PARTICLE CONCENTRATIONS IN AN AIR-CONDITIONED OFFICE BUILDING WITH NORMAL AND HIGH EFFICIENCY FILTRATION

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ABSTRACT

Indoor and outdoor particle concentrations and ventilation rates were measured versus time in a large office building without tobacco smoking. Periodically, high efficiency filters replaced the normal filters in air handling systems. For all particle sizes, indoor concentrations varied considerably with time. Even with the normal air filters, which have a low efficiency for submicron particles, number concentrations of submicron particles were a factor of three to six smaller indoors compared to outdoors. The high efficiency filters reduced the indoor-outdoor particle concentration ratio for submicron particles by 70% to 95%. For larger particles, the decreases in indoor concentrations were substantially smaller. Comparisons of model predictions with measured data indicate a large rate of removal of submicron indoor particles by some process other than ventilation or air filtration, and also provide evidence of significant indoor generation or resuspension of particles larger than 1 μm.

INTRODUCTION

There is evidence from epidemiological studies that increased morbidity and mortality are associated with increased exposures to small particles [1]. Although these studies have relied on outdoor particle data, most people's exposures to particles occur primarily indoors. Indoor air contains indoor-generated particles and particles that enter the building with outside air. The published literature provides very limited information on the time variation of particle concentrations and size distributions in large commercial buildings. Additionally, the effectiveness of high efficiency filters in reducing indoor particle concentrations has not been well documented. This paper presents and discusses such data, obtained during a study of the influence of high efficiency filtration on office workers' acute health symptoms.

RESEARCH METHODS

The study was performed on two floors of a large, urban, air-conditioned office building with sealed windows. The floor area and occupancy were 4130 m^2 and 165 persons on Floor 2 and 4840 m^2 and 280 persons on Floor 4. The floors were almost entirely open plan, with extensive carpeting and fabric-covered partitions. Smoking was prohibited. Each floor had four identical air handling units (AHUs). For each AHU, outside air mixed with recirculated indoor air drawn from the mechanical room and the mixture passed through a bank of eight filters, each with nominal cross-sectional dimensions of 0.6 m by 0.6 m. The filtered air passed through the supply fan, cooling coils, and supply air ducts and entered the occupied space through diffusers in the suspended ceiling. Return air was drawn through grilles in the suspended ceiling and flowed through the ceiling plenum to the mechanical rooms. The rated maximum supply air flow from each set of four AHUs was 18.4 $m^3 s^{-1}$. Outside air dampers were in the minimum open position during occupancy, except during one 0.5 h period.

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Particle concentrations as a function of time were measured outdoors and at two indoor locations per floor at a height of 1.8 m. Laser optical particle counters measured number concentration in five size bins (0.3-0.5 µm, 0.5-0.7µm, 0.7-1.0µm, 1.0-2.0µm, >2.0 µm). Monitoring occurred during the workday periods of Thursdays and Fridays, for seven consecutive weeks during summer, 1996. There are a few periods of missing data. The particle counters were factory calibrated before and after the study. Additionally, all particle counters were intercompared twice and measured data have been "corrected" using one of the instruments as a reference. Many additional environmental parameters were measured, but only the ventilation rate measurements are pertinent to this paper. The tracer gas procedure used to measure equivalent steady outside air ventilation rates (ESVRs) is described elsewhere [2]. The ESVRs are averages for the workday periods of Thursday and Friday.

During weeks three and five, high efficiency air filters were installed in the AHUs on Floor 4. During weeks four and six, these filters were installed on Floor 2. At other times, the building's normal air filters were utilized. At the start of the study, all air filters were new. Using data for filters with the same ASHRAE efficiency rating [3], the estimated efficiency of the normal filters is 3%, 15%, 40%, and 80% for particles with diameters of 0.3 µm, 0.85 µm, 1.5 µm, and 3 µm, respectively. The high efficiency filters have an efficiency rating of 95% for 0.3 µm particles. From filter theory, their efficiency should be higher than 95% for particles either smaller or larger than 0.3 µm. Switching between the normal and high efficiency filters caused no discernible change in the supply air flow rate. Based on filter performance data, the loading of less than 10 g of dust on these filters during the study should not significantly change their air flow resistance or efficiency.

