INTRODUCTION

Recent studies provide incontrovertible evidence that SARS-CoV-2 spreads via airborne transmission, mainly through the long-distance transport of fine particulate matter (PM) in indoor environments.\(^1\)\(^2\) Therefore, there is an urgent need to find effective controls to limit indoor transmission of fine PM during and beyond the COVID-19 pandemic. High-efficiency filtration systems in heating, ventilation, and air conditioning (HVAC) systems play a vital role in controlling indoor air quality by removing various indoor air pollutants, such as particulate matter (PM), microorganisms (e.g., bacteria and viruses), and gaseous pollutants.\(^3\)

Filters, such as those rated with a minimum efficiency reporting value (MERV), are commonly used in HVAC systems to capture particles on filtration fibers.\(^3\)\(^-\)\(^7\) In addition, electrostatic enhanced air filters (EEAF) can assist particle removal by active ionization.\(^4\)\(^8\)\(^9\) In January 2021, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommended a MERV of no less than 13 filters for building HVAC systems,\(^10\) to reduce the transmission of indoor infectious airborne viruses in heating, ventilation, and air conditioning (HVAC) systems during the COVID-19 pandemic.

Minimum Efficiency Reporting Value 13 filters are a common choice for a single-stage filtration system. It is reported that...
compared to MERV 10 filters, MERV 13 filters reduce the average virus concentration by about 10% in office buildings, but increasing filter efficiencies above the performance of MERV 13 was associated with limited benefit. Multi-stage filtration systems are commonly used, especially for large commercial buildings. For example, a system that consists of final filters and prefilters makes it possible to prevent the rapid clogging of high-efficiency filters and considerably increases their lifetime to reduce operation costs.

Therefore, evaluating a multi-stage system assembled from different lower-performance filters (such as MERV 6, MERV 8, and MERV 11 filters) is necessary to offer a reference for selecting cost-effective filters.

A standardized method to evaluate the performance of filters installed in HVAC systems is provided in ASHRAE Standard 52.2 and is commonly used in rating commercial MERV filters in North America. To assess MERV filters, the standard defined three particle size efficiencies (PSE), \( E_1: 0.3–1.0 \text{ \mu m} \), \( E_2: 1.0–3.0 \text{ \mu m} \), and \( E_3: 3.0–10.0 \text{ \mu m} \) diameters as applied to salt particles. The standard has several limitations when evaluating filters’ ability to reduce infectious aerosol transmission. Zhang et al. used MS2 bacteriophage as a surrogate for a viral pathogen and found that particle size efficiency of \( E_1 \) provided a conservative prediction for the viral filtration performance of a filter. In addition for MERV 11 and MERV 13 filters, the \( PSE_{0.3–1.0} \) should be equal to or larger than 20% and 50%, respectively (under standard testing procedure). However, ASHRAE Standard 52.2 does not offer \( PSE_{0.3–1.0} \) reference values for lower MERV 8 filters. An absence of this information makes filter selection for two-stage HVAC filtration systems challenging.

Furthermore, the particle size distributions of infectious aerosols are necessarily considered on what particle sizes would be the most relevant for COVID-19 transmission. However, concentrations of virus-laden aerosol are still poorly known. The current evidence showed that depending on sampling locations, SARS-CoV-2 RNA existed at different size fractions (fine ≤2.5 \mu m, coarse 2.5–10 \mu m, and large ≥10 \mu m). Azimi et al. assumed that approximately 20%, 29%, and 51% of influenza RNA contents were associated with particles of 0.3–1.0 \mu m, 1.0–3.0 \mu m, and 3.0–10.0 \mu m, respectively. Connecting the size distribution of influenza virus to PSE from ASHRAE Standard 52.2, it is found that MERV 13 filters have 10%, 26%, and 45.9% of \( PSE_{0.3–1.0} \), \( PSE_{1.0–3.0} \), and \( PSE_{3.0–10.0} \), respectively. This result reveals that \( PSE_{0.3–1.0} \) is a particle size bin that deserves the greatest attention compared with other particle size ranges.

Another limitation of ASHRAE Standard 52.2 is the minimum diameter of 0.3 \mu m it recommends for the testing of PM, but it does not represent the worst-case scenario in terms of filter penetration. Abundant nanoparticles (defined as <0.3 \mu m diameter particles in this study) falling well below this limit are produced by various human activities, such as cooking, smoking, and cleaning, and be present in indoor environments. Experimental measurements of filtration performance on ventilation filters with particles smaller than 0.3 \mu m have already been presented in several papers. Hanley et al. reported that a minimum in efficiency often occurred in the 0.1–0.5 \mu m diameter size range for in-duct air cleaners. More importantly, the structure of SARS-CoV-2 ranges from 90 to 120nm, which mainly exists in saliva aerosols; the SARS-CoV-2 RNA has been detected in particles below 0.3 \mu m. Therefore, while the evidence for airborne transmission of SARS-CoV-2 loaded saliva nanoparticles is limited, it is nevertheless important to consider particles at a size of 0.1–0.3 \mu m.

