Indoor ultrafine particles of outdoor origin: importance of building operating conditions

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DISCLAIMERS

Indoor ultrafine particles of outdoor origin: importance of building operating conditions

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SUMMARY

Airborne ultrafine particles (UFP) have been associated with human mortality and morbidity. Human exposure to ambient UFP occurs indoors due to entry of UFP into buildings. This study investigates UFP infiltration as a function of building operating conditions such as central air distribution fan operation and window position. Experiments were conducted involving continuous monitoring of indoor and outdoor UFP concentrations along with air change rate measurement in a test house. The study results showed that the UFP infiltration varies with particle size, air change rate and central fan operation. Infiltration increases with particle size from 5 nm to 100 nm. Larger window openings lead to higher infiltration factors due to increased air change rates. Smaller values of infiltration factor were observed with the central fan on, which was likely caused by additional particle deposition loss to the furnace filter and duct surfaces.

KEYWORDS

Penetration, deposition, infiltration factor, indoor-outdoor relationship, human exposure

1 INTRODUCTION

Ultrafine particles (UFP, <100 nm in diameter) have been shown to have adverse health effects such as oxidative damage to DNA (Bräuner et al., 2007) and mortality (Stölzel et al., 2007). Their small size allows them to penetrate cells, where they have been found to induce inflammation in the respiratory tract (Oberdörster et al., 2005) and cardiovascular effects (Schulz et al. 2005). Their large surface area compared to their volume may result in their toxic components being more biologically available than for larger particles (Oberdörster et al., 2005). Human exposure to airborne ultrafine particles (UFP) occurs mainly indoors, where people spend almost 90 % of their time (Klepeis et al., 2001). Indoor UFP concentrations are affected both by indoor sources and by infiltration of UFP from outdoors. Major indoor sources include both gas and electric stoves (Dennekamp et al., 2001; Wallace et al., 2008), cigarettes, candles, incense, gas clothes dryers (Wallace, 2005), electric motors in household appliances such as vacuum cleaners and power tools (Szymczak 2007), and heating elements in hair dryers, steam irons, and other common household items. Major outdoor sources include both gasoline and diesel engines (Kittelson et al., 1998), as well as natural atmospheric reactions producing occasional “nucleation bursts” (Gaydos, 2005).

In the absence of indoor sources, the UFP concentrations in buildings are governed by the entry of outdoor air particles via infiltration, natural ventilation and mechanical ventilation. The infiltration factor (F_{inf}) relates equilibrium indoor concentrations to outdoor concentrations in the absence of indoor sources. F_{inf} varies between buildings depending on outdoor conditions and building characteristics. The objective of this study is to investigate F_{inf} as a function of particle size and the building operating conditions, specifically central air distribution fan operation and window position. The study results will help understand the dependence of human exposure to UFP on building operating conditions and the relative importance of indoor and outdoor sources

2. METHODS

Experimental measurements have been conducted in a one-level 340 m^3 manufactured test house (Figure 1). It is partially carpeted and minimally furnished. Indoor activities were avoided by conducting the measurements during weekends, when the house was unoccupied.

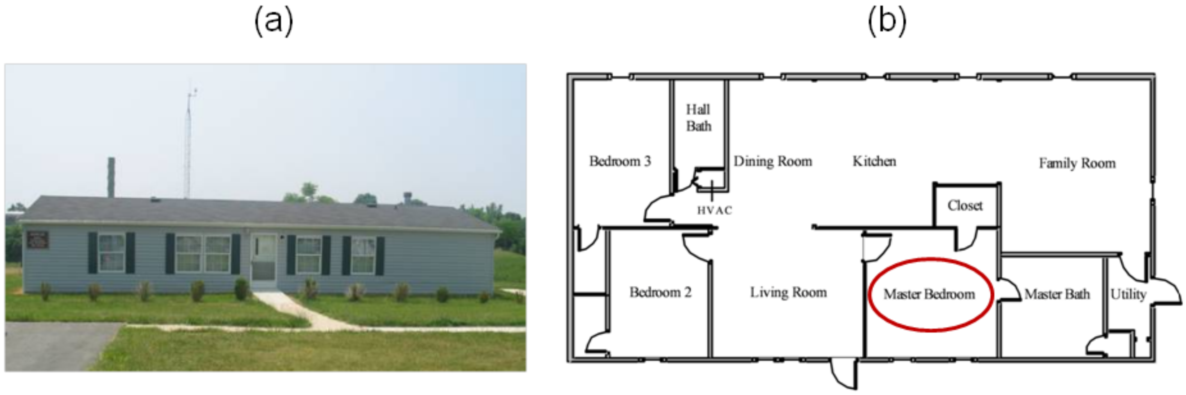

Figure 1. a) Manufactured test house; b) Floor layout of the house

In the absence of indoor sources, outdoor and indoor UFP concentrations (2 nm to 100 nm) were alternately measured in the master bedroom using a Scanning Mobility Particle Sizer (SMPS), while varying window positions and central fan operation mode (on or off). The indoor concentration resulting from the entry of outdoor particles can be expressed by the mass balance equation:

$$\frac{dC_{in}}{dt} = PaC_{out} - (a+k)C_{in} \qquad (1)$$

where P is the penetration coefficient (dimensionless); a is the air change rate (h^{-1}); k is the rate of deposition onto interior surfaces, including ductwork and furnace filters for homes with forced air (h^{-1}), and C is the UFP number concentration (#/cm^3).

The equilibrium solution ($\frac{dC_{in}}{dt} = 0$) is given by

$$C_{in} = \frac{Pa}{a+k} C_{out} \qquad (2)$$

where the fraction of outdoor air found indoors at equilibrium is the infiltration factor F_{inf}:

$$F_{\text{inf}} = \frac{Pa}{a+k} \qquad (3)$$

F_{inf} varies between homes and is a function of building operating condition and window position. In this study, for cases with the central fan on and off, F_{inf} was monitored with closed-window, one window open, and two windows open.

For the varying window positions, outdoor air change rate (a) was measured using the tracer gas decay method with sulfur hexafluoride (SF_6) as the tracer gas and an electron capture detector to measure SF_6 concentrations in six rooms sequentially every minute. When the central mechanical fan was on, supply air flowed through the ventilation system at the rate of 2000 m^3/h, or nearly 6 house volumes per hour. In the case of fan on, tracer gas concentrations were typically similar across all rooms of the house with <5 % relative standard deviation (RSD) within 10 minutes of injection. Air change rates were calculated for each of the six rooms by regressing the logarithm of the SF_6 concentration against time across a 70-minute period. Under closed-window conditions, the air change rates typically agreed across all rooms to within 10 % RSD. When one or two windows are open, the majority of RSDs remained within 10 %; however, the rooms with the open windows sometimes had different air change rates leading to increased RSDs, but still generally within 20% of the average rate.

The experiments typically provided about 60 to 70 consecutive hours of sampling with about 1400 to 1600 concentration measurements during each test. The difference form of the mass balance model (1) was used to estimate F_{inf}, P, and k:

$$\frac{C_{in}(i+1) - C_{in}(i)}{\Delta t} = PaC_{out}(i) - (a+k)C_{in}(i) \quad (4)$$

$$C_{in}(i+1) = Pa\Delta t C_{out}(i) + (1-(a+k)\Delta t)C_{in}(i) \quad (5)$$

In this recursive model, the indoor concentration at time $i+1$ equals the intrusion of outdoor air during the previous step plus the indoor concentration at time i minus the losses due to air change and deposition. Using this model, we calculated the estimates of P and k that minimize the sum of squared errors based on the difference between the modeled and measured indoor concentrations. The infiltration factor (F_{inf}) was then determined by calculating $Pa/(a+k)$, where a was the average air change rate over the weekend. The estimated values of P and k were accepted if the R^2 of the regression of the modeled and observed indoor concentrations exceeded 80 %.

3 RESULTS

Figure 2 presents the regression analysis between the measured and modeled concentrations for one size category (20 nm to 22 nm). The penetration coefficient P and deposition rate k that predicted the measured (time-varying) concentrations with the smallest error were calculated as 0.67 h^{-1} and 0.36 h^{-1}, respectively. The resulting infiltration factor F_{inf} was 0.49. Since the R^2 value for the regression is 0.97, the estimates for P, k, and F_{inf} were considered valid.

