Study of Viral Filtration Performance of Residential HVAC Filters

BY JOHN ZHANG, PH.D., MEMBER ASHRAE; DOUG HUNTLEY; ANDY FOX; BRYAN GERHARDT; AL VATINE, MEMBER ASHRAE; JOHN CHERNE

Researchers recently carried out an experimental study to understand the efficacy and effectiveness of residential HVAC filters at removing airborne virus particles in the airstream. It concluded that high-efficiency residential HVAC filters were effective at capturing airborne virus particles in the air passing through the filter.

Background

Studies have shown that droplets generated by coughing and sneezing can contain bacteria and virus, which covers a very wide particle size range.[1] Small droplets can suspend in the air, then dry to form fine particles, which can stay in the air for hours. SARS-CoV-2, which is the virus responsible for COVID-19, is known to transmit through droplets, contact and aerosols. Recent research[2] discovered that SARS-CoV-2 can be widely distributed in the air and on object surfaces.

Another study[3] concluded that airborne transmission, particularly via nascent aerosols from human atomization, is highly virulent and represents the dominant route for the transmission of this disease. In another study,[4] viable virus was detected in aerosols up to three hours post-aerosolization. The World Health Organization[5] recommended the use of airborne precautions whenever applicable in addition to standard, contact and droplet precautions. ASHRAE's Epidemic Task Force[6] recently issued COVID-19 position statements, which indicate that transmission of SARS-CoV-2 through air is sufficiently likely that airborne exposure to the virus should be controlled.

Removing bioaerosols by filters and other devices has been extensively studied by researchers in the past (see sidebar). This study focused on viral filtration of residential HVAC filters with different minimum efficiency rating values (MERV), e.g., MERV 5, MERV 12, MERV 13 and MERV 14.

Test Method

Figure 1 is a diagram of the test system. The single-pass viral filtration efficiency of residential HVAC filters was measured using a virus aerosol challenge, MS2 bacteriophage, in a horizontal stainless-steel test duct constructed per ASHRAE Standard 52.2-2017,[7] *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*. MS2 is one of the four bioaerosols

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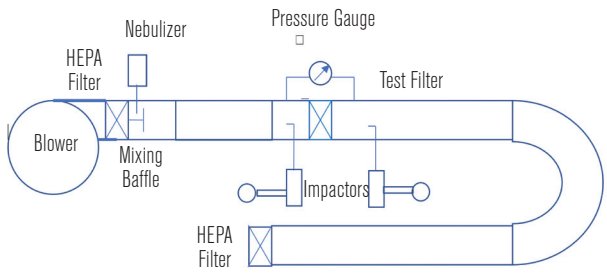
FIGURE 1 Test system for measuring viral filtration efficiency of HVAC filters.



recommended by the EPA[8] for air filtration tests. MS2 virus has approximately the same aerosol characteristics as a human virus and can serve as a surrogate for viruses of similar and larger size and shape. MS2 virion (viral particle) is about 27 nm in diameter, as determined by electron microscopy,[9] much smaller than the SARS-CoV-2 virion, which measures about 120 nm in diameter.[10,11]

Another test method used for evaluating the inactivation efficacy of an air cleaning device is ASHRAE Standard 185.1-2015, *Lights for Use in Air-Handling Units or Air Ducts to Inactivate Airborne Microorganisms*, which is developed for testing UV-C light devices in air-handling ducts for inactivation of airborne microorganisms. ASHRAE Standard 185.1-2015 uses *Mycobacterium parafortuitum* and *Aspergillus sydowii* as test microorganisms. In this study, MS2 bacteriophage was used as the test microorganism because it is safe to use and has the relevant size and shape to viruses that have significant public health concerns, such as the SARS-CoV-2 virus.

The tests were performed under positive pressure with a blower pushing air through a HEPA filter bank to provide particle-free air into the test duct airstream. MS2 microorganisms were grown on appropriate media, harvested and resuspended in saline to 5×10^6 plaque-forming units per milliliter (pfu/mL). Saline is commonly used in making bacterial suspension because the cells get acclimatized and escape being ruptured. Our experience showed that when using saline, specific size distribution of a virus can be achieved repeatedly.

