number was selected to be large enough to provide a statistically significant number of particles in each room of the house, considering particle losses and gains (infiltration, deposition, exfiltration and filtration). The air infiltration and the thermal boundary conditions that affect the flow filed in the house were assumed to be constant during the analyzed period of time (2 h), and therefore steady-state airflow model was used with unsteady-state particle tracking. Since a coarse CFD mesh at wall and ceiling surfaces, such as the one used in this analysis, could cause unrealistically large deposition [9], the particle boundary conditions at ceiling and walls were adjusted to be reflective, allowing deposition only on floor surfaces. A sensitivity analysis of calculation time step for particle tracking, conducted as the part of the validation efforts, suggested that the calculation of the velocity and particle concentration field for every 3 s provided a reasonable balance between accuracy and computational time.

Several metrics are used to assess the performance of the two air cleaners and their placement within a room. The first is effectiveness, H, which was defined by Miller-Leiden et al. [7] as:

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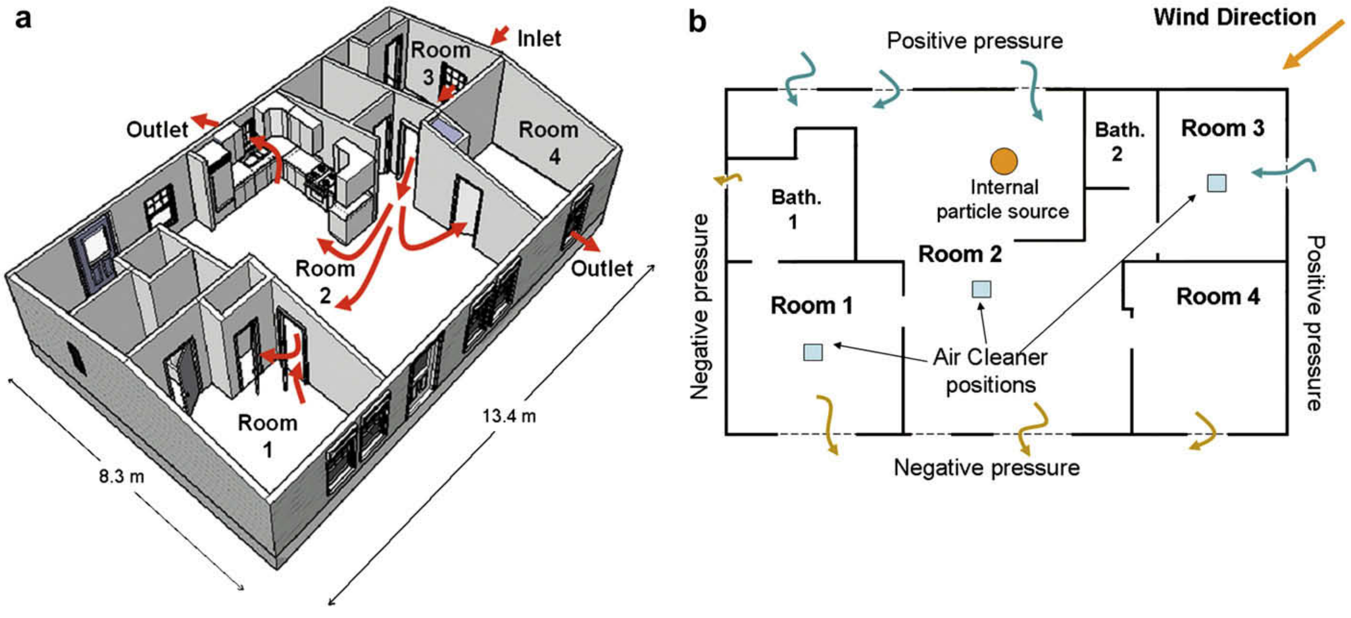

Fig. 1. Isometric and plan view of UTest house used for research; (a) shows a schematic of airflow in the CFD validation tests and (b) shows internal particle source position, air and particle infiltration/exfiltration patterns and positions of a portable cleaner in simulation models.

$$H = 1 - \frac{C_{ac}}{C_{no\ ac}} \qquad (1)$$

where C_{ac} is the whole-house average particle concentration with an operating air cleaner and $C_{no\ ac}$ is the concentration without an operating air cleaner. In addition to effectiveness, we also characterize the indoor to outdoor concentration ratio of particles. In order to further explore differences in H and the concentration ratios, we also calculate the fate of particles for the different air cleaner and location scenarios. To evaluate the effect of air cleaner positioned at different locations, we used cumulative occupant exposure reductions calculated by integration of H over the simulation period. Furthermore, we compared the cumulative occupant exposure reduction obtained in analysis that considers nonuniform particle distribution in the house with the exposure reduction in the case of perfect mixing in the whole house. This comparison shows the impact of nonuniform particle distribution on cleaner performance. Each of these metrics are particle-size dependent and results are calculated for a matrix of three particle sizes (0.74, 3.2, and 10 μm), two air cleaners (AC a with CADR = 50 m^3/h and AC b with CADR = 500 m^3/h), and three air cleaner locations (Room 1 = master bedroom, Room 2 = kitchen/dining room/central space, and Room 3 = bedroom).

