

Effective positioning of portable air cleaning devices in multizone residential buildings

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SUMMARY

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, the use of portable air cleaners in buildings with open doors and particle circulation between rooms can cause nonuniform spatial concentrations. Using validated computational fluid dynamic simulations, 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 $\text{m}^3 \text{hr}^{-1}$ and 500 $\text{m}^3 \text{hr}^{-1}$), and (3) position of portable air cleaner. The results show very large variation of the overall particle removal (by deposition, exfiltration, and filtration) for different positions of portable cleaning device. In extreme cases, the effective positioning of cleaning device can result in a dramatic change in overall particle removal.

KEYWORDS

Portable air cleaner, Human exposure, Residential building, Particle transport, Modeling

INTRODUCTION

Portable air cleaners are popular air cleaning devices that are used in 10 – 30% of American homes (CARB, 2007; Shaughnessy and Sextro, 2006). 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 500 $\text{m}^3 \text{hr}^{-1}$ 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 at the high end of this range (e.g., Offermann et al., 1985; Shaughnessy et al. 1994; Mullen et al., 2005; Waring et al., 2008). In order to put CADR in context, Miller-Leiden et al. (1996) 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, but also on other particle removal mechanisms such as deposition and exfiltration (Shaughnessy and Sextro, 2006). Ward et al. (2005) model effectiveness values of 0.5 to 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. (2008) predict effectiveness values of approximately 0.5 for ultrafine particles for an ion generator in a 50 m^3 room. The effectiveness decreases 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 work assumes well mixed indoor spaces. Many residential spaces are not well-mixed and instead consist of rooms that have complex air flows between them. Furthermore, infiltration and exfiltration of particles are not necessarily uniformly distributed in a typical home which can contribute to non-uniform concentrations. The goal of this paper is to use a computation fluid dynamics (CFD) model to assess the effect of portable air cleaner CADR and location on overall and room 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 mechanism for particle removal in each scenario (i.e., exfiltration, deposition on surfaces, removal by the air cleaner), and assess the reduction in particulate exposure that would be expected from the position and use of air cleaners.

METHODS

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: 1) AC1 is a HEPA filter with ion generator with high efficiency (100%) and high flow rate and CADR of 500 m³/h and 2) an ion generator (AC2) with a similarly high efficiency (100%) and a much lower flow rate and CADR of 50 m³/h. The performance of these two filters is analyzed in each of three characteristic locations in the house. Three different particle (0.74, 3 and 10 μm) sizes were considered to take into account effect of particle properties and likely sources on the distribution in the space. A total of 19 simulations were completed (2 air cleaners × 3 room locations × 3 particle sizes = 18 + 1 baseline simulation with no air cleaner).

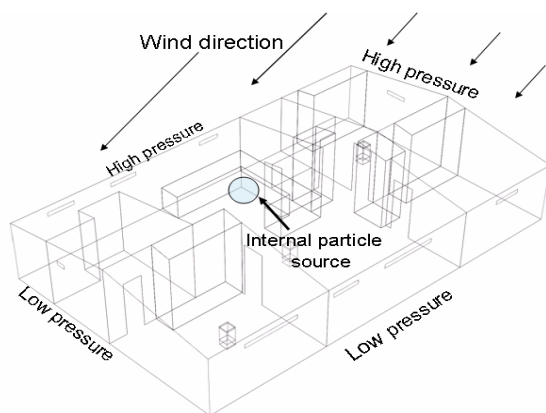


Figure 1. Geometry of test house and wind direction that creates infiltration of 0.5 ACH.

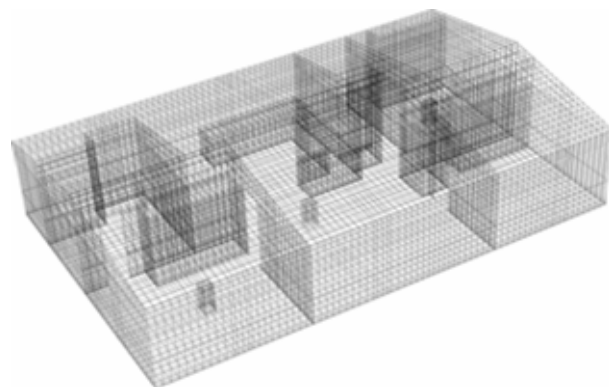


Figure 2. CFD model of residential house for airflow and particle distribution calculation.