This study aims to offer suggestions on evaluating and selecting suitable filters for HVAC filtration systems to remove infectious airborne particles, with a particular focus on two-stage filtration systems. The \( PSE_{0.1–1.0} \), \( PSE_{0.3–1.0} \) and quality factor (QF) of 12 commercial filters, including MERV filters, an EEAF and their combined two-stage filtration systems, were assessed by a pilot-scale testing rig. Besides, considering the electrostatic enhanced effects of active ionization, the EEAF sample was tested in the full-recirculation mode of the test rig. The removal efficiencies of the EEAF with and without charge were obtained by concentration decay experiment in a closed-loop experimental setup; therefore, its enhanced performance in a recirculated HVAC system can be demonstrated.

2 | EXPERIMENT

2.1 | Filters and characteristic tests

The selection of the tested filters was based on several considerations. (1) ASHRAE Standard 62.1-2019 recommended a MERV of not <8 that should be installed to remove PM\(_{10}\) in buildings, while a MERV of not less than 11 was recommended for removal of PM\(_{2.5}\). Therefore, MERV 8 and MERV 11 filters were chosen as the prefilter and final filter for the two-stage filtration system. (2) It is reported that for smaller particles (e.g., PM\(_{2.5}\)), there is little difference in the efficiency of a MERV 1 filter and a MERV 8 filter. Therefore, MERV
6+ MERV 11 filter combinations were chosen to compare performance distinction on $P_{SE_{0.1-1.0}}$ and $P_{SE_{0.1-1.0}}$.

Commercial MERV 6, MERV 8, MERV 11, and MERV 13 filters were purchased from Canadian retail stores during the COVID-19 pandemic. Each filter was cut into a square (keep original surface characteristics) and installed into a 12.70 × 12.70 × 2.54 cm filter holder whose edges were sealed by tape. Samples were prepared for each MERV-rating filter and correspondingly labeled, that is, the first MERV 6 sample was labeled MERV6-1 and so on. Table 1 shows the information of the samples. The pleat ratio is defined as the number of pleats per centimeter (pleat/cm). The thickness (Table 1) is the average of five-time measurements of the fiber thickness when the pleated filter is flattened.

A commercial EEAF (35.56 × 35.56 × 2.0 cm) composed of glass fibers and an active ionizing system was donated by a Canadian company. The charging system consisted of a bar charged by alternating current (AC) and a metal mesh case (grounded). To match the size of the filter (as shown in Section 2.2), a case (12.70 × 12.70 × 2.0 cm, with a grounded frame) was fabricated to house the glass fibers and the discharging bar as shown in Figure 1 (labeled as EEAF-S). In keeping with the design of the commercial EEAF, cotton threads provided structural support to the filter fibers. The discharging bar was connected to an AC adaptor with an output of 24 V and 200 mA (60 Hz). When the discharging bar was charged, an alternating electric field was developed, which contributed to aerosol aggregate to larger particles30 to improve the glass fiber efficiency.

For the two-stage filtration system, MERV 8 ($n = 3$) and MERV 6 filter ($n = 2$), and EEAF-S ($n = 1$) was used as the prefilters, and MERV 11 filters ($n = 3$) were final filters in the single-pass test rig. Consequently, there were nine MERV 8+MERV 11 filter combinations, six MERV 6+MERV 11 filter combinations, and three EEAF-S+MERV 11 filter combinations.

### Table 1: Descriptions of the MERV filters

| Label* | MERV ratings | Thickness (mm) | Pleat ratio (pleat/cm) | Pressure drop (Pa) | Filtration velocity (m/s) | Pressure drop (Pa) | Filtration velocity (m/s) | Pressure drop (Pa) | Filtration velocity (m/s) |
|--------|--------------|----------------|------------------------|-------------------|--------------------------|-------------------|--------------------------|-------------------|--------------------------|
| 13-1** | 13           | 0.518          | 0.49                   | 25.8              | 1.10                     | 46.7              | 0.83                     | 69                | 0.55                     |
| 13-2** | 13           | 0.545          | 1.35                   | 17.4              | 0.39                     | 29.6              | 0.29                     | 44                | 0.19                     |
| 13-3** | 13           | 0.637          | 1.39                   | 23.5              | 0.40                     | 40.6              | 0.30                     | 58.9              | 0.20                     |
| 11-1** | 11           | 0.795          | 1.24                   | 20.5              | 0.41                     | 37.3              | 0.31                     | 56                | 0.21                     |
| 11-2** | 11           | 0.559          | 0.52                   | 21.2              | 0.96                     | 35.5              | 0.72                     | 52                | 0.48                     |
| 11-3** | 11           | 0.721          | 1.21                   | 20.0              | 0.37                     | 34.5              | 0.28                     | 49                | 0.18                     |
| 8-1**  | 8            | 0.642          | 0.45                   | 20.3              | 1.04                     | 33.9              | 0.78                     | 49.5              | 0.52                     |
| 8-2**  | 8            | 0.372          | 0.50                   | 15.0              | 1.00                     | 25.9              | 0.75                     | 37.5              | 0.50                     |
| 8-3**  | 8            | 0.612          | 0.41                   | 23.0              | 1.15                     | 40.1              | 0.86                     | 58.9              | 0.57                     |
| 6-1**  | 6            | 0.412          | 0.36                   | 19.8              | 1.16                     | 33.1              | 0.87                     | 48.1              | 0.58                     |
| 6-2**  | 6            | 0.449          | 0.36                   | 16.1              | 1.45                     | 27.7              | 1.09                     | 40.1              | 0.73                     |

*1.0, 1.5 and 2.0 m/s are air velocities.; **a–f are labels of the manufacturers.