Suspension of the organisms was then aerosolized into the test duct using a nebulizer. Nebulizers have been widely used for generating bioaerosols. Nebulizer generators produce droplet aerosols with mass median aerodynamic diameters of 1 µm to 3 µm.[12] Mixing baffles designed per ASHRAE Standard 52.2-2017 were mounted in the downstream of the inlet HEPA filter. The

Studies on Bioaerosol Removal

Eninger et al.,[14] investigated the feasibility of a novel testing protocol that allows differentiating between the physical (total) and viable bioaerosol penetrations through respirator filters. They found no statistically significant differences were observed between penetration values obtained for physical (total) and culturable viruses for the two control respirators. In another work,[15] a test system was designed to determine the removal efficiencies of fibrous air filter media with traditional nonbiological airborne particles (dioctyl phthalate, polystyrene latex, etc.) and bioaerosols. The study found that efficiencies measured with the bioaerosols and nonbiological aerosols had similar characteristics, with the efficiency for the former generally found to be a little higher.

The biological inactivation efficiency by HVAC in-duct ultraviolet (UV) light systems and filters was investigated in another study.[16] It found that the viral filtration efficiency and MERV rating had a similar trend, i.e., the higher the MERV, the higher the viral filtration efficiency. In other words, the filter efficiency measured with inert particles provided a fair indication of the filter performance against bioaerosols.

In research[17] conducted to assess if application of nonbiological aerosols reflects air filters' capacity to collect particles of biological origin, the collection efficiency for nonbiological aerosol was tested with the filter test system and ISO Fine Test Dust, while bioaerosols contained four bacterial strains of different shape and size: *Micrococcus luteus, Micrococcus varians, Pseudomonas putida* and *Bacillus subtilis*. Nonbiological aerosol-containing particles of the same shape and surface characteristics (like diethyl-hexyl-sebacat [DEHS] spherical particles) did not give representative results for all particles present in the filtered air.

John Zhang, Ph.D., is senior specialist, Doug Huntley is senior lab manager, Andy Fox is lead specialist and Bryan Gerhardt is an advanced specialist in the Construction and Home Improvement Market Division of 3M Company. Al Vatine is president and John Cherne is microbiologist at LMS Technologies.

MS2 aerosol was introduced upstream of the mixing baffles. An 8 ft (2.4 m) duct section was inserted between the mixing baffles and the sampling probe of the upstream impactor to improve the mixing. The distance between the aerosol injection point and the upstream sampling probe was about 10 ft (3 m), allowing uniform mixing of the clean air and aerosol and complying with the ASHRAE Standard 52.2-2017 requirement for achieving adequate mixing.

Figure 2 shows the particle size distributions of the MS2 bacteriophage aerosol in the test duct measured using a scanning mobility particle sizer (SMPS) at three different duct airflow rates. The particle size distributions were similar, indicating the stability of the MS2 aerosol in the test duct at different residence times, i.e., 1.3 s at 3400 m^3/h (2,000 cfm) and 2.5 s at 1740 m^3/h (1,024 cfm). The peaks of the distributions are between 30 nm and 60 nm, larger than the MS2 virion size of 27 nm, indicating that some droplets contained multiple virions.

The sampling point of the SMPS was at the same plane as the upstream sampling probe of the impactor. For each filter test, three upstream air samples and three downstream air samples were taken using impactors for 5 min at calibrated sampling rates of 28 L/min (7.4 gal/min). The impactor was the sixth stage of a six-stage sampler that had a cutoff size of 0.65 µm. Although the cutoff size of the impactor was larger than the peak size of the MS2 aerosol, a portion of the MS2 aerosol had particles larger than the cutoff size of the impactor and were collected by the impactor.