For the analysis we used geometry and boundary conditions of the UTest House which has 3 bedrooms and 2 baths (Figure 1). The floor area and volume of the house are 110 m² and 250 m³ respectively, and for the analyzed period of time, we assumed no HVAC operation. The infiltration through the cracks and openings in the facades provided 0.5 air changes in the house transporting particles between indoor and outdoor environment. The wind direction determined the position of infiltration and exfiltration spots on the building envelope (Figure 1). In addition to the air flow generated by infiltration, the open doors between rooms and nonuniform temperature of building surfaces created the airflow that mixed the air in the house and transported the particles between rooms. To analyze unsteady state concentration distribution in the space, an initial burst injection of particles in the kitchen provided

instantaneous increase of concentration of particles in this area of the house, which was nine times higher than concentration in the rest of the house. Due to the kitchen particle source, at 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.

To analyze the portable air cleaner effectiveness we studied concentration field in the house with and without air cleaners. For obtaining valid data for evaluation of portable air cleaner performances in the environment such as a house with multiple zones, particle concentration distribution in the whole house is needed. Also, for analysis of air cleaner performance with an unsteady state source, such as a burst of particles caused by human activity (e.g., cooking or vacuuming), we need the temporal distribution of the particle concentration field. We selected particle tracking model for calculating the spatial and temporal particle concentration distribution in the house. This numerical modelling of particle dynamics was based on the air velocity field calculated by computational fluid dynamic (CFD). This simulation-based analysis allowed us to study different portable air cleaner performance for identical boundary conditions such as infiltration of outdoor air, particle source intensity, and temperature field. To develop a reliable numerical simulation models we conducted a set of experimental validation tests in the room size environmental chamber (Rim and Novoselac, 2008). Using these tests particle tracking parameters were adjusted for modelling of particle dynamics in indoor environment.

Figure 2 presents the CFD model of the test house used in this analysis and Figure 3 illustrates major airflow between rooms obtained by this model. The internal wall-surface temperatures were 4°C higher than external wall-surface temperatures, which created realistic buoyancy driven flow in the house (Novoselac et al., 2006). This flow created air mixing through the doors between the rooms. Portable air cleaners were positioned: a) in the central largest space that had the highest initial concentration because of the kitchen source (ACa in Figure 3); b) in the room that was, considering general airflow, upstream from this central space (ACb in Room 3); and c) in the room that was downstream from central space with major particle source (ACc in Room 1). After the burst emission of particles in the kitchen area (Figures 1 and 3), the portable air cleaner was energized and particle concentrations in various rooms were calculated over the period of 2 hours. Also, the number of exfiltrated, deposited and filtered particles was recorded during the two-hour period of simulation. The CFD and particle tracking models calculated the velocity and concentration field for every 3 seconds of the analyzed period. In order to have a statistically significant number of particles in each room of the house, considering particle losses and gains (infiltration, deposition, exfiltration and filtration), the total number of initial particles in the house for each simulation was 210,000.

The performance of filters is evaluated considering the number of particles 1) in the whole house and 2) in the room with the air cleaner. To quantify the performance of the portable air cleaner in specific environment (airflow and particle concentration) the air cleaner effectiveness

$H = 1 - (C_{\text{with_cleaner}} / C_{\text{without_cleaner}})$ is used as defined by Miller-Leiden et al. (1996).

The concentration of particles in the house without an operating air cleaner, $C_{\text{without_cleaner}}$, is calculated for the same initial and boundary conditions, but the effects of the air cleaner on the velocity and pressure field and particle concentration in the space are excluded. Furthermore, 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.