The initial pressure drops of the new filters were tested by a micro-manometer (TSI/Alnor Model 5825) at air velocities of 1.0, 1.5, and 2.0 m/s, as shown in Table 1. The thickness of the filter was measured by a digital micrometer thickness gauge (Mitutoyo absolute, Japan). The ozone concentration produced by the EEAF-S was measured by an ozone monitor (465 L, TELEDYNE-API, CA) by continuously sampling at the downstream sampling point (45° sampling probe) of the single-pass test rig $(1.0 \pm 0.1 \text{ m/s flow velocities})$.

### 2.2 Experimental setup and sampling

1. Experimental setup and devices

A multi-functional pilot-scale setup capable of operating in either closed-loop or single-pass mode was used. A schematic of the setup is shown in Figure 2. The square duct (12.70 × 12.70 cm² cross-sectional area) was integrated with a two-stage filtration system. The system had 2 slots for filter holders (2.54 cm width) with 5.08 cm gaps between the filters. Airflow was controlled and recorded by a customized control system (Opto 22, USA), consisting of 3 axial fans and a flowmeter (Model AT400, KANOMAX Inc., USA). In addition, the temperature and the relative humidity were recorded by the control system. MERV filters, EEAF-S, and their combinations were tested at air velocities of 1.0, 1.5, and 2.0 m/s, and a temperature of 18.0 ± 0.3°C in the single-pass mode of the test rig. Besides, to explore the agglomeration effects, EEAF-S and its combinations (with MERV filters) were tested at an air velocity of 1.1 ± 0.1 m/s and a temperature of 17.4 ± 0.6°C in the closed-loop test rig.

The distance from the aerosol injection point to the upstream air sampling section was only 50.8 cm, which was not enough to allow for good mixing; therefore, two cross-shaped sampling
probes (labeled as 45° and 90° sampling probes), an injection probe, and a mixing baffle were added (as shown in Figure 2); their designs are shown in Figure S1. The probes consisted of 20 holes of various diameters (5 holes per branch) on one side of the cross-tubes to ensure the airflow passing through each hole was the same. Besides, isokinetic sampling at upstream and downstream sampling points was evaluated by connecting a flow calibrator (Defender 510H, Mesalabs) with the isokinetic sampling probes and optical particle sizer. As a result, the sampling system can maintain isokinetic sampling within 10% at 1.0 m/s, 1.5 m/s, and 2.0 m/s air velocity.

The mixing baffle had a 40% open area on its plate surface, in accordance with the design guidance of ASHRAE Standard 52.2.16

Main apparatus qualification tests were conducted as shown in Table S1. As shown in Figure 2, the particle generation system was composed of compressed air, a Collison nebulizer (1 Jet, CH TECHNOLOGIES, USA), a Kr-85 charge neutralizer (Model 3077A, TSI Inc., USA), and a diffusion dryer (Silikagel, DDU 570, TOPAS). 20% KCl (20.0 g of KCl to 100 ml of ultrapure water) was used as the source of salt PM. An optical particle sizer (OPS Model 3330, TSI Inc., USA) was used to detect particles with diameters in the range of 0.3–1.0 μm and with channel sizes of 0.30–0.40, 0.40–0.55, 0.55–0.70, and 0.70–1.00 μm, through which size-resolved analysis was performed. Concentrations of 0.3–1.0 μm particles were obtained by adding the concentration values of all channels together. Concentrations of particles in size range of 19.5–299.6 nm (defined as 0.02–0.3 μm in this study) were measured by a Scanning Mobility Particle Sizer (SMPS) consisting of a differential mobility analyzer (DMA Model 3081, TSI Inc., USA) and a condensation particle counter (CPC Model 3776, TSI Inc., USA). For each sample, concentrations of 19.5–299.6 nm and 0.3–1.0 μm particles were detected by SMPS and OPS. Figure S2 shows an example of the average particle size distribution in upstream of the experimental setup for MERV 13 filters at 1.0 m/s velocity.

2. Sampling methodology in single-pass mode

For the single-pass test mode (Figure 2A), the OPS was connected to 45° sampling probes, while the SMPS was connected to 90° sampling probes. Filters were assessed in the following steps using the single-pass experiment test rig. First, three upstream and downstream background samples were continuously collected before feeding in the particles. Next, the compressed air (20 Psi) was turned on for the particle generation system. While particles were steadily fed into the duct, four upstream and three downstream aerosol samples were collected alternately at the upstream and...
downstream locations. Finally, the compressed air was turned off, and after 2 minutes, three background aerosol samples were taken at the upstream and downstream locations.

