In-situ residential HVAC filtration efficiency for fine and ultrafine particles

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Introduction

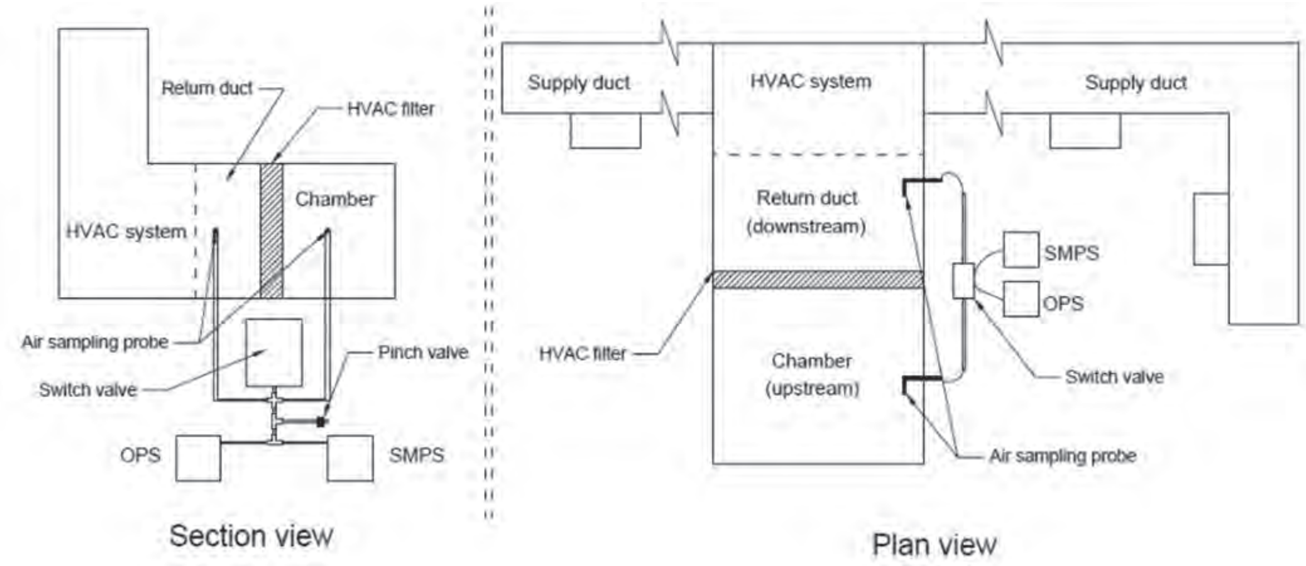
Human exposure to airborne fine particles (i.e., $PM_{2.5}$, or the mass concentration of particles smaller than 2.5 µm) and ultrafine particles (i.e., UFPs, or the number concentration of particles smaller than 0.1 µm) are consistently linked to a variety of adverse health effects including asthma exacerbation, cardiopulmonary mortality, lung cancer, and stroke.[1–3] Although these associations are typically made using outdoor particle concentrations, much of human exposure to airborne particles actually occurs indoors, particularly in residences.[4–6] This is because (i) people spend most of their time at home,[7] (ii) particles of outdoor origin can infiltrate and persist in residences with varying efficiencies,[8] and (iii) there are also many indoor sources of airborne particles of various sizes in residences, including smoking, cooking, burning incense and candles, operating office equipment, indoor oxidative chemistry, and resuspension from settled dust.[6] The combination of all of these impacts makes particulate matter exposure inside residences likely the most important indoor pollutant for human health, according to one recent estimate.[9]

High-efficiency particle air filtration in central heating, ventilating, and air-conditioning (HVAC) systems is increasingly being used to reduce concentrations of particulate matter of both indoor and outdoor origin inside residences. However, questions remain about their effectiveness for reducing indoor particle concentrations in homes operating under realistic occupied conditions. For one, the predominant filter test standard in the U.S., ASHRAE Standard 52.2-2012 and its Minimum Efficiency Reporting Value (MERV) metric, only characterizes removal efficiency for particles 0.3-10 µm in size, although the vast majority of particles present in both indoor and outdoor environments (by number) are smaller than 0.3 µm.[10–13] The same issues are true for other filter test standards such as AHRI 680[14] as well as a variety of rating systems that have been developed by air filter manufacturers and retailers. For example, 3M uses a “Microparticle Performance Rating” (MPR) to characterize its products. The MPR measures the ability of an air filter to capture particles 0.3 to 1 µm in size. The retailer Home Depot uses a “Filter Performance Rating” (FPR) to characterize its air filtration products. FPR ranges from 1 to 10 based on the weighted air filter performance of large particle removal (60%), small particle removal (30%), and weight gain/lifetime (10%).[15] A comparison between the MERV rating system and MPR and FPR is shown in Table 1.[16]