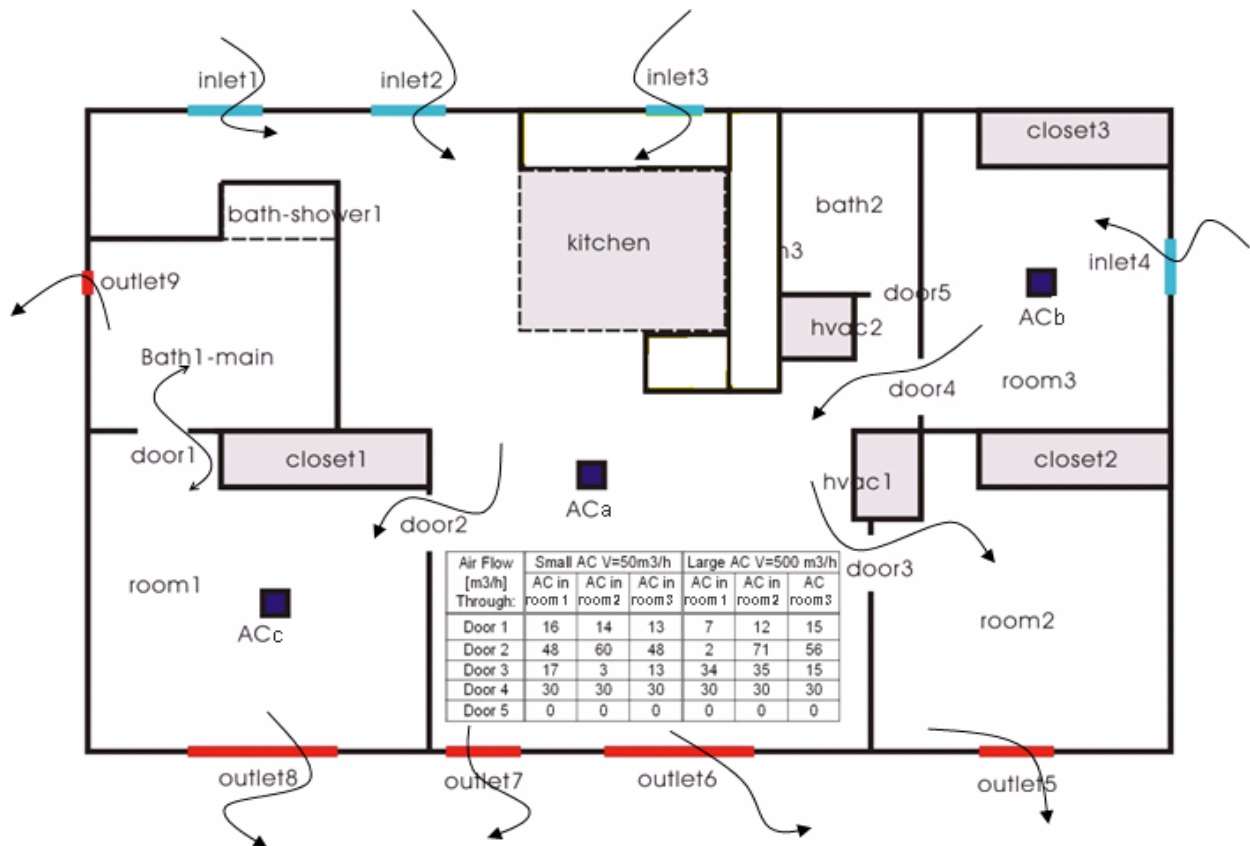


Figure 3. Floor plan of test house with airflow in the house for various position of air cleaners (Values in the table present flow between room for ACs positioned in room 1, 2, or 3).

RESULTS AND DISCUSSION

The two analyzed types of portable air cleaners have considerably different CADRs, due to the difference in air flow rates. The flow rate affects not only CADR but also the interzonal air flows and particle distributions in the space. For example, the air cleaner (AC1) with 500 m³/h flow rate has approximately 10 times larger discharge velocity and almost a hundred times larger momentum than AC2 (50 m³/h air flow rate). The large momentum of the air jet affects velocity and pressure distributions in the space. The table in Figure 3 illustrates the effect that air cleaner type and position have on the airflow distribution with the overall air flow through some doors unaffected (i.e., Doors 4 and 5) and others greatly affected (Doors 2 and 3).

Influence of position of portable air cleaner

Figure 4 shows the effects that positions of air cleaners have on the effectiveness, H . The right axis of each plot shows the indoor average concentration of particles normalized with the concentration of particles in infiltrated (outdoor) air. Figures 4c and 4d show that AC2 with the 50 m³/h flow rate has small air cleaner effectiveness for ultrafine particles (0.74 μm). Furthermore, AC2 has negligible effect on the removal of large particles (10 μm) in the whole house, because it can not effectively compete with other removal mechanisms for larger particles. Figure 4b shows that for AC2, the overall number of particles in the house does not depend on the cleaner location. With the low-CADR of AC2, the reduction of $C_{\text{indoor}}/C_{\text{outdoor}}$ in the house is primarily due to deposition or exfiltration, depending on the particle size.