One additional upstream sample was collected so that the estimated upstream concentration \( U_{i,e,t} \) could be calculated by taking the average of two upstream measurements recorded before and after the downstream measurements \( D_{i,o,t} \) were taken. The PSE was obtained by Equation (1) and Equation (2), and the correlation ratio \( R \) was the ratio of downstream to upstream particle counts without the filter installed in the test duct, which was equal to \( P_{o} \) without a filter.31

\[
\text{PSE} = \left( 1 - \frac{\text{downstream particle concentration}}{\text{upstream particle concentration}} \right) \times 100 = \left( 1 - \frac{\bar{P}}{\bar{R}} \right) \times 100, \tag{1}
\]

\[
\bar{P}_{o} = \frac{\sum_{i=1}^{n} P_{i,o}}{n} = \left( \frac{\sum_{i=1}^{n} D_{i,o,t} - D_{b}}{U_{i,e,t} - U_{b}} \right)/n, \tag{2}
\]

Here, \( D_{b} \) and \( U_{b} \) are the average background counts before and after the penetration test at the downstream and upstream sampling points, respectively, and \( n \) is the number of samples \((n = 3)\).

3. Sampling method in a closed-loop mode

In the closed-loop test rig, the inlet and outlet of the OPS were connected to 45° sampling probes upstream and downstream of the filters, respectively (Figure 2B). Particles in a pilot-scale experimental setup decay quickly when certain filters (e.g., MERV 13 filters) were installed. Therefore, instead of maintaining the sampling time of the single-pass mode (1 min), the OPS was set to continuous sampling at 10 s intervals to obtain sufficient data points for decay curve fitting at the closed-loop mode.

For each experiment, after three background samples were collected at the beginning of the experiment, the compressed air (20 Psi) was fed into the nebulizer to inject particles into the closed-loop system until the total particle concentration \((0.3 \text{–} 1.0 \mu m)\) was larger than 1500 p/cm\(^3\). The compressed air was then turned off, and the particle injection halted. Sampling was stopped when the concentration measured by the OPS was near background values. The removal efficiencies of the filters for particles of \(0.3 \text{–} 1.0 \mu m\) diameters were calculated by Equation (3)-(6), and three tests were repeated to obtain the average value of the PSE by Equation (7) in a closed-loop test rig. Besides, the standard deviations were calculated based on the repeated test.
According to AHAM AC-1-2020, aerosol concentration in a closed-loop test rig can be expressed as a function of time,

\[ C_{ij} = C_{0i} e^{-kt}, \quad (3) \]

where \( C_{ij} \) is the concentration at time \( t \), \( C_{0i} \) is the initial concentration at \( t = 0 \) s, and \( k \) is the decay rate constant, which is obtained by

\[ k = \frac{\sum t_i \ln C_{ij} - (1/m) \sum t_i \ln C_{0i}}{\sum (t_i)^2 - (1/m) \sum t_i^2}, \quad (4) \]

where \( m \) is the number of data points.

The clean air delivery rate (CADR) in the duct system is obtained by

\[ CADR = Vk = Q (E_c - E_i), \quad (5) \]

where \( V \) is the volume of the test rig \((0.122 m^3)\), \( Q \) is the airflow rate, \( E_c \) is the total removal efficiency, and \( E_i \) is the system decay removal efficiency. Therefore, Equation (3) can be written as

\[ C_{ij} = C_{0i} e^{-\frac{Q(E_c-E_i)}{n} t}, \quad (6) \]

\[ PSE = \sum_{i=1}^{n} (E_{cn} - E_c) \quad (7) \]

2.3 Analysis method

1. Calculation of the overall removal efficiency

For a two-stage filtration system combining the \( PSE \) of filter 1 \( PSE_{d,filter1} \) and filter 2 \( PSE_{d,filter2} \) in series, the overall removal efficiency \( PSE_{d,overall} \) for particles with a diameter range of \( d \) (\( \mu m \)) could be predicted by Equation (8),

\[ PSE_{d,overall} = 1 - (1 - PSE_{d,filter1})(1 - PSE_{d,filter2}). \quad (8) \]

When AC was applied to the filters, PM passing through the polarized field was charged positively and negatively in alternation; then PM with positive and negative charges agglomerated with each other to form larger particles, which were easier to capture with the filter fibers. These agglomerated particles were also more likely to deposit on the duct wall of the test rig. Therefore, the overall \( PSE_{0.3-1.0} \) of an EEAF in the closed-loop test rig should consider the filter removal efficiency \( E_{c,EEAF} \), the mechanical system removal efficiency \( E_{cm} \), and the enhanced removal efficiency of the duct system \( E_{c,ed} \) as expressed in the following equation:

\[ PSE_{0.3-1.0,overall} = 1 - (1 - E_{c,EEAF})(1 - E_{cm})(1 - E_{c,ed}). \quad (9) \]

