HVAC filters as "passive" samplers: fate analysis of indoor particles

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SUMMARY

To assess the potential use of HVAC filters as passive indoor samplers in a typical residence, we evaluated the removal of particles in the 0.001-100 µm range resulting from settling, exfiltration, and capture in the HVAC filter. The results suggest that large particles are likely to deposit, particles in the 0.3-3 µm range are likely to be removed by exfiltration or, if a high efficiency filter is installed, to be captured by the HVAC filter. Ultrafine particles (< 0.1 µm) are also likely to be captured by filters, particularly for elevated recirculation air exchange rates. HVAC filter efficiency and the recirculation air exchange rate play a key role in the use of HVAC filters as representative samplers of indoor particles. High efficiency filters with elevated recirculation air exchange rates (>5.2 h^{-1}) are particularly effective for a wide range of particle sizes suggesting that HVAC filters may be a promising means for assessing indoor particulate contaminants.

KEYWORDS

Particulate matter, Filtration, Air sampling, Removal mechanisms.

INTRODUCTION

Indoor air quality investigations often focus on air and settled dust samples to assess chemical and biological contamination. Both types of samples have limitations, including the spatial variability of indoor contaminant concentrations and short-term sampling techniques that provide only a snapshot of contaminant concentrations. The specific contaminants and levels found in particles suspended in air and in settled dust are often different (i.e., Rudel *et al.*, 2003) possibly due to the fact that air and settled dust sampling methods preferentially sample different particle size ranges. HVAC filter dust is a potential resource for indoor environment investigations that has received little attention. Analysis of HVAC filter dust may enhance our understanding of indoor occupant exposure by providing an integrated measure of indoor pollutant concentrations associated with particles. In order to explore the validity of this idea, we considered several particle removal mechanisms to better understand the dynamics involved and to evaluate conditions and particle sizes for which HVAC filters are effective samplers. Several researchers have explored the mechanisms that affect the removal of particles (i.e., Abt *et al.* 2000; Liu and Nazaroff, 2001) as well as the loading of HVAC filters (i.e., Waring and Siegel, 2008). In addition, Zhao and Wu (2009) investigated particle fate in ventilation systems for a range of different scenarios. The objective of the current study was to evaluate for which conditions and particle sizes HVAC filters can be considered effective samplers. In addition we wanted to compare the use of HVAC filters to more traditional sampling approaches such as periodic air measurements and analysis of settled dust. We evaluated the influence of filter efficiency, air recirculation rate, and air exchange rate on the size-dependent particle fate. The results from this analysis will be useful for assessing the effectiveness of using HVAC filters as an indoor sampling technique.

METHODS

We performed a scaling analysis to estimate the probability that 0.001-100 µm particles would be removed from indoor air in a typical residence by deposition, exfiltration, or filtration through the HVAC filter. The volume of the residence was selected considering a typical floor area of 163.3 m^2 (US Bureau of Census, 2005) and assuming a ceiling height (h) of 2.4 m.

To estimate the removal probability for each mechanism, we considered the characteristic time of each process. This value was then normalized by the sum of all the characteristic times, and the resulting fraction represented the removal probability of the process for that specific particle size. For deposition, we considered the deposition loss rate coefficients (β) reported by Riley *et al.* (2002). For exfiltration, we utilized the 10^{th}, 50^{th} and 90^{th} percentile values of the air exchange rate distribution reported by Murray and Burmaster (1995). These values, corresponding to λ = 0.2, 0.5 and 1.3 h^{-1}, were used to evaluate how the tightness of the residence may affect the potential use of HVAC filters as passive samplers. For filtration, the air recirculation rate (λ_r) multiplied by the size-dependent removal efficiency (η) of the HVAC filter was utilized. We considered two different λ_r values (5.2, 1.1 h^{-1}) by assuming continuous and cyclic duty operation for a typical 3-ton air conditioner. For the baseline scenario (1.1 h^{-1}), the HVAC system was assumed to cycle normally and be on for 22% of the time (Noris *et al.*, 2009), while for the second case (5.2 h^{-1}) the system was assumed to run continuously (for mechanical ventilation). Three different clean filters with minimum efficiency reporting values (MERV) of <5, 6 and 11 were considered using the filtration efficiencies employed by Waring and Siegel (2008). Particle deposition in the HVAC system ducts was neglected based on the results of previous studies (Sippola and Nazaroff, 2003; Waring and Siegel, 2008).