Figure 4a shows that for the larger CADR of AC1 and smaller particles ($0.74 \mu\text{m}$), the position of the air cleaner has significant influence on overall air cleaning in the house. The air cleaner effectiveness H can vary more than a factor of two when AC1 is located in different rooms. The results show the best performance when the air cleaner is positioned in the central space of the house (ACa in Figure 3), which is also a room with the largest initial concentration because of the source in the kitchen. Similar results are obtained for $3.4 \mu\text{m}$ particles. For the large particles ($10 \mu\text{m}$), H with AC1 varies from 0.3 to 0.6 due to the air cleaner location (Figure 4b). For large particles the air cleaning effectiveness drops after 30 minutes due to the effect of deposition of large particles. When most of the large particles are deposited, the air cleaner effectiveness is very low because the concentration of particles in the space with and without cleaners is the same (i.e., very low).

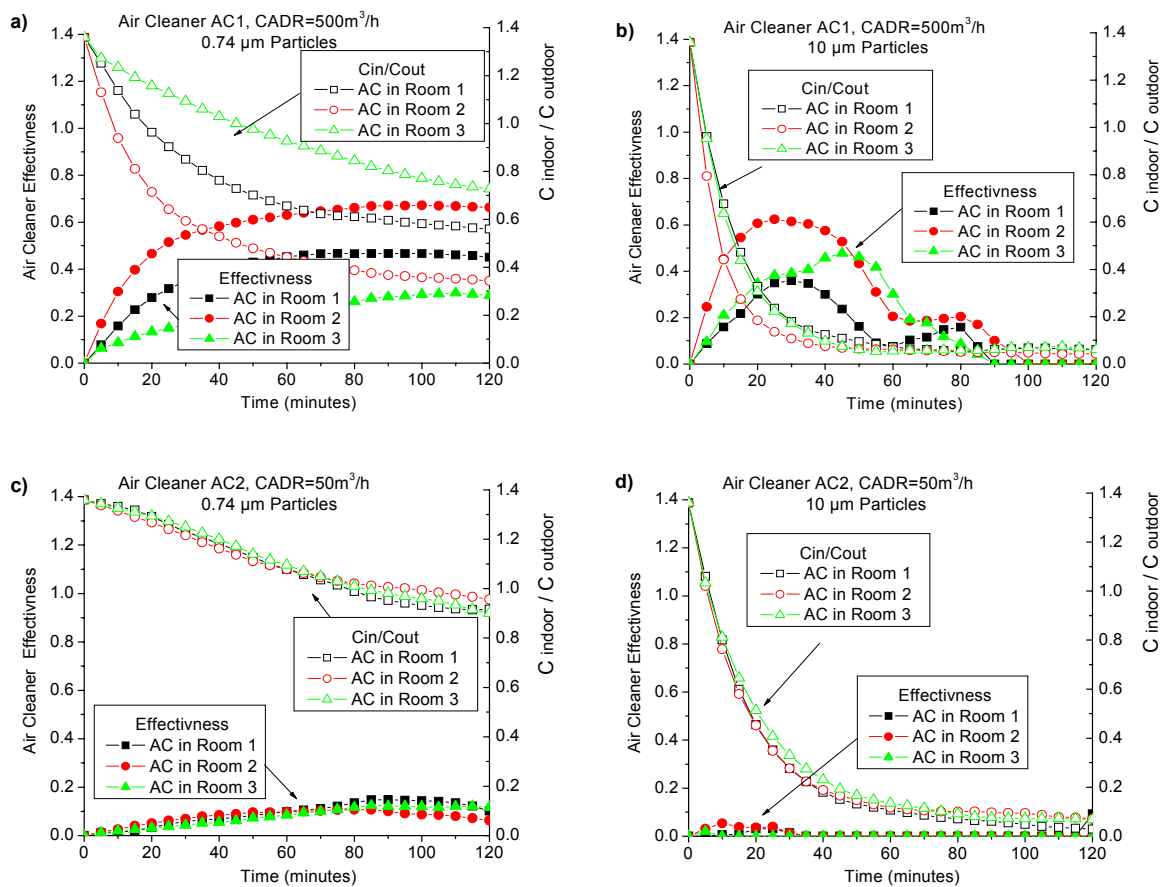


Figure 4. Effect of AC locations on air cleaning effectiveness for particles ultrafine and large particles (AC Effectiveness $H = 1 - C_{\text{with cleaner}} / C_{\text{without cleaner}}$ is defined for the average concentration in the house).