To obtain the enhanced removal efficiency for the MERV filters \( E_{c,MERV} \). Equation (9) was combined with the mechanical removal efficiency for MERV filters \( E_{c,MERV} \) obtained in the single-pass mode. The overall \( PSE \) \( (PSE_{0.3-1.0,overall}) \) for the combined MERV filters and the EEAF filter can be expressed as follows:

\[ PSE_{0.3-1.0,overall} = 1 - (1 - E_{c,EEAF})(1 - E_{cm})(1 - E_{c,MERV})(1 - E_{c,MERV}). \quad (10) \]

The recirculation rate \( R \) of the test rig was calculated by Equation (11).

\[ R = \frac{Q}{V}. \quad (11) \]

2. The quality factor

The quality factor \( (QF) \) is widely used to illustrate the relationship between the pressure drop \( (\Delta p) \) and the efficiency of a filter \( (PSE_{0.1-1.0}) \), as formulated in Equation (12). The \( QF \) reflects the performance of the filtration system; a higher \( QF \) means higher removal efficiencies and lower energy consumption caused by the filter pressure drop. It should be noted that the \( QF \) is comparable only to the same operating conditions.

\[ QF = -\ln \left(1 - \frac{PSE_{0.1-1.0}}{\Delta p} \right). \quad (12) \]

Spearman correlation \( (r) \) analysis was performed using SPSS software (SPSS Statistics 19).

3 RESULTS AND DISCUSSION

3.1 Particle size removal efficiencies of filters

The initial removal efficiencies of filters for 0.02–1.0 \( \mu m \) particles at 1.0 m/s, 1.5 m/s, and 2.0 m/s (air velocity) are shown in Figure 3. The average standard deviation (SD) in removal efficiencies across all filters and all particle sizes was 5%, with the result across all particle sizes ranging from 1% to 11% for individual filters. Two-stage filtration systems (MERV 8+MERV 11, MERV 6+MERV 11, and EEAF-S+MERV 11) were also tested by the experimental setup; Figures 4 and 5 show their particle size removal efficiencies at 1.0, 1.5, and 2.0 m/s air velocities, respectively. The average SD of removal efficiencies for a two-stage filtration system was 3%, with the average across all particle sizes ranging from 0% to 13% for each filtration system. Equation (8) was used to calculate the combined removal efficiency of two-stage filtration systems. The differences in the calculated and tested removal efficiencies were within 10% except for the results of 0.02–0.1 \( \mu m \) particles (Table S2).

The working mechanisms of fibrous filters can be explained by the effects of interception, diffusion, impaction, and settling (assuming that electrostatic interaction is negligible). Although the
Theoretical efficiency predicts the most penetrating particle size occurs around 0.3 μm, it is reported that smaller particles may show the lowest removal efficiency at a higher velocity.37

Brochot et al.38 explored the most penetrating particle size of different commercial filters and found that the 150–500 nm range provides a better estimation of the MPPS in size range of 20–500 nm. Hanley et al.24 found that a minimum filtration efficiency often occurred in the 0.1–0.5 μm diameter size range. Shi et al.21 reported that the MPPS for glass fiber filters was observed in the size interval 100–200 nm, while the MPPS for charged synthetic filters was observed in the size interval 40–100 nm. In this study, the lowest removal efficiencies occurred at 0.1–0.4 μm particles for all filters. At 1.0 m/s air velocity, all filters had the lowest removal efficiency at 0.3–0.4 μm particles, while for several filters and two-stage filtration systems, the lowest removal efficiencies were observed for particles at 0.1–0.3 μm when the air velocity was higher (1.5 and 2.0 m/s), as shown in Figures 3, 4 and 5. This result, combined with the conclusions of the literature, indicates that particles with 0.1–0.3 μm diameter should be considered for evaluating MERV filters, especially at high velocities.

3.2 Filtration performance comparison between MERV filters

The PSE0.3–10 and PSE0.1–10 of MERV 13, MERV 11, MERV 8, and MERV 6 filters at three velocities were assessed, as shown in Figure 6. According to ASHRAE Standard 52.2,16 the PSE0.3–10 of MERV 11 and MERV 13 filters should be equal to or larger than 20% and 50%, respectively (under standard testing procedure). The average PSE0.3–10 of MERV 13 filters were 54 ± 22%, 51 ± 21%, and 51 ± 14% at 1.0, 1.5, and 2.0 m/s, respectively, which met the requirement of the standard. It should be noted that the initial removal efficiencies were evaluated in this study, instead of removal efficiencies after the dust-loading procedure as the standard requested. The average PSE0.3–10 and PSE0.1–10 of filters were shown in Table S3.