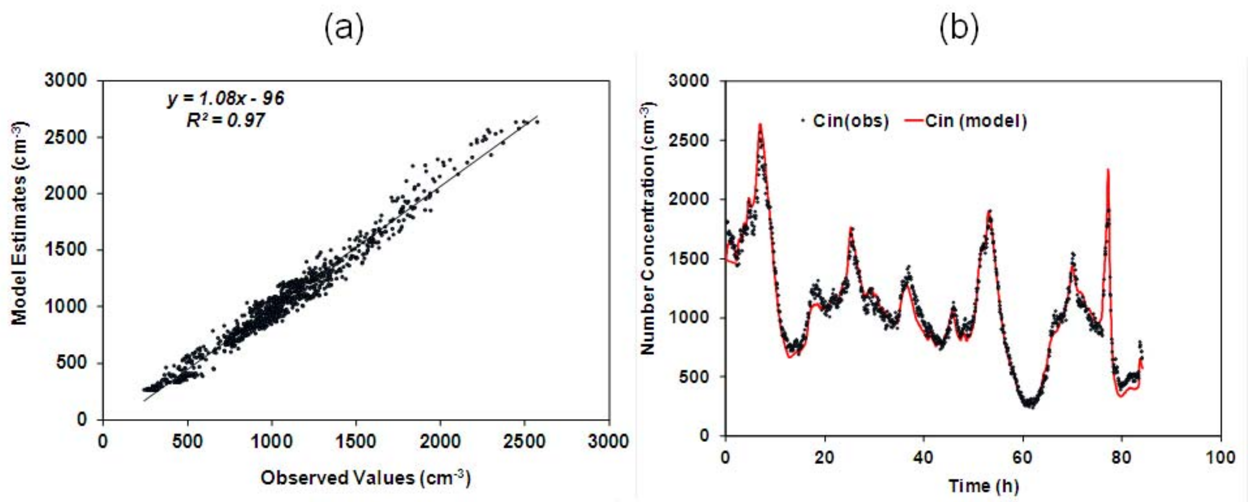

Figure 2. Scatterplot comparing model predictions to observed indoor concentrations (Fan on)

Figure 3 shows size-resolved estimates of the infiltration factor (F_{inf}) for three ventilation conditions (closed windows and one and two open windows) with the central fan on. The figure shows the functional dependence of F_{inf} on particle size and ventilation condition. The infiltration factor increases with particle size and window opening area.

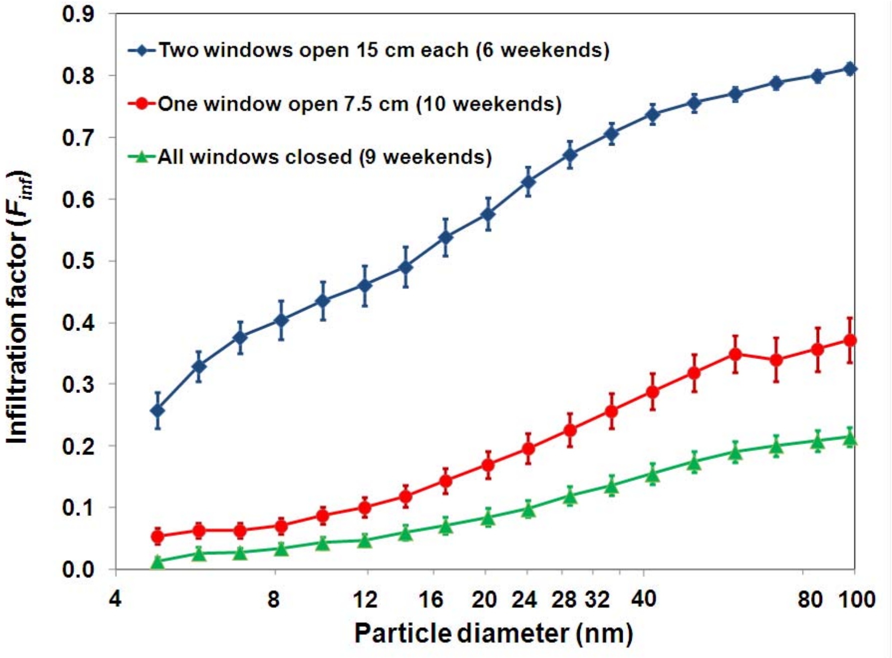

Figure 3. Infiltration factors observed for the three ventilation conditions with the central fan on. The error bars represent the standard error of the mean. The measurement data for closed window and open window open are reported in Rim et al. (2010)

Figure 4 shows the effect of the central mechanical fan operating condition on UFP infiltration factor and deposition rate. Figure 4a indicates that the infiltration factor is consistently larger for the central fan off case than the fan on case. This difference was caused by the higher particle deposition rates occurring with the central fan on (Figure 4b). The deposition rate was up to five times larger with the central fan off than that with fan on case.