Loss mechanisms for particles

Figure 5 illustrates the different effects that each air cleaner has when positioned in the central space in the house (ACa in Figure 3), on different loss mechanisms for $3.4 \mu\text{m}$ particles. The difference in the number of particles in the air in the whole house for the two filter types is primarily due to the number of filtered particles. Because of the large flow rate and air mixing in the space, AC1 (CADR = $500 \text{ m}^3/\text{h}$) removes most of the particles from the central space in the house during the first 20 minutes of operation. After that, the rate of particle removal by this filter is steady (Figure 5a), 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. Considering the whole house, the AC2 (CADR 50m³/h) removes five times less particles than AC1, and it needs a considerably longer time to achieve a steady-state concentration in the space.

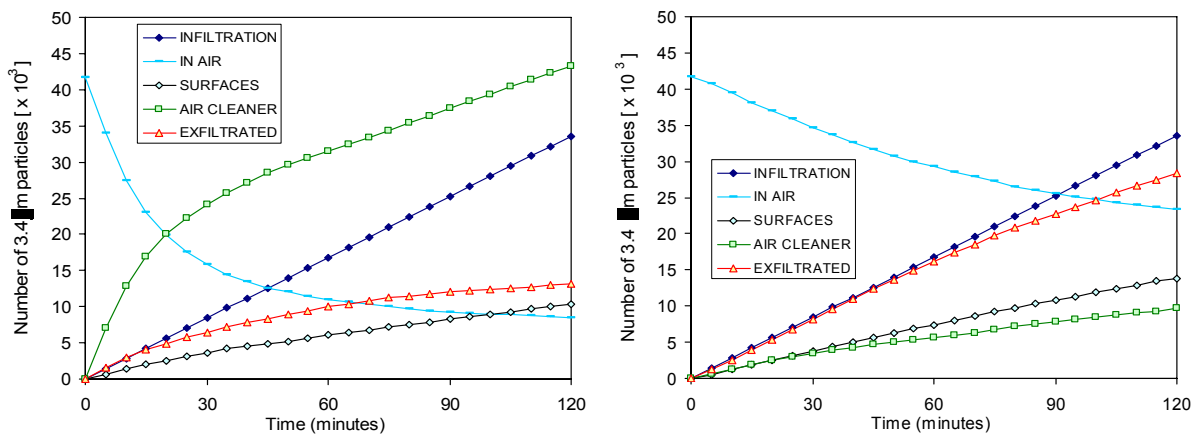
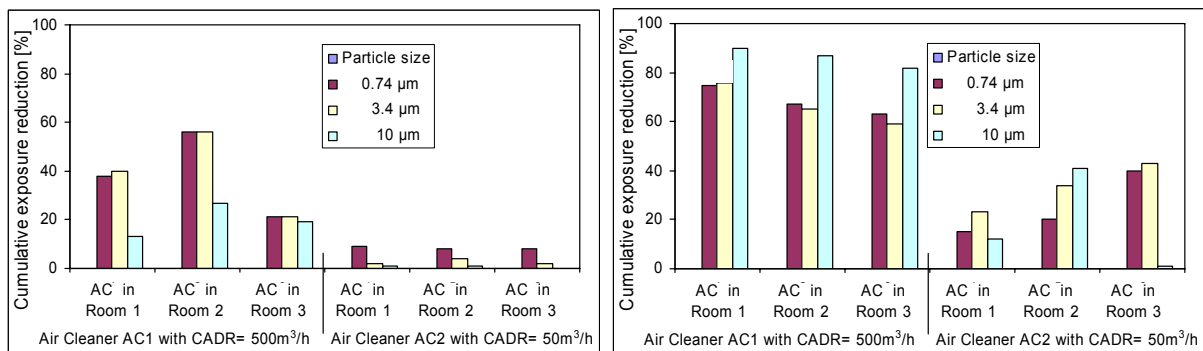


Figure 5. Filtered, deposited and exfiltrated number of particles in the whole house for cleaners with different CADRs when the air cleaner is in the central space of the house (ACa in Figure 3).

Cumulative occupant exposure reduction

The influence of air cleaner type and position on cumulative occupant exposure reduction is presented in Figure 6 for all characteristic particle sizes. Figure 6a shows the cumulative exposure reduction that is based on the average concentrations for the whole house. This information is relevant for exposure analysis of an occupant who occupies several different rooms and therefore gets exposed to an average concentration. The results presents in Figure 6a clearly indicate superiority of AC1 with the large CADR when the reduction of overall concentration in the house is considered. 0.74 and 3.2 μm particles have similar cumulative exposure reductions due to the fact that supply jet momentum from AC1 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 distribution in the house. Similar to the air cleaner effectiveness, the largest cumulative exposure reduction is for the case when the AC1 is positioned the central space of the house.



a) Reduction defined for the whole house

b) Reduction defined for the room with AC

Figure 6. Cumulative exposure reductions for different AC types and AC locations in the house.