4. Validation of simulations

To generate known flow boundary condition for validation test, the house air-conditioning system was off and the infiltration flow rate was controlled by two calibrated fans (Energy Conservatory Duct Blasters) and one airflow station (Ebtron GTA 116). Positioning the calibrated fans in the windows of the house provided approximately 2 air changes per hour (ACH) of ventilation flow. This ACH was selected as the solution that provides flow rate that is significantly larger than infiltration rate of the UTest house, but low enough to enable buoyancy driven air and particle transport in the house. The first calibrated fan was connected to the window in Room 3 (Fig. 1a), controlling the supply amount of outdoor air to 520 m^3/h. The calibrated fan was exhausting 260 m^3/h through the window in Room 2 (Fig. 1). The remaining amount of supply air (260 m^3/h) was exhausted through the window of Room 4 (Fig. 1b); the flow station positioned in this window monitored if the balance between inflow and outflow was achieved. Also, the temperature of internal surfaces including walls, floor, ceiling and windows were measured together with the inlet and outlet air temperatures to provide thermal boundary conditions for the validation test.

Since the Lagrangian particle modeling depends largely on the velocity field, the validation test also provided data for testing the CFD results. Age of air distribution in the house depends very much on airflow filed, and it was used as the validation parameters for CFD calculation of velocity field. To measure age of air, the decay of CO_2, used as the tracer gas, was monitored at 6 positions in the house (GE Telaire 7001). Before the start of the particle tracking experiment, the uniform injection of CO_2 increased the concentration in the house to the level that was uniform and one order of magnitude above the background level. With the start of experiments the age of air was measured by recording CO_2 decay rate at the center of Rooms 1, 2, 3 and 4 and Bathrooms 1 and 2 (Fig. 1b) according to ASHRAE Standard 129 [14]. Comparison of simulated and measured age of air distribution in the house was used to adjust the CFD modeling parameters such as thermal boundary conditions and computational grid.

To generate nonuniform spatial and temporal particle distribution, particles were injected in the inlet stream of air by burning incense at the intake of the duct blaster positioned in the window of Room 3. This particle source was active for 11 min, and it generated a large quantity of particles over a range of 0.3 μm (the lower size limit of the particle counter) to 3 μm with a concentration that was an order of magnitude higher than the initial (background) particle concentration in the house. For the particle distribution and concentration measurement four optical particle counters (TSI Aerotrak) were used. Measurement of particle concentrations in the particle-size range of 0.3–1.2 μm at the inlet in Room 3, two outlets (in Rooms 2 and 4), and in the middle of Room 1, provided information about movement of particle cloud through the house and the particle concentration decay rates. This measurement was conducted over a 60 min period, which was long

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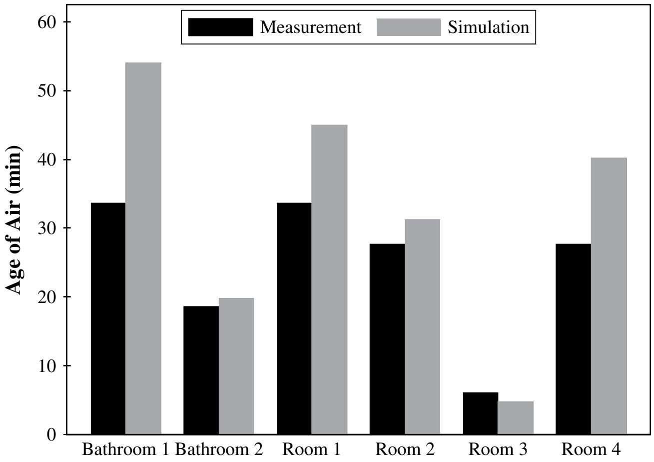

Fig. 2. Comparison of measured and simulated age of air distribution in the simulation validation experiments.

enough to record decay of concentration at most measuring points to the background level. In the particle tracking validation model, particles with the size of 0.74 μm (a median size of particles from incense burning) were injected in the inlet air, and comparison of simulated and measured values of particle concentrations in Room 1 and at the two outlets enabled testing of this component of the simulations.