A number of questions remain regarding how residential HVAC filters perform in real environments. First, it remains to be seen how filters rated by these test standards perform for removing finer (e.g., ultrafine) particles in addition to the typical 0.3 µm to 10 µm size ranges. Second, filters installed in central residential HVAC systems may be subject to different face velocities, particle concentrations, particle compositions, and environmental conditions that do not reflect test conditions in Standard 52.2.[17] Third, filters may also experience substantial bypass airflow in poorly constructed filter housings in residential installations.[18] Given these issues with existing air filtration test standards, we have been utilizing a simple in-situ test method to measure the size-resolved single-pass particle removal efficiency

Table 1. Comparison of common rating systems used for residential HVAC filters

MERV	MPR	FPR	ASHRAE Minimum Initial Efficiency		
			0.3 – 1 µm	1 - 3 µm	3 – 10 µm
MERV 19-20	N/A	N/A	99.99%	–	–
MERV 17-18	N/A	N/A	> 95%	–	–
MERV 16	N/A	N/A	> 95%	> 95%	> 95%
MERV 14-15	N/A	N/A	75 – 95%	> 90%	> 90%
MERV 13	Black 2200 Navy Blue 1900 Purple 1500	10 Blue	< 75%	> 90%	> 90%
MERV 12		8 - 9 Purple	–	80 – 90%	> 90%
MERV 11	Red 1000	7 Red	–	65 – 79%	> 85%
MERV 10	–		–	50 – 64%	> 85%
MERV 8	Light Blue 600	5 Green	–	–	70 – 85%
MERV 7	–	4 Green	–	–	50 – 69%
MERV 6	400	–	–	–	35 – 49%
MERV 0 - 5	–	–	–	–	20 – 34%



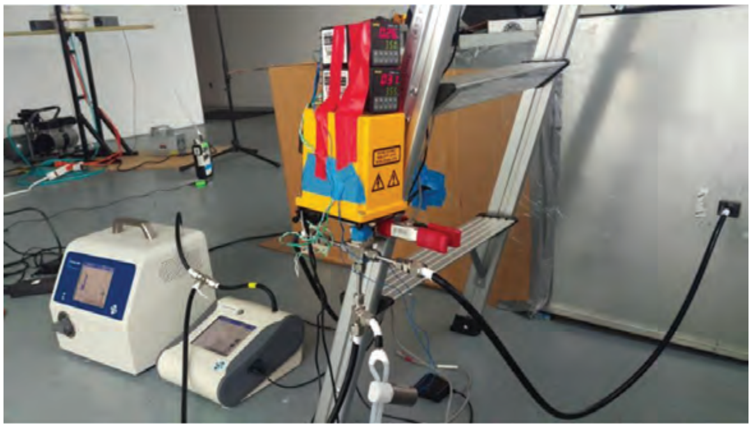


Figure 1. Section view, plan view, and photo of the experimental setup.

over a wide range of fine and ultrafine particle sizes (from 0.01 to 2.5 µm) of a wide range of commercially available filters for use in residential buildings.[19] Here we briefly report on the test method and some preliminary results.

Methods

The measurements are relatively straightforward. Indoor particle concentrations are elevated inside a ~650 ft^2 unoccupied apartment unit on the campus of Illinois Institute of Technology, and size-resolved particle concentrations (from ~10 nm to ~10 µm) are measured upstream and downstream of the filter using a combination of a TSI NanoScan Scanning Mobility Particle Sizer (SMPS) and a TSI Optical Particle Sizer (OPS). A 100% recirculating central air-handling unit is installed in the living room and connected to interior rigid sheet metal ductwork. The system is not connected to a heating or cooling system, but it is designed to mimic a typical residential air handler and distribution system. The air-handling unit can accommodate 16” x 25” filters with depths ranging from 1” to 5” (or more).

Particles are generated into a 3 ft × 1 ft × 2 ft chamber that is installed in front of the return plenum through a combination of burning incense and operating a TSI Model 8026 particle generator to aerosolize *NaCl* particles. Each test is conducted for approximately 1 hour. Upstream and downstream concentrations are measured through an automated electronically actuated sampling system connected to the aerosol instruments using conductive tubing. Each sampling period is set for 4 minutes, providing a total of 8 minutes per upstream/downstream combination, or about 7 complete upstream/downstream cycles within 1 hour of testing.