The collection plates, having a double layer of agar consisting of a hard Lysogeny broth (LB) bottom layer and a soft top layer incorporating *E. coli*, were then incubated at 35°C (95°F) and 96% relative humidity for 24 hours. After incubation, the recovered plaque-forming units (PFU) were enumerated. Only PFUs 1.0 mm or larger were counted.

Because viability of microorganisms in the test duct may affect the test results, the upstream PFUs and downstream PFUs of the empty test duct were measured and compared. The results are shown in *Table 1*. Although significant fluctuation existed in the upstream and downstream PFUs, the ratio of the upstream PFUs to the downstream PFUs remained relatively close together, indicating good viability of MS2 bacteriophage in the test duct.

FIGURE 2 Particle size distribution of MS2 bacteriophage aerosol.

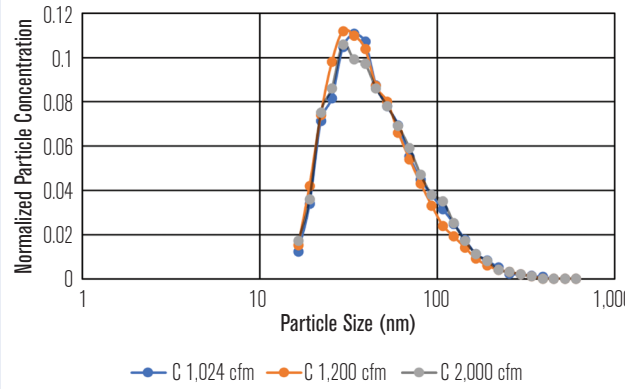


TABLE 1 PFU measurements in empty duct.

SAMPLE	UPSTREAM COUNTS (#)	DOWNSTREAM COUNTS (#)	UPSTREAM/DOWNSTREAM
1	167	159	1.05
2	306	321	0.95
3	98	89	1.10
Average			1.03

TABLE 2 Filter information.

FILTER ID	FILTER MEDIA BASIS WEIGHT, G/M^2	ELECTROSTATIC CHARGE	PLEAT SPACING, MM	MERV RATING	FILTER SIZE (IN.)	QUANTITY
A	50	Yes	16.7	5	20 × 25 x 1	6
B	65	Yes	7.1	12	20 × 25 x 1	6
C	65	Yes	7.1	13	20 × 25 x 1	6
D	75	Yes	5.6	14	20 × 25 x 1	6

The efficiency (E) was then calculated using the formula.

$$Efficiency = \frac{\text{Upstream PFU} - \text{Downstream PFU}}{\text{Upstream PFU}}$$

Filter Information

Four types of residential HVAC filters were investigated in this study. Because our intention was to focus this study on high-efficiency HVAC filters, i.e., MERV 12 and higher, we selected MERV 12, MERV 13 and MERV 14 filters because these high-efficiency filters are commonly used in homes. A MERV 5 filter was selected as a comparative filter. All filters were made with electrostatically charged filter media. Filter information is shown in *Table 2*.

Testing was conducted at 22°C (72°F) and 50% relative humidity. The flow rate of the air passing through the filter was set at 1740 m^3/h (1,024 cfm), resulting in a velocity of 1.5 m/s (295 fpm) at the face of the filter. Six samples of each filter type were tested one by one in sequence.

Test Results

As shown in *Table 3*, to avoid bias due to the test sequence, tests were run in a semirandomized order. The upstream PFU counts and downstream PFU counts were adjusted for hole corrections.[17] The upstream counts and downstream counts given are the averages of three air samples. The pressure drops across the filter, shown in inches of water gauge and Pascal, and calculated efficiencies are also shown.

Statistical analysis results for viral filtration efficiency (VFE) are shown in *Table 4*. Standard deviations of VFE were relatively wide, which can be attributed to the variability in the bioaerosol sampling, as well as relatively small sample size (N = 6). It is also interesting to see that the coefficient of variation decreases with the increasing MERV rating, indicating that results were more repeatable at higher MERV. The mean efficiency and median efficiency values were close to each other, indicating the test data was relatively symmetrically distributed.