5. Results and discussion

The study results are organized first to show the validation of CFD and particle tracking models and then the major results from the portable air cleaner performance analysis.

5.1. CFD and particle tracking validation

Fig. 2 shows the airflow field validation results. It compares CFD results and measured values for the age of air calculated and measured at the center of the six spaces (two bathrooms and four rooms in Fig. 1). Age of air depends on the air mixing in the space caused by either forced convective flow due to the momentum of supply air, or by the buoyancy flow due to surface-air temperature difference. The results in Fig. 2 show that CFD captured the overall age of air distribution in the house, but generally predicted higher values for age of air than measured values. For rooms that are further away from the supply in Room 3 (Bathroom 1, Room 1, and Room 4) the difference in measured and calculated values exceed 20%, which is the uncertainty of age of air measurement in this experiment. It appears that air mixing between Room 2 and Room 1 and between Room 2 and Room 4, predicted by CFD, is slightly smaller than measured. The most probable reason for this is the difference in the buoyancy driven air mixing between the simulation and experiment caused by inaccuracy of both measured and simulated thermal boundary conditions. The other possible reason for faster measured decay rate of CO_2 in Rooms 2 and 4 is the localized infiltration of outdoor air and exfiltration of indoor air through the cracks located in these rooms. Overall, considering the accuracy of experimental data, size of the house and complexity of the flow in this heavily partitioned space with multiple outlets, the flow validation test demonstrates accuracy that is sufficient for comparative analysis of flow field with different portable air cleaners.

Fig. 3 shows the results of measured and simulated temporal and spatial particle concentration distributions for the validation case. Since the particles were injected in the supply air of Room 3 by burning incense, the particle source intensity was not uniform. Initially, the incense sticks emitted most particles and in time emission decayed gradually as the incense sticks burned out (Fig. 3a). Monitoring of particle concentration in inlet air provided data about particle source intensity, and this data were used for characterization of particle source in the simulation model. Since the initial particle concentration at the inlet in Room 3 was the highest in the whole house, all results presented in Fig. 3 are normalized by the initial inlet particle concentration.

Fig. 3a compares the measured and simulated particle concentrations at outlets in Rooms 2 and 4. The results show that CFD provides the same peak concentration at both outlets as the measurements, with slight time delays for the maximum value. At the outlet in Room 2, the delay is 3 min and at the outlet in Room 4, the delay is 5 min. A possible reason for these minor delays could be due to inaccuracies in the flow field, such as the smaller air mixing between the rooms detected in the age of air validation test. Another possibility is inaccuracy in the particle diffusion calculations based on the CFD turbulence model. In general, the results in Fig. 3a demonstrate that particle tracking can reasonably predict the particle concentration and dynamics of particle clouds driven by the airflow in the space.

Fig. 3b shows the measured and simulated particle concentration in Room 1 (Fig. 1b) which is also the most challenging particle tracking validation case. In the validation case Room 1 is not connected to any outlet and there is no airflow to the outdoor environment through this room. Therefore, excluding very small

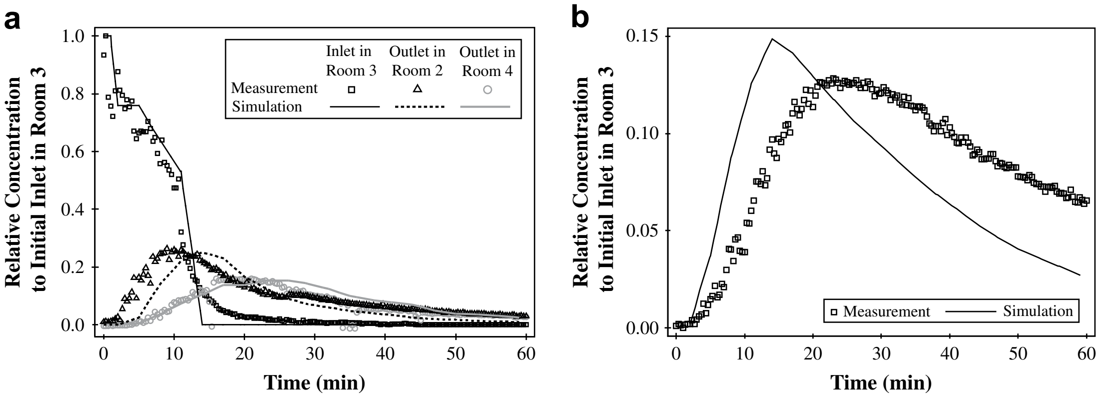

Fig. 3. Validation results for the applied particle tracking modeling method (a) particle concentration at the inlet and the two outlets (b) particle concentration at the center of Room 1.

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Table 1
Airflow distribution between rooms in the residence.