The size-resolved single-pass particle removal efficiency is then calculated in each particle size bin (approximately 20 bins total) for each 8-minute sampling period by subtracting the ratio of the average downstream concentration to the average upstream concentration from unity. The average size-resolved removal efficiency is then reported as the average removal efficiency across all 7 sampling periods for a given filter test. In both upstream and downstream sampling periods, the first minute of data are discarded to ensure that the sampling lines were cleared from the previous measurement. Size-resolved removal efficiencies for each test filter is reported as an average and standard deviation across the 7 combined upstream/downstream sample periods. Figure

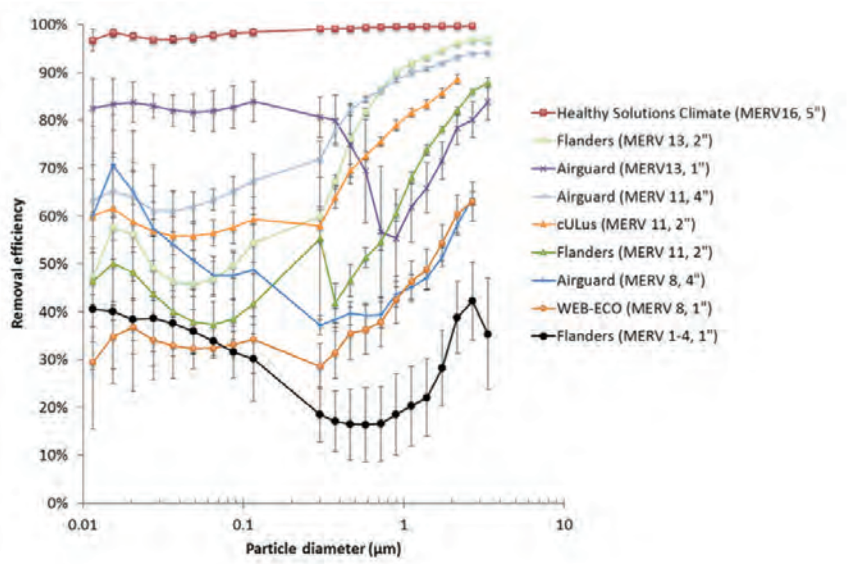


Figure 2. Mean and standard deviation of size-resolved in-situ particle removal efficiency measured for 9 filters labeled with MERV.

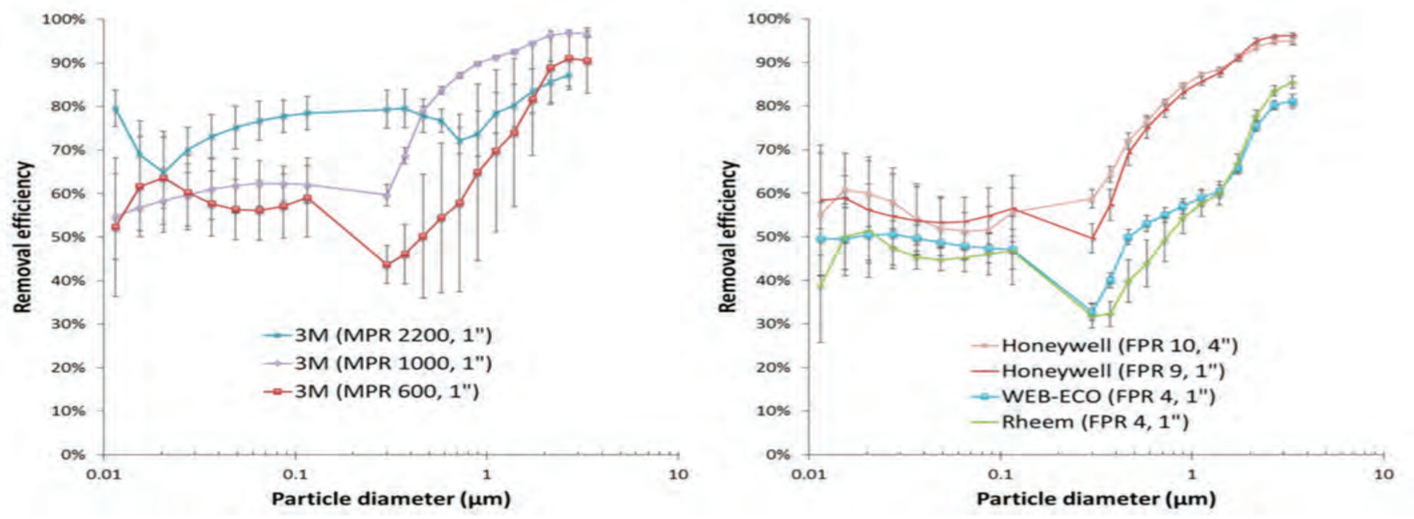


Figure 3. Mean and standard deviation of size-resolved in-situ particle removal efficiency measured for 3 filters labeled with MPR and 4 filters labeled with FPR.