To aid in interpretation of the experimental data, a steady state mass balance equation for a well-mixed space was employed for particles in each size range:

$$S+(Q_o-Q_{inf})(1-E)C_o+Q_{inf}PC_o=Q_sC+\lambda_{dep}VC+Q_rEC \qquad (1)$$

where: S = indoor particle generation rate; Q_0 = rate of outside air entry based on the tracer gas measurements; Q_{inf} = rate of air infiltration flow through the building envelope (not filtered); E = the filter efficiency; C_o = outdoor particle concentration; P = penetration factor for infiltrating particles; C = indoor particle concentration; λ_{dep} = a particle deposition coefficient that accounts for particle deposition on indoor surfaces; V = indoor air volume; and Q_r is the rate at which recirculated indoor air flows through the filters; $[Q_r=Q_s-(Q_o-Q_{inf})]$, where Q_s is the total supply air flow rate. Three of the model parameters can be only roughly estimated. A reasonable value of the product of Q_{inf} and V is ~ 0.1 h^{-1}; however, if the AHUs pressurizes the building (the design intent), Q_{inf} may be negligible during AHU operation. For particles smaller than ~0.7 µm, P may be very close to unity [4,5,6]. Table 1 provides reported values of λ_{dep} as a function of particle size. The base case values are based on a compilation of data from three papers [6, 7, 8]. Relative to the base-case values, Lewis [5] reported a factor of three to four higher deposition coefficients for submicron particles under quiescent conditions and even higher deposition coefficients under turbulent conditions. Values for the particle generation rate S in large office buildings are not known; however, valuable information can be gained from modeling with S set equal to zero.

RESULTS

Within each floor, the measured values of ESVR were relatively constant, ranging from 1.8 to 2.1 m^3 s^{-1} on Floor 2 and from 3.2 to 3.5 m^3 s^{-1} on Floor 4. There were no significant correlations between particle concentrations and ventilation rates, presumably because of the small range in ventilation rates. However, the higher particle concentrations on Floor 4 during normal filtration may be a consequence of the higher ventilation rates on Floor 4.

Figure 1 provides an example of the time-averaged particle number concentrations in each size range. Three observations follow. First, the particle number concentration is dominated by the smallest particles. Second, even with normal filters, indoor concentrations of submicron particles are lower than outdoor concentrations by a factor of three to six. Third, number concentrations of submicron particles are much lower with high efficiency filtration.

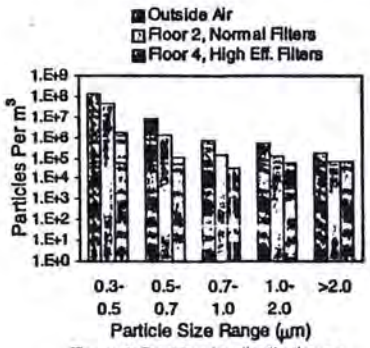

Figure 1. Particle size distribution on week 5.

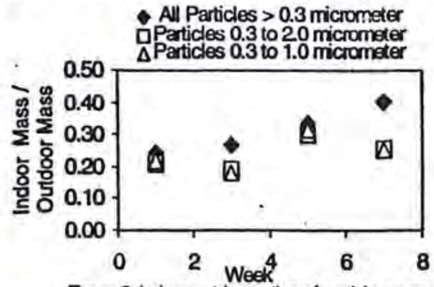

Figure 2. Indoor-outdoor ratios of particle mass concentrations with normal filtration, Floor 2.