Net air volume flow rate [m^3/h]	No AC	AC a (CADR = 50 m^3/h)			AC b (CADR = 500 m^3/h)		
		AC in Room 1	AC in Room 2	AC in Room 3	AC in Room 1	AC in Room 2	AC in Room 3
From Room 1 to Bath. 1	16	16	14	13	7	12	15
From Room 2 to Room 1	58	48	60	48	2	71	56
From Room 2 to Room 4	18	17	3	13	34	35	15
From Room 2 to Bath. 2	0	0	0	0	0	0	0
From Room 3 to Room 2	30	30	30	30	30	30	30

deposition losses (smaller than 1%), most of the particles get in and out from this room through the doors in-between Rooms 1 and 2 and Room 1 and Bathroom 1. Since the airflow between these rooms is mostly slow buoyancy driven flow, particle diffusion has large effect on particle dynamics.

The results presented in Fig. 3b show a good agreement of measured and simulated peak particle concentration with the relatively small discrepancy in the temporal concentration distribution. The CFD and particle tracking modeling predicted a peak concentration 8 min earlier than the measurements and also a faster particle decay at the central area of Room 1. This contradicts to the age of air validation results which indicate that CFD predicted lower intensity of air mixing in the Room 1. The possible reason for early peak particle concentration predicted by CFD and particle tracking is (1) the inaccurate prediction of airflow turbulence that affects the particle diffusion, or (2) the coarse time step used in the particle tracking model.

Validation results presented in Fig. 3 indicate that with appropriate boundary conditions the simulation parameters, such as turbulence model, CFD mesh, number of particles, and calculation time step, can be adjusted to achieve sufficiently accurate prediction of particle dynamics in the large simulation domain such as the whole residential house. Some discrepancy in the temporal scale between measured and simulated values is apparent. However, this has a small effect on air cleaner effectiveness because it is present in all simulations, both with and without air cleaner. Therefore, the validation results suggest that adequate accuracy needed for the comparative analysis is achieved.

5.2. *Performance of portable air cleaners*

For seven indoor airflow cases (2 air cleaners × 3 room locations + one additional baseline case with no air cleaner) particle concentration distributions were calculated for three particle sizes considering the particle distribution in each rooms and whole house. The following sections provide only the most important results and are intended to illustrate: (1) the effects that air cleaners have on airflow field in the whole house, (2) air cleaner effectiveness, (3) particle loss mechanisms, and (4) effects that portable cleaner placement has on occupant exposure reduction.