RESULTS AND DISCUSSION

Figure 1 shows the removal probability via different mechanisms for the baseline scenario (MERV 6 filter, λ_r= 1.1 h^{-1} and λ= 0.5 h^{-1}). The results indicate that, for a mid-efficiency filter, large particles (> 3 µm) are likely to deposit on surfaces and are unlikely to get captured on filters. Particles in the 0.03-3 µm range are likely to be removed by exfiltration or, if a high efficiency filter is installed, captured on the filter (Figure 2). For ultrafine particles (< 0.1 µm), the particle filter removal probability increases since filter efficiency for these particles increases for all three MERV ratings. There are two peaks in the filter capture probabilities, approximately at 0.01 and 3 µm. For the baseline scenario conditions, filtration is about 18 times less likely to capture a 0.1 µm particle before it is removed by exfiltration and 12 times less likely to capture a 5 µm particle before it deposits on a surface. Particles between 0.03 and 1 µm are most likely to be removed by exfiltration and are less likely to be found in settled dust or in the dust that collects on a mid efficiency filter.

Additional results of the analysis are presented in Figures 2, 3 and 4. In each graph we modified one parameter from the baseline scenario. Figure 2 shows that the filter efficiency is a more important variable for sampling particles in the range between 0.03 and 3 µm than for particles below 0.03 µm or above 3 µm. These results are due to the fact that the HVAC filter efficiency is particle-size dependent especially in the range from 0.01 to 3 µm (Hanley *et al.*, 1994). A MERV 11 filter is about 9 times more likely to capture a 0.5 µm particle than a MERV 6 filter and about 150 times more likely than a MERV <5 filter. If a high efficiency filter is used, there is an elevated probability of capturing particles in the 0.3 - 3 µm and 0.005 – 0.03 µm ranges and high efficiency filters are likely to be good samplers for these particle sizes. In the range 0.3 – 3 µm, the model predicts that more than one thirds of the particles should be captured on a high efficiency filter. High efficiency filters with elevated recirculation air exchange rates (> 5.2 h^{-1}) are particularly effective, with more than 30% capture probability up to 7 µm. For larger particles, deposition onto surfaces is the dominant removal mechanism and filters are unlikely to be good samplers.

Figure 3 illustrates the influence of the HVAC system duty cycles on the filter capture probability. The profiles for the two λ_r values investigated follow similar patterns, with the probability for removal via filtration for normal (cycling) use reduced approximately by the duty cooling cycle fraction (0.22). The greatest difference between the two duty cycle scenarios is evident for particle sizes that are more likely to be captured on the filter, 0.01 and 3 µm. The results demonstrate that, if a mid efficiency filter is used, the HVAC system would need to operate for an elevated duty cycle in order for the filter to be an effective sampler.

As can be seen in Figure 4, the residence air exchange rate also has an influence. Abt *el al.* (2000) also reported the importance of air exchange rate on the effectiveness of the removal mechanisms. However, this parameter does not seem to be as important as the filter efficiency or the λ_r with extremely similar patterns and capture probability among the three scenarios investigated. As a consequence, filters could potentially be used as samplers independently of the tightness of the residences investigated.

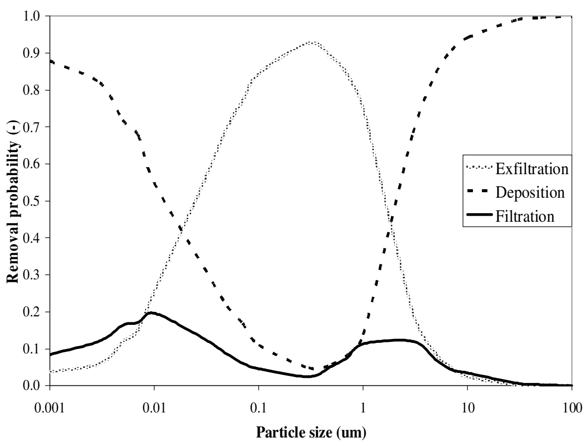


Figure 1. Removal probability by the different mechanisms for baseline scenario (MERV 6, λ_r=1.1 h^{-1} and λ=0.5 h^{-1}).