Considering the impact of the MPPS, the PSE0.1–10 was regarded as the evaluating parameter in this study. The average PSE0.1–10 for MERV 13 filters was 50 ± 22%, 44 ± 21%, and 43 ± 13% at 1.0, 1.5, and 2.0 m/s, respectively. A high SD was found for MERV 13 filters, which was caused by the low performance of MERV 13-1 filters. The PSE0.1–10 for MERV 13-1 was 25%, 20%, and 28% at 1.0, 1.5, and 2.0 m/s duct velocities, while the average PSE0.1–10 of MERV 13-2 filter and MERV 13-3 filter was 63 ± 3%, 56 ± 2%, and 51 ± 1% at three velocities. As shown in Table 1, MERV 13-1 had the lowest pleat ratio (0.49 pleat/cm) and the thinnest thickness (0.518 cm) compared to other MERV 13 filters and even MERV 11 filters, leading to the worst performance of MERV 13-1 filter. The pleat ratio (Table 1) and the PSE0.1–10 at 1.0, 1.5, and 2.0 m/s were found to be positively correlated, with a correlation coefficient of 0.916, 0.914, and 0.808 (p < 0.01), respectively (as shown in Table S4). Therefore, for the selection of MERV filters, a larger pleat ratio is recommended.
**FIGURE 4** Particle size removal efficiencies of combined MERV 8 and MERV 11 filters tested at various air velocities

**FIGURE 5** Particle size removal efficiencies of combined MERV 6 and MERV 11 filters at various air velocities
The QF of MERV 13, MERV 11, MERV 8, MERV 6 filters, EEAF-S and two-stage filtration systems at three velocities were assessed, as shown in Table 2. For each MERV filter, QF decreased with the velocity increased. For MERV filters, the QF increases with the MERV rating, which means higher MERV ratings improve performance. Therefore, compared to MERV 6, MERV 8, and MERV 11 filters, MERV 13 filters have the best trade-off between the pressure drop and the QF.

On the one hand, filters with higher MERV 13 ratings have been used widely in buildings. ASHRAE Standard 52.2 required that MERV 13–16 filters should reach 50%, 75%, 85%, and 95% removal efficiencies on particle with 0.3–1.0 μm. Hecker and Hofacre tested various filters made by different manufacturers and found that for MERV 13 filters at each velocity challenge. Furthermore, by a simulation approach, it has been proved that MERV 13 filters were predicted to achieve risk reductions at a lower cost than outdoor air ventilation. Therefore, filters with MERV higher than MERV 13 are suitable for a single-stage filtration system to prevent transmission of 0.1-1.0 μm particles. On the other hand, it is reported that MERV 13 filters offered the best trade-off between performance and cost compared to other MERV filters such as MERV 14 and HEPA filters. Therefore, the conclusion can be that installing MERV 13 filters achieved the best performance in preventing airborne transmission of 0.1-1.0 μm particles for a single-stage filter system in the HVAC, although QF for filters with MERV higher than MERV 13 requires further exploration experimentally.

3.3 Filtration performance comparison between two-stage filtration systems

Figure 7 shows the PSE\textsubscript{0.1-1.0} of two-stage filtration systems. The average PSE\textsubscript{0.1-1.0} for MERV 8+MERV 11 filters at 1.0, 1.5, and 2.0 m/s were 51±4%, 40±5%, and 36±4%, while the results for MERV 6+MERV 11 were 42±4%, 35±5%, and 30±3%, respectively (Table 3). Pressure drops of filtration systems are shown in Figure S3. It indicates that the measured pressure drop is consistent with the calculated data for two filters. The pressure drops for MERV 6+MERV 11 and MERV 8+MERV 11 had no distinct difference. The QF for each two-stage filtration system was calculated by Equation (12), as shown in Table 2. The highest QF at each air velocity indicates that MERV 8+MERV 11 filtration system has the best performance compared to other combinations.

The PSE\textsubscript{0.1-1.0} of MERV 13 filters is regarded as the guideline to evaluate the removal efficiencies of the two-stage filtration systems. However, as discussed earlier, the high SD of the PSE\textsubscript{0.1-1.0} for MERV 13 filters was found, leading to the comparison of the two-stage filtration system with MERV 13 filters at each velocity challenge. Therefore, 50% of PSE\textsubscript{0.1-1.0} is chosen as a reasonable minimum value to evaluate the performance of a two-stage filtration system. On the one hand, according to ASHRAE Standard 52.2, a minimum 50% of PSE\textsubscript{0.3-1.0} is required for MERV 13 filters. On the other hand, the average PSE\textsubscript{0.1-1.0} of MERV 13 filters is smaller than or equal to 50%, which means 50% can be a conservative guideline for MERV 13 filters. As shown in Figure 7, PSE\textsubscript{0.1-1.0} for all MERV 8 and MERV 11 two-stage filtration systems were over or slightly lower than 50%.