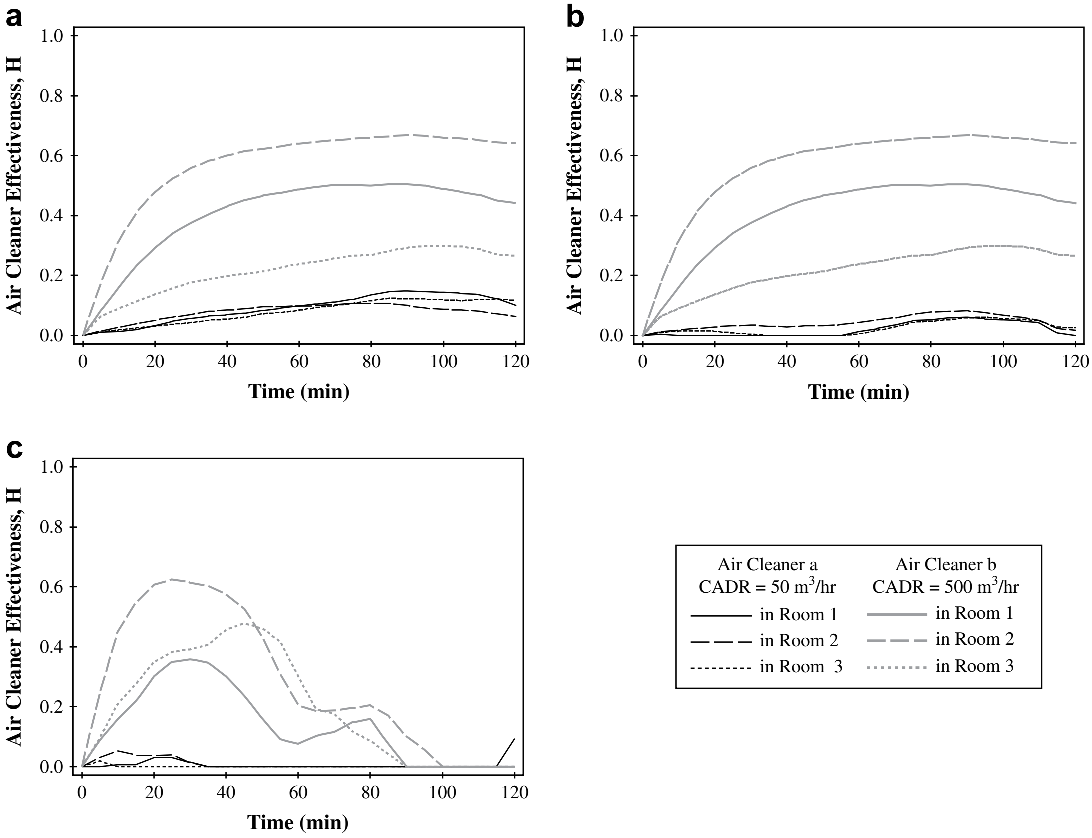

Fig. 4. Air cleaner effectiveness, *H*, as a function of time for different CADRs and room placements for (a) 0.74 μm particles, (b) 3.2 μm particles, and (c) 10 μm particles.

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5.2.1. *Airflow with different air cleaner properties and positions*

Table 1 shows the effect that the two analyzed air cleaners (AC a with CADR = 50 m^3/h and AC b with CADR = 500 m^3/h) have on net airflow between the rooms caused by the air cleaner. The results show that even the small airflow rate of 50 m^3/h associated with AC a can have a significant impact on overall airflow pattern in the space. For example, the addition of AC a in Room 2 causes the net flow from Room 2 to Room 4 to drop from 18 to 3 m^3/h. The addition of the forced convective flow from the AC a slightly increases the mixing in the space. However, it redistributes the pressure field not only in the room with air cleaner but also in the surrounding rooms causing change in the net flow between rooms. The impact of AC b, which has a much larger flow rate of 500 m^3/h, is even larger. This large flow rate increases significantly the mixing not only in the space with air cleaner but also in surrounding rooms. Table 1 shows that the large momentum discharge jet from AC b has significant impact on the overall airflow in the house regardless of position. Overall, the results suggest that portable air cleaners, particularly units with high flow rates, can alter contaminant transport between zones in a building.

5.2.2. *Air cleaner effectiveness*

Air cleaner effectiveness, H, as defined in Eq. (1), as a function of time is shown in Fig. 4. For all three particle sizes, the effectiveness for AC a is less than 15% and is not strongly dependent on air cleaner location. As it is shown in the following section related to the particle loss mechanisms, the CADR of this air cleaner is too small to compete with other removal mechanisms including loss by deposition and removal by exfiltration. This is consistent with the findings of others that a low-CADR air cleaner, such as an ion generator, does not have a high effectiveness in typical indoor environments. [2,3,6]. The higher CADR air cleaner, AC b, has an effectiveness value that is strongly dependent on particle-size, location, and time. For 0.74 and 3.2 μm particles the effectiveness increases to a steady-state value of 0.6–0.7 if the air cleaner is located near the source of particles in Room 2, 0.4–0.5 if the air cleaner is downstream of the source in Room 1, and approximately 0.2 if the air cleaner is upstream of the source in Room 3. This range of effectiveness values highlights the importance of air cleaner placement near sources. For 10 μm particles, effectiveness is a strong function of time for AC b. Each placement of the air cleaner reaches a maximum value (0.62 in Room 2, 0.45 in Room 3, and 0.38 in Room 1) within the first hour of operation and then declines to zero effectiveness in the second hour. These lower effectiveness are due to the fact that 10 μm particles have a much larger settling velocity and this deposition loss eventually dominates particle removal [2]. When most of the large particles are deposited, the air cleaner effectiveness is very low because the concentration of particles in the air with and without cleaners are similar and both are very low. For these larger particles, air cleaner placement is important for effectiveness, but only in the short term. A larger conclusion is that CADR is much less important for steady-state removal of larger particles because these particles are already removed by other mechanisms.

Fig. 5 shows the indoor to outdoor concentration ratios as a function of time. The results reinforce the findings of Fig. 4. Specifically, AC a has too low CADR for placement to matter for any particle size; it has a steady-state concentration ratio of just above 1 for 0.74 μm particles, 0.9 for 3.2 μm particles, and just above 0 for