1 shows drawings and a photo of the experimental setup. Realistically, given challenges in aerosolizing large particles in real environments, we are typically able to calculate removal efficiencies for particles from 10 nm to about 3 µm, which provides a dataset for both fine and ultrafine particles.

For each filter test, airflow rates and filter pressure drop are also measured and recorded. Filter pressure drop is measured using an Energy Conservatory DG-700 differential pressure gauge connected to ambient indoor air on one end and to a pressure tap just a few inches downstream of the filter (in the return plenum) on the other end. The airflow rate is estimated for each test by measuring the pressure in the supply plenum and relating back to TrueFlow plate measurements. Temperature and relative humidity in the room is measured throughout each test using an Onset HOBO U12. Air velocity measurements were also taken with a Fluke air velocity meter (Model #975) to confirm that isokinetic sampling is being achieved within a reasonable range (i.e., ~10%).

Results

To date, we have successfully measured size-resolved fine and ultrafine particle removal efficiency of 16 commercially available residential filters. These filters are new and not previously loaded, and we have not taken steps to artificially load them at this point. We are providing all of the results in an electronic database online for others to access for free: http://built-envi.com/portfolio/filter-testing/. The summary data include particle removal efficiency measured across 21 particle size bins, filter pressure drop, airflow rate, and indoor temperature and relative humidity measured during the test. Here we provide just a few highlights from the first set of filter tests conducted using the setup.

Figures 2 and 3 show the mean and standard deviation of size-resolved removal efficiency measured for 16 filters labeled with three different rating systems: MERV (n = 9), MPR (n = 3), and FPR (n = 4). Most filters had the lowest measured removal efficiency for particle sizes around 0.3 µm and the highest efficiency for particle sizes

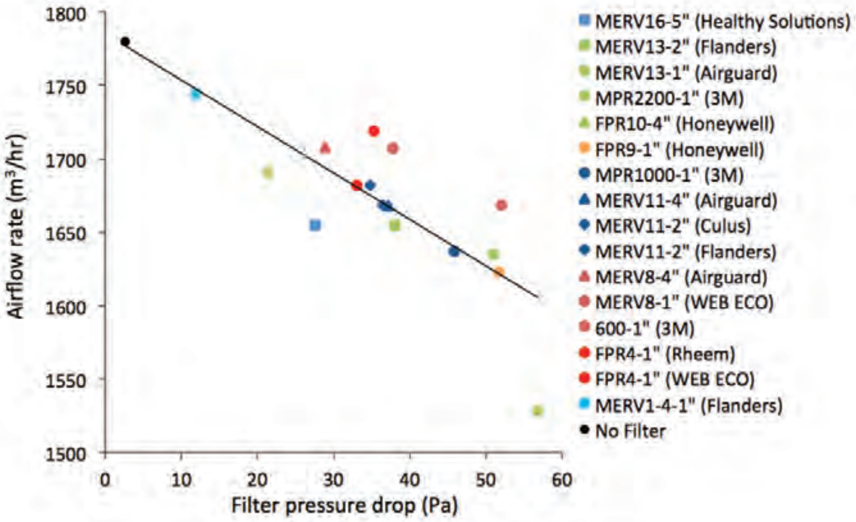


Figure 4. Correlation between measured filter pressure drop and air handler airflow rates. 1” filters are marked with circles, 2” filters are marked with diamonds, and 4” filters are marked with triangles.

