Comparison of HVAC filter test methods for particle removal efficiency

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1 Introduction

The use of HVAC filters in buildings is one strategy to reduce occupant exposure to particulate matter. However, HVAC filters are typically tested only in laboratory settings and little is known about how they perform in real environments. This work 1) explores the advantages and disadvantages of two test methods used to quantify the removal efficiency of HVAC filters in the field, 2) refines and applies a whole-house method to a medium-efficiency filter installed in a test house, 3) and compares the results to upstream/downstream tests and laboratory tests as measured by an independent lab and by the manufacturer.

2 Methods

The measurement of particle concentrations upstream and downstream of a filter is a relatively quick method to estimate filter removal efficiency, but large errors can result from restricted sampling locations, unmixed flow, and non-isokinetic sampling. Conversely, a "whole-house" test method, which measures the overall particle loss rate with and without a filter installed in an operating HVAC system, can be used to capture the effects of the entire system, including filters, ducts, leakage, and filter bypass. However, the whole-house method requires complete indoor mixing, minimizing the influence of outdoor particles, and multiple instruments to simultaneously measure particles, air exchange rates, and HVAC airflow rates.

A whole-house filter test method based on Offermann et al. (1992) and MacIntosh et al. (2008) was refined for this work. The method consists of artificially elevating particle concentrations (by burning incense and shaking a used vacuum cleaner bag) and measuring the subsequent concentration decay (with optical particle counters) with and without a filter installed in the operating HVAC system. Concurrently, air exchange rates are measured by tracer gas decay. Our method differs from earlier work in four ways: 1) we supply HEPA- and activated-carbon-filtered outdoor air to the house to maintain positive pressurization, which should eliminate the infiltration of outdoor particles, diminish secondary organic aerosol formation from reactions of ozone and unsaturated organic compounds, and shorten the test duration; 2) we measure system airflow rates during each test with a more accurate flow plate device; 3) we operate several mixing fans to achieve reasonably well-mixed conditions to satisfy the assumption in a mass balance; and 4) we perform a nonlinear least-squares regression on the data to ensure accurate estimates of particle loss rates. A number balance on the space is shown in Equation 1:

$$C_{i,in}(t) = C_{i,in}(t=0)e^{-Lt} + \frac{S}{L}\left(1 - e^{-Lt}\right) \qquad (1)$$

where $C_{i,in}$ = indoor particle concentration of diameter i at time t (#/m^3), S = particle source term (#/m^3-hr), and L = particle loss term (1/hr). Loss terms (L) for three conditions are shown in Table 1, which include air exchange rates (λ), deposition to indoor surfaces (β), and the product of HVAC system airflow (Q_{HVAC}, m^3/hr) and system removal efficiency of particle size i (η_i, -), divided by the volume (V, m^3) of the space. Condition (1) yields the background removal rate in the space, albeit likely increased above normal background because of the operation of mixing fans. More importantly, system removal efficiency (η_i) depends on the filter installation condition: condition (2) with no filter yields the removal efficiency of the duct system alone ($\eta_{i,ducts}$) and condition (3) with a filter yields the combined removal efficiency of the duct system and the filter ($\eta_{i,ducts+filter}$). Any increased background removal due to mixing fans is accounted for in the differences.

Table 1. Loss terms for three filter conditions

Operating Condition	Loss term, L (hr^{-1}) =	Losses to:
(1) HVAC off	$\lambda + \beta$	Surfaces
(2) HVAC on, no filter	$\lambda + \beta + \frac{\eta_{i,ducts} Q_{HVAC}}{V}$	Surfaces and ductwork
(3) HVAC on, filter	$\lambda + \beta + \frac{\eta_{i,ducts+filter} Q_{HVAC}}{V}$	Surfaces, ductwork, and filter

Because air exchange rates are simultaneously measured, λ can be subtracted from the total loss rates in all three conditions in Table 1. Subtracting the subsequent particle loss rates of condition (1) from condition (2) yields the increased removal rates due to airflow through the HVAC system *without* a filter. Similarly, subtracting the total particle loss rates of condition (1) from condition (3) yields the increased removal rates due to airflow through the HVAC system *with* a filter. The difference in particle removal rates between conditions (2) and (3) represents the contribution to removal rates of the filter alone.

From there, the size-resolved particle removal efficiency of the HVAC ductwork alone can be estimated by subtracting the loss rates of conditions (2) and (1), and multiplying by the space volume (V) and dividing by the HVAC system airflow rate (Q_{HVAC}). Similarly, the size-resolved particle removal efficiency of the combination of the HVAC ductwork and filter can be estimated by subtracting the loss rates of conditions (3) and (1), and multiplying by V and dividing by Q_{HVAC}. Finally, because the filter and ductwork are in series, filter efficiency can be estimated by Equation 2.

$$\eta_{i,filter} = 1 - \frac{1-\eta_{i,ducts+filter}}{1-\eta_{i,ducts}} \qquad (2)$$

This method, along with concentration measurements upstream and downstream of the filter, was performed in an unoccupied test house with a medium-efficiency filter installed (MERV 7, as defined by ASHRAE Standard 52.2). Results are compared to lab tests as reported by both an independent test lab and the manufacturer. Uncertainty is reported as 95% confidence intervals for the replicate laboratory tests, standard deviations of average concentrations for the upstream/downstream method, and standard deviations of six replicate tests and measurement uncertainty for all parameters added in quadrature for the whole-house method.

3 Results

A comparison of the four methods is shown in Figure 1. Average percentage differences between removal efficiencies measured by the whole-house and upstream/downstream methods were 58%, 0%, and 35% for 0.3-1.0 µm, 1-3 µm, and 3-10 µm particles, respectively (absolute differences were 7%, 0%, and 20%).

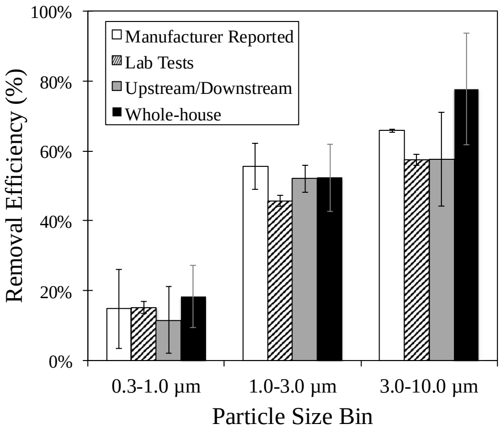

Figure 1. Average particle removal efficiency of a medium-efficiency (MERV 7) filter in the test house, as measured by four methods.

Removal efficiencies reported by the manufacturer were similar to, and higher than, those measured by all three methods for 0.3-1.0 µm and 1-3 µm particles, respectively. For 3-10 µm particles, lab tests and the upstream-downstream methods underestimated removal efficiency relative to manufacturer-reported values and the whole-house method overestimated, albeit with large uncertainty. Average uncertainties for the two in-situ methods were similar: approximately 9% and 12% for the upstream/downstream and whole-house methods, respectively.

4 Conclusions

A robust in-situ test method to characterize the actual performance of HVAC filters and duct systems is necessary for a complete understanding of the impact of filters in real environments. These results suggest promise for both field methods with the central challenge to their utility being large uncertainties.

5 References

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