Figure 6b shows the cumulative exposure reduction in the room with the air cleaner. Due to the small room volumes and imperfect mixing of air between the rooms, the cumulative exposure reduction is much higher in the room with the air cleaner than in the whole house.

For the air cleaner with high CADR the cumulative exposure reduction is high (60-90%) due to the large airflow circulation in the relatively small spaces. The results on Figure 6b also show that unlike for the whole house, the air cleaner with small CADR (AC2) reduces exposure in the room by as much as 40%. Depending on the position of the filter in the house, the cumulative exposure reduction ranges from 15% to 50% for 0.74 μm and 3.4 μm particles. These results are encouraging for the use of low-CADR air cleaners in similarly small rooms, however, some low-CADR air cleaners, such as ion generators, emit ozone and such emissions are particularly problematic in small rooms (e.g., Mullen et al., 2005; Waring et al., 2008).

CONCLUSIONS

The results show that overall air cleaning effectiveness, defined for the whole house, depends very much on the CADR of the portable air cleaning device. The air cleaner with the ten times larger CADR has a 2 – 10 times greater effectiveness; the air cleaner with the smaller CADR has a maximum effectiveness of less than 20%. Also, both the airflow pattern in the house and position of air cleaning device in the house can have very large effects on particle removal. For particles in the range from 0.74 to 3.4 μm , different positions of portable air cleaners can produce difference in the whole house air cleaning effectiveness up to a factor of three. Generally, a good location for a portable air cleaning device is the central space of the house, particularly if there are nearby sources. Unlike for the whole house, the air cleaner with small CADR can reduce exposure in a room, although, for ion generators, such benefit will also come with increased exposure to ozone or other byproducts of the air cleaning device. For a single residential room the air cleaner with the large CADR had an effectiveness of approximately 60-90% depending on particle size and air cleaner placement, and the smaller air cleaner had an effectiveness of 15-45%. 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.

REFERENCES

- California Air Resources Board 2007. Survey of the Use of Ozone Generating Air Cleaners by the California Public. Principal Investigator: Thomas Piazza. University of California, Berkeley, 05-301.
- Miller-Leiden, S., Lobascio, C., Nazaroff, W.W., Macher, J.M. 1996. Effectiveness of in-room air filtration and dilution ventilation for tuberculosis infection control. *Journal of Air Waste Management Association*, 46, 869-882.
- Mullen, N., Yu, X., Zhao, P., Corsi, R.L., Siegel, J.A. 2005. Experimental characterization of portable ion generators. *Indoor Air 2005: Proceedings of the 10th International Conference on IAQ and Climate*, pp. 2957-2961.
- Novoselac, A., Burley J. B., and Srebric J. 2006. Development of New and Validation of Existing Convection Correlations for Rooms with Displacement Ventilation Systems. *Energy and Buildings*, 38 (3), 163-173.
- Offermann, F.J., Sextro, R.G., Fisk, W.J., Grimsrud, D.T., Nazaroff, W.W., Nero, A.V., Revzan, K.L., Yater, J. 1985. Control of respirable particles in indoor air with portable air cleaners. *Atmospheric Environment*, 19, 1761-1771.
- Rim, D. and Novoselac, A. 2008. Transport of Particle and Gaseous Pollutants around Human Body under Natural and Forced Convection. Accepted to *ASHRAE Transactions*.
- Shaughnessy, R.J., Levetin, E., Blocker, J., Sublette, K. L. 1994. Effectiveness of portable indoor air cleaners: Sensory testing results. *Indoor Air*, 4, 179-188.
- Shaughnessy, R.J., Sextro, R.G. 2006. What is an effective portable air cleaning device? A review. *Journal of Occupational and Environmental Hygiene*, 3, 169–181.

- Ward M., Siegel JA. and Corsi RL. 2005. "The effectiveness of stand alone air cleaners for shelter-in-place," *Indoor Air*, 15(2), 127-134.
- Waring, M.S., Siegel, J.A., Corsi, R.L. 2008. Ultrafine particle removal and generation by portable air cleaners. Accepted to *Atmospheric Environment*.