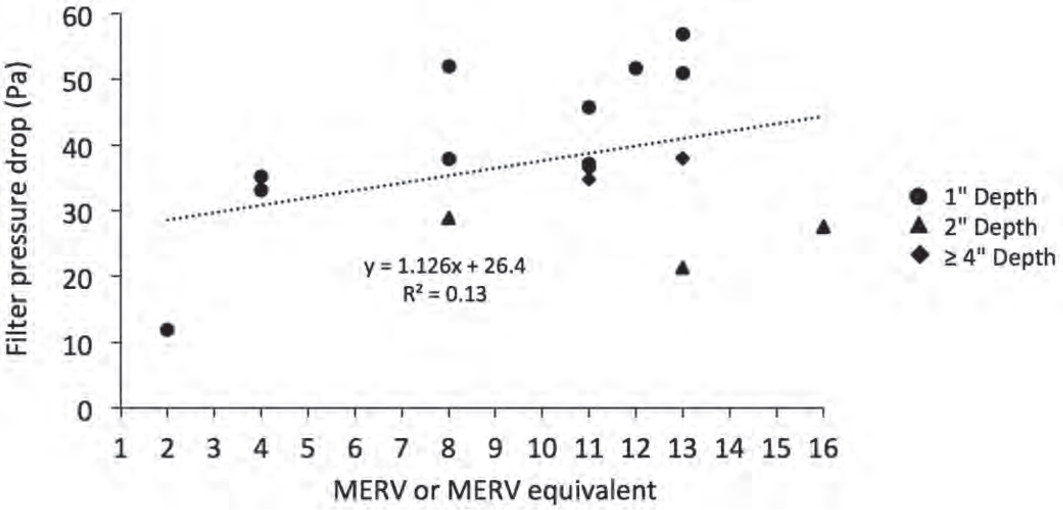


Figure 5. Correlation between manufacturer-reported MERV (or MERV equivalent) and measured filter pressure drop

near 2.5 µm, consistent with fibrous media filtration theory and previous measurements. Removal efficiencies were also fairly constant across the 10-100 nm UFP size ranges for most filters. Removal efficiencies for particles greater than 0.3 µm largely scaled with rated removal efficiency, which is consistent with the various filtration test standards. However, removal efficiencies for UFPs did not necessarily scale with rated removal efficiency. For example, UFP removal efficiencies measured using two MERV 8 filters (WEB-ECO 1” and Airguard 4”), two MERV 11 filters (cULus 2” and Flanders 2”), and MERV 13 filters (Flanders 2” and Airguard 1”) differed by nearly a factor of two for many UFP sizes when comparing results within the same rating. These differences are likely attributed to a combination of differences in media charge, pleating, and filter depth. The differences in UFP removal efficiencies were not as large for filters rated by MPR and FPR.

Figure 4 shows the correlation between filter pressure drop and HVAC airflow rate for the 16 tested filters installed in the test system. The minimum airflow rate decrease (~2%) was measured with a 1” MERV 1-4 filter installed. The maximum airflow rate decrease (~16%) was measured with a 1” MERV 13 filter installed. Figure 4 also shows that filters with extended depths were able to maintain higher airflow rates than those with lesser depths.

Finally, Figure 5 demonstrates that there was only a weak correlation (R^2 = 0.13) between measured filter pressure drop and manufacturer reported efficiency rating (i.e., MERV or MERV equivalent when other efficiency rating systems are converted to MERV using Table 1) when analyzing the data across all filter depths. However, there was a strong correlation between measured filter pressure drop and reported efficiency rating when analyzing only 1” or 2” depth filters (R^2 = 0.78 and 0.74, respectively), but no correlation when comparing only 4-5” filters (R^2 = 0.10). These data suggest that extended depth filters can achieve low pressure drop and high fine and ultrafine particle removal efficiency, but that 1” and 2” filters cannot.

Conclusions

We are beginning to build an online database of in-situ size-resolved particle removal efficiency measurements for a wide range of filters commonly used in residential buildings. With 16 filter tests completed to date, we have found that the removal efficiency for ultrafine particles generally ranged from ~35% to ~98% for MERV 8 filters and MERV 16 filters, respectively. For particle sizes between 0.3 and 1 µm, the removal efficiency of the filters ranged from a minimum of ~16% for MERV 1-4 filters to a maximum of ~99% for MERV 16 filters. Similarly, removal efficiencies for particle sizes 1 µm to 2.5 µm ranged from ~30% for MERV 1-4 to 100% for MERV 16. UFP removal efficiencies are more varied. These results are beginning to show that in order to achieve substantial removal of both fine and ultrafine particles by central HVAC filters in residential environments, higher efficiency filters than what is typically recommended in standards such as ASHRAE 62.2-2016 are required. We encourage you to ship us your clean (or dirty) filters if you want them tested and we will add your results to the online database!* ▪

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*We encourage you to ship us your new (or used) 16” x 25” filters for testing.

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