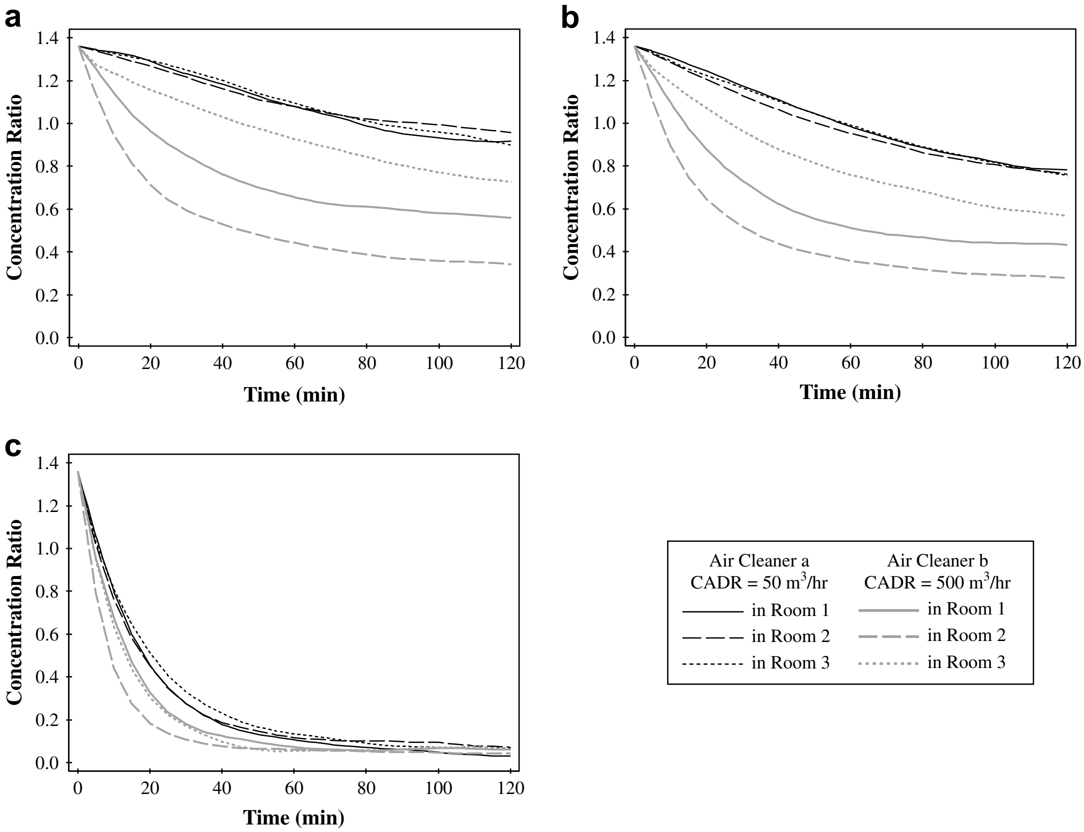

Fig. 5. Indoor/outdoor concentration ratios as a function of time for different CADRs and room placements for (a) 0.74 μm particles, (b) 3.2 μm particles, and (c) 10 μm particles.

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10 μm particles. This air cleaner has a minimal effect on the steady-state indoor/outdoor concentration ratio, which is consistent with its low effectiveness. For the larger CADR air cleaner, AC b, location matters in the same manner as for effectiveness for all particle sizes, with striking differences for different placements for 0.74 and 3.2 μm particles and very small differences for 10 μm particles. Similar to the results in Fig. 4, air cleaner CADR matters considerably for smaller particles and is much less important for larger particles, which have much larger removal by deposition.

5.2.3. *Loss mechanisms for particles*

Fig. 6 illustrates the different effects that each air cleaner has on different loss mechanisms when positioned in the central space in the house (Room 2 in Fig. 1). The difference in the number of particles in the air is primarily due to the number captured by the air cleaner. In general, the plots with AC a (the second column in Fig. 6) look very similar to the cases with no air cleaner (first column) indicating that the air cleaner captures relatively few particles. Because of the large flow rate and air mixing in the space, AC b (CADR = 500 m^3/h) removes most of the particles from the central space in the house during the first 20 min of operation. After that, the rate of particle removal by this air cleaner is steady, and the rate of change in particle concentration depends on the rate of infiltration of external particles to central space and particle transport from other rooms to this space. AC a (CADR 50 m^3/h) removes five times less particles than AC b, and it needs a considerably longer time to achieve a steady-state concentration in the space.

In addition to general differences between the air cleaners, there are also important differences based on particle size. For AC a, exfiltration (0.74 μm particles) and deposition plus exfiltration (0.32 and 10 μm particles) remove 4–10 times more particles than the air cleaner, further indication that a low-CADR air cleaner cannot compete with other removal mechanisms. For AC b, more 0.74 and 3.2 μm particles are removed by the air cleaner than by deposition or exfiltration. However, for 10 μm particles, over three times as many particles are removed by deposition than by the air cleaner. Commensurate with their settling velocities, very few 0.74 μm particles settle, slightly more 3.2 μm particles, and considerably more 10 μm particles. The 3.2 μm and, especially, the 10 μm particles are much more likely to be resuspended by human activities [15,16]. Such resuspended particles would be much more likely to be removed by AC b than AC a.