### Table 2 QF (Pa\textsuperscript{−1}) of different filter samples

| Filter          | 1.0 m/s       | 1.5 m/s       | 2.0 m/s       |
|-----------------|---------------|---------------|---------------|
| MERV 13 (n = 3) | 0.0372 ± 0.0247 | 0.0175 ± 0.0120 | 0.0110 ± 0.0056 |
| MERV 11 (n = 3) | 0.0219 ± 0.0033 | 0.0107 ± 0.0025 | 0.0057 ± 0.0011 |
| MERV 8 (n = 3)  | 0.0133 ± 0.0042 | 0.0052 ± 0.0019 | 0.0032 ± 0.0014 |
| MERV 6 (n = 2)  | 0.0064 ± 0.0022 | 0.0032 ± 0.0009 | 0.0022 ± 0.0010 |
| EEAF-S (n = 1)  | 0.0045         | 0.0039         | 0.0012         |
| MERV 8+MERV 11 (n = 9) | 0.0179 ± 0.0018 | 0.0075 ± 0.0006 | 0.0046 ± 0.0004 |
| MERV 6+MERV 11 (n = 6) | 0.0141 ± 0.0020 | 0.0065 ± 0.0012 | 0.0037 ± 0.0006 |
| EEAF-S+MERV 11 (n = 3) | 0.0102 ± 0.0007 | 0.0049 ± 0.0005 | 0.0025 ± 0.0005 |
at 1.0 m/s. Average $PSE_{0.1-1.0}$ of MERV 8 + MERV 11 filters were 40% and 36% at 1.5 and 2.0 m/s, respectively, which were lower than 50%. $PSE_{0.1-1.0}$ of MERV 6 + MERV 11 filters and EEAF-S + MERV 11 filters cannot reach the minimum requirement of 50%. In conclusion, the two-stage filtration system (MERV 8 + MERV 11) is comparable to MERV 13 at 1.0 m/s air velocity, but insufficient at 1.5 and 2.0 m/s operating conditions.

### 3.4 Characteristics and performance of the electrostatic enhanced air filter

This study used an AC electric field-based filter (EEAF-S), which removes particles ascribed to active ionization effects. The morphology of the EEAF-S is shown in Figure S4, which presents that the PM deposits on the surface of the glass fibers after use. However, low-ozone emission is possibly generated from EEAF as a by-product during the active ionizing process, which can damage respiratory organs and degrade various materials. Therefore, it is necessary to examine the ozone generation of the developed EEAF-S. As shown in Figure S5, when the EEAF-S was charged, no ozone increase was observed at the downstream sampling point compared with the non-charged operation.

There is no clear standard protocol for the evaluation of EEAF. However, considering that small particles possibly tend to agglomerate by active ionization effects over time into large particles removed by deposition or recirculation, EEAF-S and its combinations with MERV filters were tested in a closed-loop test rig at 1.0 m air velocity. According to Equation (11), the recirculation rate (at 1.0 m/s air velocity) is 475/h for the closed-loop setup, which is much higher than that for real conditions (e.g., 6/h) and AHAM AC-1-2020 (about 45/h). Therefore, the testing result under the closed-loop test rig cannot represent the performance in a real building. Besides, it should be mentioned that although $PSE_{0.1-1.0}$ was used to evaluate filters in Sections 3.2 and 3.3, because of the experiment limitations, only 0.3–1.0 μm particles could be detected in the closed-loop test rig. This section aims to demonstrate the electrostatic enhancement of EEAF-S in a full recirculation condition, in which the HVAC systems in buildings are commonly operated for energy-saving purposes.

First, we compared the $PSE_{0.3-1.0}$ of MERV filters under single-pass mode and closed-loop mode to demonstrate the feasibility of using a closed-loop mode to assess the performance of the filters. The $PSE_{0.3-1.0}$ of MERV 6-1, MERV 8-1, MERV 11-2, and MERV 13-3 samples tested in the closed-loop and single-pass test rigs, respectively, are shown in Table 3. The results showed that the $PSE_{0.3-1.0}$ for a MERV filter in a single-pass system or a closed-loop system was consistent (the differences in the $PSE_{0.3-1.0}$ were ≤3%), and the closed-loop test rig could be used in the particle (0.3–1.0 μm) removal test. Besides, the testing results in the upstream and downstream were compared, and it is indicated that the calculated removal efficiencies (by Equations (6) and (7)) were the same under the same operational condition.

The EEAF-S, the two-stage filtration systems combining MERV 6-1 and EEAF-S or MERV 8-1 and EEAF-S, were assessed in both

![Figure 7](image-url)
closed-loop and single-pass modes (Table 4). The decay curves for these filters in the closed-loop test rig are shown in Figure 56; Equation (4) was used for curve fitting. When the EEAF-S was uncharged, its removal efficiency was very limited (1%). When it was charged, the EEAF-S exhibited $P_{SE_{0.3-1.0}}$ of 13 ± 2% in the single-pass mode test rig. The $P_{SE_{0.3-1.0}}$ was observed to be 2% higher when the EEAF-S was tested in the closed-loop test rig as compared to the single-pass mode. Therefore, the enhanced duct removal efficiency due to particle charging could be calculated by Equation (9), in which the $E_{c,EEAF}$ was assumed to be the average $P_{SE_{0.3-1.0}}$ of the EEAF-S in the single-pass test rig (13%), and the $E_{c,s}$ was 1%. These values were tested using the procedure outlined in Section 2.2 for the closed-loop test rig before the installation of the filters. Consequently, the enhanced efficiency due to the duct deposition of agglomerated PM could be calculated as 1%

The $P_{SE_{0.3-1.0,overall}}$ for the combinations MERV 6-1 + EEAF-S and MERV 8-1 + EEAF-S in the single-pass test rig were 26% and 33%, respectively, as calculated using Equation (8), while the experimental data were 26 ± 2% and 35 ± 4%, respectively. The calculated data were consistent with the experimental data for a single-pass mode. The $P_{SE_{0.3-1.0}}$ for MERV 6-1 + EEAF-S, and MERV 8-1 + EEAF-S in a closed-loop mode reached 50 ± 2% and 57 ± 2%, respectively, results much higher than those for the single-pass mode, owing to particle aggregation. In addition, results of MERV 6-1 + EEAF-S and MERV 8-1 + EEAF-S filtration systems had similar $P_{SE_{0.3-1.0}}$ of MERV 13 filters at similar velocities.