The particle mass in each size bin was calculated using a particle density of 2.5 g cm^{-3} and particle sizes of 0.4, 0.6, 0.85, 1.5, and 3.0 µm for the five bins. During normal filtration, the smallest and largest bins contained 70% to 86% of the particle mass. During high efficiency filtration, particles larger than 1.0 µm accounted for 87% to 96% of the particle mass.

There were large week-to-week and within-day variations in particle number concentrations. Indoor concentrations roughly tracked outdoor concentrations, at least with normal filtration. There were numerous spikes in indoor particle concentrations at specific locations. Episodic localized releases or resuspensions of particles are one potential explanation for the spikes. Figure 2 plots the estimated indoor-to-outdoor (I/O) particle mass ratios versus week for Floor 2. Indoor mass concentrations track outdoor concentrations, although quite imperfectly. Considering particles smaller than 2 µm, the I/O mass ratios ranged by approximately a factor of two. The corresponding outdoor particle mass concentrations varied over a range of six.

Table 1 provides measured ratios of indoor particle number concentrations to outdoor concentrations (I/O ratios) from periods with normal filtration. The I/O ratios are only 0.15 to 0.55, thus, outdoor particle data are a poor direct measure of indoor particle exposures. The highest measured I/O ratios occur for the largest particles. Table 1 includes predictions of the I/O ratios for the three sets of particle deposition coefficients. For these predictions, we used the measured ESVRs and the previous estimates of filter efficiency. We assumed that supply air flow rates were 66% of the maximum, that the product- Q_{inf} V - (i.e., infiltration rate) was 0.1 h^{-1}, and that the P was unity. Finally, the predictions assume negligible indoor particle generation, which is most likely to be a reasonable assumption for the smallest particles.

For the submicron particles and the base-case or Lewis quiescent deposition coefficients, the predicted I/O ratios exceed the measured ratios by a factor of two to three. Accounting for indoor particle generation would increase the discrepancy. Doubling the air infiltration rate or decreasing P to 0.5 reduces this discrepancy insignificantly. Doubling the filter efficiency, which is probably unrealistic, leaves discrepancies near a factor of two. Therefore, the comparison of measured and predicted ratios suggests that particle deposition coefficients are underestimated or that there is some large unexplained removal process for submicron particles. For example, the discrepancy between the predicted and measured I/O ratios diminished substantially with the higher Lewis turbulent deposition coefficients in the model.

Table 1. Measured and predicted ratios of indoor-to-outdoor particle number concentration.

Floor	Part. Size (µm)	Filter Eff.	Base Case λ_d (h^{-1})	Lewis Quies-cent λ_d (h^{-1})	Lewis Turbu-lent λ_d (h^{-1})	Measured (C_{in}/C_{out})	Predicted C_{in}/C_{out} With Base Case λ_d	Predicted C_{in}/C_{out} With Lewis Quiescent λ_d	Predicted C_{in}/C_{out} With Lewis Turbulent λ_d
2	0.3-0.5	0.03	0.06	0.26	2.2	0.27	0.75	0.57	0.17
2	0.5-0.7	0.1	0.09	0.26	1.4	0.15	0.52	0.43	0.20
2	0.7-1.0	0.15	0.15	0.31	1.7	0.18	0.41	0.35	0.16
2	1.0-2.0	0.4	0.35	0.43	2.0	0.23	0.17	0.16	0.09
2	>2.0	0.8	0.80	0.72	3.1	0.52	0.05	0.05	0.03
4	0.3-0.5	0.03	0.06	0.26	2.2	0.44	0.83	0.67	0.23
4	0.5-0.7	0.1	0.09	0.26	1.4	0.26	0.65	0.56	0.28
4	0.7-1.0	0.15	0.15	0.31	1.7	0.28	0.53	0.47	0.23
4	1.0-2.0	0.4	0.35	0.43	2.0	0.38	0.25	0.24	0.13
4	>2.0	0.8	0.80	0.72	3.1	0.55	0.07	0.07	0.04

For particles larger than 1 µm in size, the measured I/O ratios exceed the predicted ratios, regardless of the choice of particle deposition coefficients. For the largest particles, the discrepancy is about a factor of ten. Reasonable changes in the model inputs will not resolve these discrepancies. Substantial indoor particle generation or resuspension, for particles larger than 1 µm, seems to be the most likely explanation for this discrepancy. Occasional periods with indoor concentrations of particles larger than 1 µm exceeding outdoor concentrations provided additional evidence of indoor generation of these larger particles.