5.2.4. *Cumulative occupant exposure reduction*

The influence of air cleaner type and position on cumulative occupant exposure reduction is presented in Fig. 7 for all characteristic particle sizes. Results show the cumulative exposure reduction that is based on the average concentrations for the whole house. These results are the most relevant for an occupant who spends time in different part of the residence and therefore gets

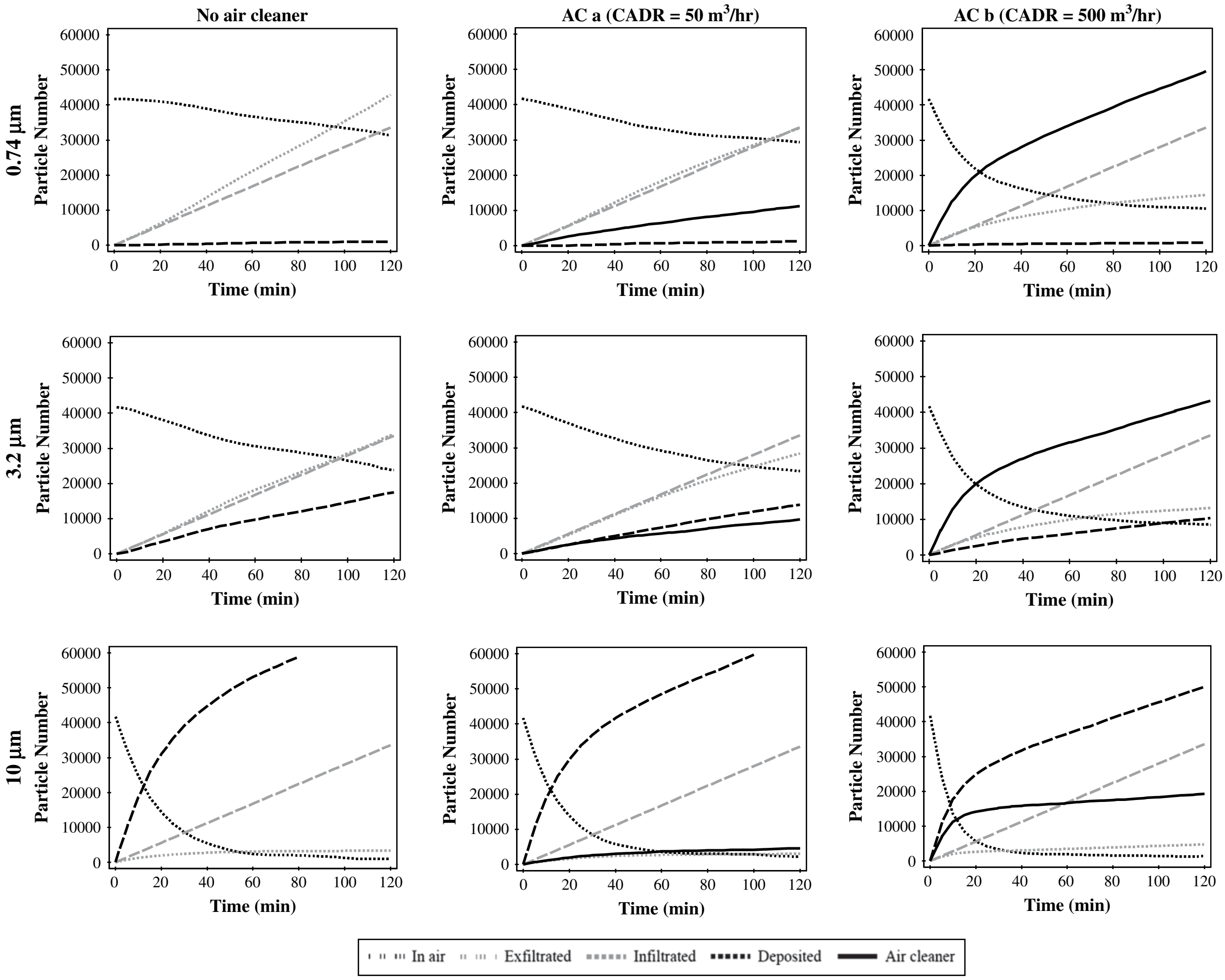

Fig. 6. Fate of particles of different sizes and for both air cleaners when positioned in Room 2.