Figure 3 shows the mean and 95% confidence interval (CI) of viral filtration efficiencies for MERV 5, MERV 12, MERV 13 and MERV 14 filters. MERV 5, MERV 12 and MERV 13 filters had a relatively wide spread in efficiency data and about a 20 point spread in the 95% CI. This wide spread of data can also be attributed the reasons discussed above.

TABLE 3 Efficiency and pressure drop of individual filters.

TEST ORDER	FILTER TYPE	PRESSURE DROP (IN. W.G.)	PRESSURE DROP (PA)	CORRECTED UPSTREAM COUNTS ()	CORRECTED DOWNSTREAM COUNTS ()	SINGLE-PASS EFFICIENCY
14	MERV 5	0.16	39	197	118	40%
20	MERV 5	0.18	45	87	53	39%
21	MERV 5	0.18	45	86	57	34%
22	MERV 5	0.17	43	82	57	30%
23	MERV 5	0.18	44	115	83	28%
24	MERV 5	0.17	42	136	120	12%
1	MERV 12	0.14	35	120	36	70%
2	MERV 12	0.15	36	198	59	70%
3	MERV 12	0.14	34	145	39	73%
4	MERV 12	0.17	41	185	36	80%
16	MERV 12	0.15	36	165	31	81%
19	MERV 12	0.17	43	136	10	93%
5	MERV 13	0.18	44	150	31	79%
6	MERV 13	0.16	40	138	29	79%
7	MERV 13	0.16	39	111	4	96%
8	MERV 13	0.17	42	106	9	92%
15	MERV 13	0.19	48	165	16	90%
17	MERV 13	0.22	54	44	1	98%
9	MERV 14	0.21	53	73	2	97%
10	MERV 14	0.24	61	107	5	95%
11	MERV 14	0.24	61	214	2	99%
12	MERV 14	0.24	59	183	6	97%
13	MERV 14	0.24	61	168	4	98%
18	MERV 14	0.26	64	112	5	96%

TABLE 4 Descriptive statistics of viral filtration efficiency data.

FILTER	N	MEAN	STD DEV	COEF VAR	MEDIAN	MINIMUM	MAXIMUM
MERV 5	6	32%	10.5%	32.8	36%	12%	40%
MERV 12	6	78%	8.8%	11.3	77%	70%	93%
MERV 13	6	89%	8.2%	9.3	91%	79%	98%
MERV 14	6	97%	1.4%	1.5	96%	95%	99%

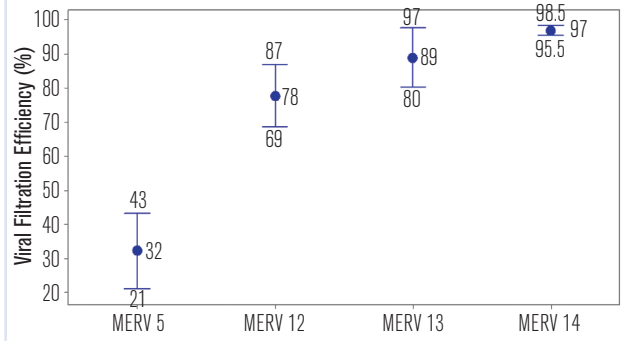
Descriptive statistics of the pressure drop data are tabulated in *Table 5*. In comparison to VFE data, the pressure drop data spread was much smaller, showing good consistency in pressure drop measurement. Since the HVAC industry often measures the pressure drop in inches of water gauge, *Table 5* also shows the mean pressure drop in inches of water gauge for each type of filter.

E_1 (0.3 µm to 1.0 µm), E_2 (1.0 µm to 3.0 µm) and E_3 (3.0 µm to 10 µm) efficiencies defined according to ASHRAE Standard 52.2-2017 are commonly used in residential and commercial HVAC applications. People are familiar with E_1, E_2 and E_3 efficiencies, while VFE is usually not reported for HVAC filters. It would be beneficial for filter users to know the relative relationship between VFE and E_1, E_2 or E_3.