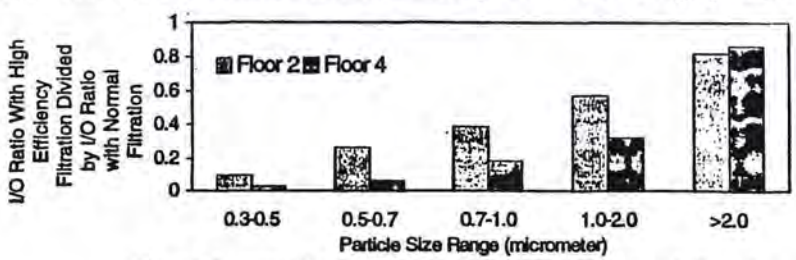

Figure 3. Influence of high efficiency filtration on I/O particle concentration ratios.

To characterize the benefits of high efficiency filtration, the I/O ratios from periods of high efficiency filtration were divided by the I/O ratios from periods of normal filtration. The results in Figure 3 illustrate that high efficiency filtration was associated with a very large reductions in the indoor concentrations for the smallest particles. As particle size increased, the benefits of the high efficiency filtration decreased, presumably because the efficiency of the normal filters increases with particle size. Averaging the results from both floors yields the following reductions in particle number concentrations: 94% for 0.3-0.5 µm; 84% for 0.5-0.7 µm; 72% for 0.7-1.0 µm, 55% for 1.0-2.0 µm ; and 16 % for >2.0 µm particles.

DISCUSSION

Published comparisons of indoor and outdoor particle concentrations in large commercial buildings without smoking are limited. Field studies [9, 10] found that particle mass concentrations were generally smaller indoors. Another study [11] found number concentration of 17 to 700 nm particles in an office building to be 40% less than outdoor concentrations. Thus, our findings that indoor particle concentrations were smaller than outdoor concentrations are typical of findings from commercial buildings without smoking. Several prior studies have also reported large temporal variations in particle concentrations within commercial buildings [e.g., 11, 12]. These findings suggest that short-term particle concentration measurements, which are very common, have a limited utility for assessment of time average indoor particle exposures.

We identified few papers quantifying the effects of high efficiency filtration in commercial buildings. In a telecommunications building [13], high efficiency filtration was associated with 50% reduction in the I/O number concentration ratios for particles larger than 0.5 µm. In model predictions of the benefits of high efficiency filtration, substantial reductions in indoor concentrations are generally predicted.

Respirable size particles are thought to be the most likely cause of adverse health effects associated with particles [1]; thus, our findings suggest that using high efficiency filters in building AHUs may be beneficial for health. However, high efficiency filters would not be expected to decrease health effects associated with indoor particles larger than approximately two micrometers in size because normal filters are relatively efficient for these large particles. Many of the intact bioaerosols may be larger than two micrometers.

CONCLUSIONS

The most important conclusions from this study follow: (1) Indoor concentrations of respirable size particles in large sealed mechanically ventilated buildings without tobacco smoking can be substantially lower than outdoor concentrations. (2) Indoor particle concentrations vary considerably with time. (3) High efficiency filters can dramatically reduce indoor number concentrations of submicron-size particles. (4) Comparisons of model predictions with measured data indicate a large rate of removal of submicron indoor particles by some process other than ventilation or air filtration, and also provide evidence of significant indoor generation or resuspension of particles larger than 1 µm.

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