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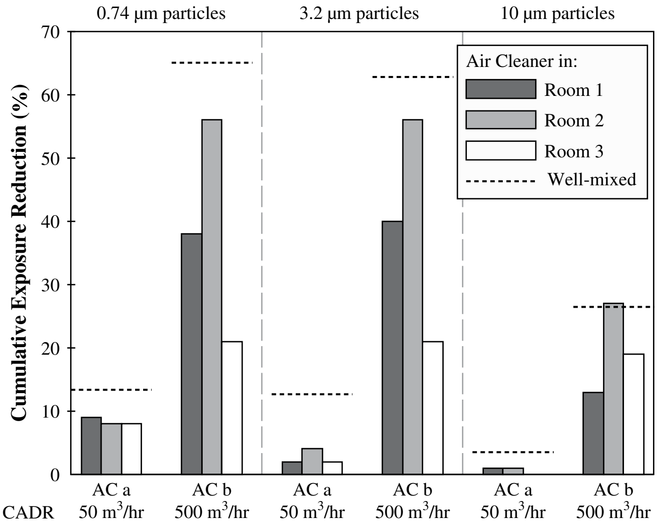

Fig. 7. Simulated cumulative exposure reductions for different air cleaner types and locations.

exposed to an average concentration. The results clearly indicate superiority of AC b with the large CADR when the reduction of overall concentration in the house is considered, and show that air cleaner with a small CADR cannot be used as a whole-house air cleaner. Also, the results show that 0.74 and 3.2 μm particles have similar cumulative exposure reductions due to the fact that the supply jet momentum from AC b creates large air velocities and increases air mixing in the house. The large velocities readily transport both the 0.74 and 3.2 μm particles, and consequently, these particles have similar spatial and temporal distributions in the house. Similar to the air cleaner effectiveness, the largest cumulative exposure reduction is for the case when AC b is positioned in the central space of the house nearest to the source.

Dotted lines in Fig. 7 show the cumulative exposure reductions calculated with the assumption of perfect mixing in the whole house. For these calculations, particle deposition was adjusted to be the same in the cases with (1) perfect mixing and (2) realistic airflow in the house. The differences in the cumulative exposure reduction are primarily due to the nonuniformity of the particle concentration field. Results show that the assumption of perfect mixing causes considerable overestimation of the benefit of portable air cleaners. This can be explained by the lower concentration of the particles in the vicinity of the portable air cleaner than further away in the case with realistic airflow. Results in Fig. 7 show that for the small portable air cleaner (AC a) this overestimation of benefits with perfect mixing assumption is relatively larger than for the large air cleaner (AC b). The flow rate and air jet from AC b causes more air mixing and cumulative exposure reduction is generally more similar to the one with the perfect mixing.

When analyzing air and particle distribution in a space with an operating HVAC system that provides more than four ACH in the space, the assumption of the perfect mixing and uniform distribution of particles becomes more accurate [9]. Therefore, comparison of cumulative exposure reduction calculated for the whole house with perfect mixing and realistic airflow (Fig. 7) can also represent the difference in exposure with filtration integrated with HVAC system and portable air cleaners (both with the same CADR). Considering just exposure reduction in this context, filtration integrated with HVAC system seems to be more beneficial. However, to provide perfect mixing, the HVAC system will need flow rate that is significantly larger than the 500 m^3/h delivered by AC b. Therefore, a strategy with a portable air cleaner with large CADR positioned in the central area of the residence and/or close to the particle source may be a reasonable compromise between operation costs and exposure-reduction benefits.

6. Conclusions

The results show that overall air cleaning effectiveness depends very much on the CADR of the portable air cleaning device. The air cleaner with large CADR of 500 m^3/h (AC b) has a 2–10 times greater effectiveness than AC a, which has an order of magnitude smaller CADR. AC a has a maximum effectiveness of less than 15%. For both air cleaners, placement of the air cleaner has a strong impact on airflow within and between the rooms. The effect of placement on effectiveness for AC b ranges over a factor of approximately four for 0.74 and 3.2 μm particles and a factor of 1.6 for 10 μm particles. The smaller CADR air cleaner cannot compete with particle removal by exfiltration and deposition for all particle sizes and hence has a small impact on indoor concentrations. The larger CADR air cleaner has a much larger impact on indoor concentrations, but this impact is more limited for 10 μm particles at steady-state as most of these particles are already removed by deposition. When compared to no air cleaner, the smaller CADR air cleaner will reduce occupant exposure by 1–10% depending on placement on particle size. The larger CADR air cleaner reduces exposure by 14–56% with much larger absolute differences due to placement and particle size. The well-mixed assumption overstates the exposure reduction by as much as factor of two indicating that caution should be used when using this assumption in typical residential environments. The results suggest that portable air cleaners can be an effective way of reducing particle exposure in residences and that air cleaner CADR and room placement are important factors in overall effectiveness.

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