Although MS2 virion is much smaller than potassium chloride (KCl) particles, the challenge aerosol used in ASHRAE Standard 52.2-2017, the MS2 bacteriophage aerosol contained particles larger than MS2 virions and particles collected by the impactor were greater than 0.65 µm. Therefore, the comparison of VFE versus E_1, E_2 or E_3 should be relevant.

Figure 4 shows the comparison of the viral filtration efficiency versus the E_1, E_2 and E_3 efficiencies of clean filters measured per ASHRAE Standard 52.2-2017. As shown in *Figure 4*, the viral filtration efficiency (VFE) is always higher than E_1, but lower than E_2 or E_3 efficiencies. In other words, E_1 efficiency can provide a conservative prediction for the viral filtration performance of a filter, also indicating that viral particles collected on sampling plates were likely to be in the size range of 0.3 µm to 3 µm, i.e., the lower size limit of E_1 and upper size limit of E_2. Note that the stability of the aerosol size distribution can have significant impact on the VFE measurement. Therefore, it is important to ensure the stability of the aerosol in the testing (see *Figure 2*).

FIGURE 3 Viral filtration efficiency with 95% confidence interval. N = 6.

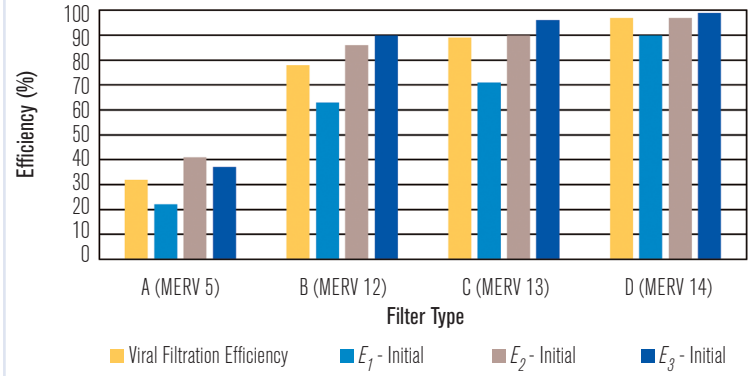


Individual standard deviations were used to calculate the intervals.

TABLE 5 Descriptive statistics of pressure drop data.

FILTER	N	MEAN, PA	MEAN, IN. W.G.	ST DEV, PA	COEF VAR	MEDIAN, PA	MINIMUM, PA	MAXIMUM, PA
MERV 5	6	43	0.17	2.3	5.2	44	39	45
MERV 12	6	38	0.15	3.5	9.2	36	34	43
MERV 13	6	45	0.18	5.6	12.6	43	39	54
MERV 14	6	60	0.24	3.1	5.1	60	54	64

FIGURE 4 Comparison of viral filtration efficiency versus E_1, E_2 and E_3. (Tested at 295 fpm.)



Summary

An experimental study was carried out to investigate effectiveness of residential HVAC filters at removing airborne virus particles. MS2 bacteriophage organisms were grown on appropriate media, harvested, resuspended in saline and then aerosolized into the ASHRAE Standard 52.2-2017 test duct using a nebulizer. Upstream and downstream air samples were taken using impactors. The collection plates were incubated, and the recovered plaque-forming units (PFU) were enumerated to determine the filtration efficiency of filters against virus particles. The following conclusions can be drawn from this study:

- High-efficiency residential HVAC filters were found to be effective at capturing airborne virus particles.
- Filter viral filtration efficiency (VFE) was found to be generally correlated to its MERV rating, i.e., the higher the MERV rating, the higher the viral filtration efficiency.
- In comparison to E_1, E_2 and E_3 efficiencies measured per ASHRAE Standard 52.2-2017, VFE was found to be higher than initial E_1 efficiency, but lower than initial E_2 and E_3 efficiencies.

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