The enhanced removal efficiency ($E_{c,MERV}$) for the MERV filter in the two-stage filtration system was calculated using Equation (10). Compared to the single EEAF-S, the combination of MERV filters and the EEAF-S caused a length change in the reactor (2.54 cm length of the duct was occupied by the MERV filters), which was negligible. Thus, the term of $(1 - E_{c,s})(1 - E_{c,EEAF})$ was the same in Equation (10) and Equation (9). Assuming the $E_{c,MERV}$ was the average value of the $P_{SE_{0.3-1.0}}$ of MERV filters in the single-pass mode, the $E_{c,MERV}$ for MERV 6-1 and MERV 8-1 samples were 68% and 65%, respectively. As a result, the two-stage filtration system combing EEAF has obvious enhanced performance when EEAF is charged.

### 3.5 Limitations

The limitations of this study were related to the laboratory-scale experimental setup and the limited number of filter samples used in the experiments. Laboratory tests provided nominal efficiency measurements, but the in situ efficiency of the filters and changes in filter performance over time might show a discrepancy in real-life applications.

For example, the particle feeding time and the volume of the injected compressed air had to be strictly controlled to ensure the repeatability of the experiment. Moreover, only 0.3–1.0 μm PM was assessed by the OPS in the closed-loop system. PM with diameters of 0.02–0.3 μm was not considered because the CPC used butanol as a condensation liquid, and thus, its outlet could not be connected with the closed-loop setup. The recirculation rate of the closed-loop setup is much higher than that for real conditions. Therefore, the amount of electrostatic enhancement of EEAF-S and its combinations should be evaluated under real conditions. Besides, the ion concentration of the EEAF requires further exploration to obtain the removal efficiency in a real building.

Although 11 commercial MERV filters, one electrostatic enhanced air filter, and their combined filtration systems were assessed in this study, the tests performed nevertheless fall short of representing the performance of all filters on the market. In addition, the practical performance of filtration systems is influenced by parameters such as the filter position in a filter combination, potential leakage during its installation, and the maintenance of the filtration system and the electrical components (e.g., the charging bar of EEAF), which should be necessarily considered in applying the results in the practical conditions. Finally, KCl salt particles were not representative of all virus-loaded particles. Further research is required to assess the performance of filters in the removal of various infectious particles.

### 4 CONCLUSIONS

Filtration in the HVAC has been regarded as one of the engineering strategies to reduce the transmission of infectious viruses such as SARS-Cov-2. This study tested particle size removal efficiencies (0.02–1.0 μm) for 11 commercial MERV filters, an electrostatic enhanced air filter, and their combinations as two-stage filtration systems at three air velocities in a pilot-scale experimental test rig. The results offer insights on upgrading ASHRAE Standards and filter selections for single-stage and two-stage filtration systems during the COVID-19 pandemic.

It is suggested that $P_{SE_{0.1-1.0}}$ should be considered as a more conservative parameter to evaluate filters, compared with the $P_{SE_{0.3-1.0}}$ in the ASHRAE Standard 52.2. The average $P_{SE_{0.1-1.0}}$ for MERV 13 filters ($n = 3$) were 50 ± 22%, 44 ± 21% and 43 ± 13% at 1.0, 1.5 and 3.5 μm.
2.0 m/s air velocities. Regardless of MERV ratings, the pleat ratios of filters and $PSE_{0.1-1.0}$ are positively correlated, indicating that filters with higher pleat ratios are recommended in selecting filters.

For a single-stage filtration system, MERV 13 filters presented the best performance owing to their higher average QF compared to MERV 11, MERV 8, MERV 6, and EAAF filters. MERV 8 + MERV 11 systems showed the highest QF compared to other two-stage combinations. Chosen 50% of $PSE_{0.1-1.0}$ as the minimum requirement of a two-stage filtration system, MERV 8 + MERV 11 systems can meet the requirement of 50% at 1.0 m/s, referring to the performance of MERV 13 filters, but their performance is still low at higher air velocities. Therefore, although MERV 8 and MERV 11 filters are suggested as the prefilters and final filters in the ASHRAE Standard 62.1–2019, MERV 8 + MERV 11 filtration systems are insufficient for a two-stage filtration system for reducing the transmission of infectious aerosols such as SARS-CoV-2 at 1.5 m/s and 2.0 m/s velocity, but are sufficient at 1.0 m/s air velocity.

Although EAAF-5 and its two-stage filtration systems showed the lowest QF, their enhanced performance was observed when it was installed in a full-recirculation test rig due to particle agglomeration.

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CONFLICT OF INTEREST

The authors have no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data are available on request from the authors.

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