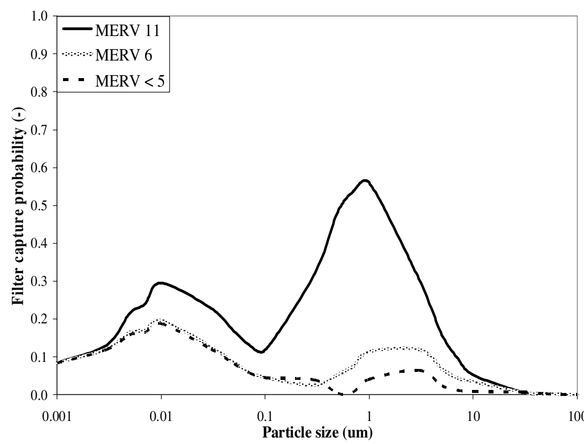
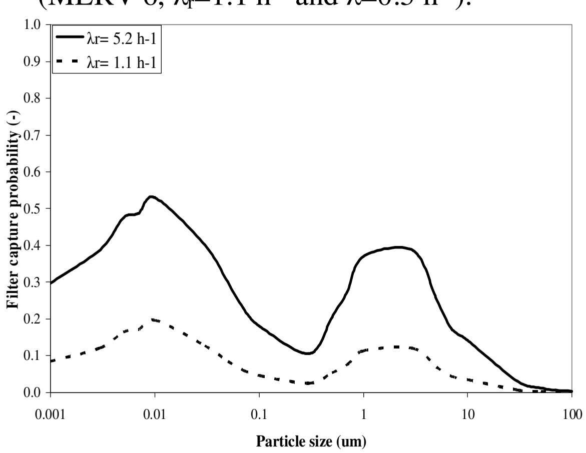


Figure 2. Filter capture probability under different filter efficiency scenarios.



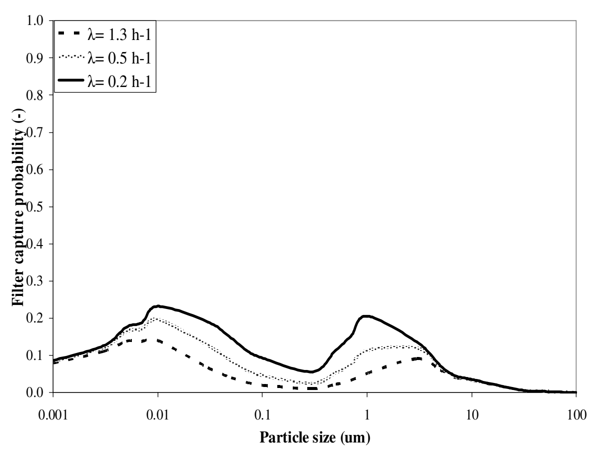


Figure 4. Filter capture probability under different air exchange rate scenarios.

This analysis suggest that the best way to increase the probability that a broader size range of indoor particles will be captured in an HVAC filter would be to increase the filter efficiency; this variable has a greater predicted effect on particle capture than increasing the λ_r or decreasing λ. High efficiency filters could potentially develop into better overall samplers than settled dust samples or conventional air samples. As can be inferred from Figure 1, settled dust samples are biased toward larger particles, while conventional air samples may be biased toward those particle sizes that are not removed effectively by other mechanisms (0.05 - 1 μm range). On the other hand, high efficiency filters seem to have good capture probability for a wide range of particle sizes. Because they are in place for long periods of time, they can also overcome the short-term sampling limitation of traditional air samplers.

CONCLUSIONS

We investigated the influence that filter efficiency, air recirculation rate and air exchange rate have on the filter particle capture probability with the objective of evaluating the use of HVAC filters as samplers. Our scaling analysis indicates that the most important of the three parameters is the filter efficiency. High efficiency filters have an elevated probability of capturing a wide range of particle sizes and could potentially develop into an attractive sampling alternative especially if the recirculation air exchange rate is elevated and the HVAC system is operated frequently. However, filters may not be good samplers for large particles or if the system operates with a reduced duty cycle. Other critical parameters, such as the location of the return grille with respect to the emission source, the zoning of the building and the frequency of the HVAC cycles, could also play a significant role and should be investigated further.

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