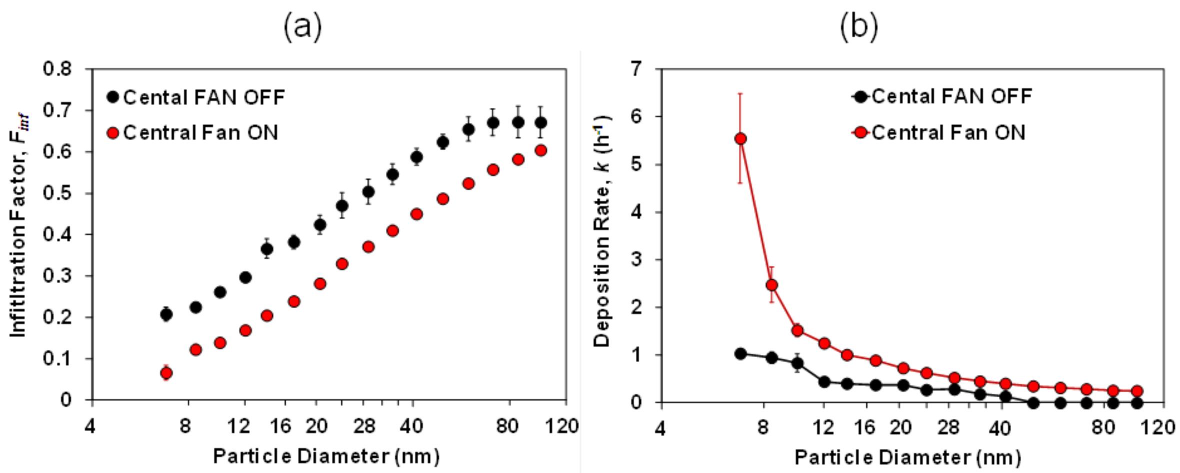

Figure 4. Infiltration factors and deposition rates (and standard errors) for two modes of central fan operation (Central fan on vs. off). The data was observed with two windows open 7.5 cm.

4 DISCUSSION

The recursive model predicted the indoor UFP concentration profiles with a reasonable accuracy. However, due to low concentrations of ambient particles smaller than 4 nm under normal conditions and larger particle loss with smaller particle sizes, the infiltration factors were estimated only for particles > 4 nm. The study results demonstrate that infiltration factor is function of particle size and building operating conditions. The trend toward reduced infiltration factors for smaller particles is due to their increased Brownian and turbulent diffusion (Hinds 1999), resulting in larger UFP losses across building cracks. The infiltration factor increases with window opening area, due in part to higher air change rates. The air change rate ranged from 0.14 h^{-1} to 0.44 h^{-1} for all windows closed, from 0.18 h^{-1} to 0.63 h^{-1} for one window open 7.5 cm, and from 0.81 h^{-1} to 1.44 h^{-1} for two windows open 15 cm. This result reflects that the contribution of outdoor UFP to the indoor UPF concentrations becomes more significant with opening window. In addition, decrease in infiltration factors associated with fan operation implies that the influence of outdoor UFP on the indoor UFP exposure can be reduced by turning on the central mechanical fan.

Much previous work has focused on infiltration, penetration, and deposition of fine particles ($PM_{2.5}$) (Özkaynak et al., 1996; Ott et al., 2000; Long et al, 2001; Howard-Reed et al., 2003; Meng et al., 2004; Wallace et al., 2004). For most of these studies, infiltration factors ranged between 0.5 and 0.8, with the lower values corresponding to more tightly closed homes and higher values to times when windows are more likely to be opened. The infiltration factors reported in this study for UFP are much smaller than for fine particles, with overall estimates of 0.09 to 0.15 with windows closed and 0.26 to 0.81 with two windows open 15 cm each. This immediately shows that the influence of outdoor air UFP on indoor concentrations is relatively smaller than that for $PM_{2.5}$. Equivalently, the relative influence of indoor sources of UFP is greater than that for $PM_{2.5}$. This has implications for epidemiological studies of UFP, since ambient UFP will provide a smaller fraction of total UFP exposure than is the case for $PM_{2.5}$. The estimates provided here of the infiltration factor for size-resolved UFP will help establish the extent of the influence of ambient UFP on total human exposure.

5 CONCLUSIONS

The study results showed that the infiltration factor varies with particle size, window opening area, and fan operation. The infiltration factor increases with particle size from 5 nm to 100 nm. Larger window openings also lead to higher infiltration factors due to increased air change rates. Smaller values of F_{inf} were observed with the central fan on than with the fan off, which was likely caused by additional particle deposition loss to the furnace filter and duct surfaces.

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