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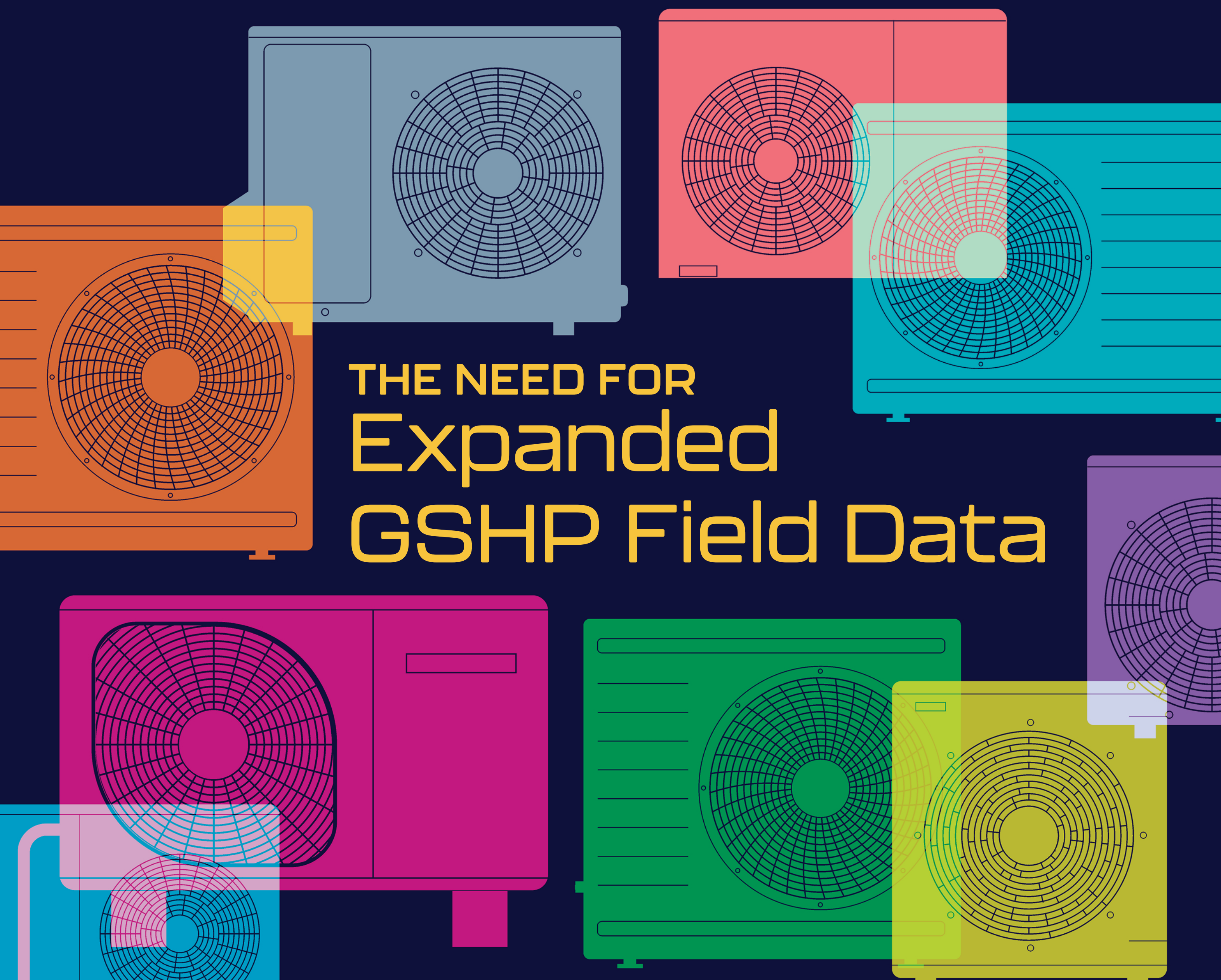

THE NEED FOR Expanded GSHP Field Data

Combined Standard 62.1/170 Ventilation Calculation | Non-Thermal Plasma Air Purification | 'Zero Energy Ready' Homes | Suppliers' New Product Preview

TOM HOLDSWORTH PHOTOGRAPHY

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Airborne Particulate Matter Filtration Using Non-Thermal Plasma Air Purification

BY TIMOTHY LAU, PH.D.; MARTIN BELUSKO, PH.D.

Particulate matter typically consists of small solid or liquid particles that can remain suspended in the air for long durations. It is typically less than tens of µm in size and can be carried over large distances by the airflow, both in natural environments (e.g., wind) or in mechanically assisted systems. In addition, it is almost impossible to avoid due to the sheer number of sources, which may include common household dust, pollen, powders, construction dust, bushfire smoke, etc. A new generation of air filtration systems to reduce airborne particulate matter is emerging that relies on air purification, rather than purely on capture and storage. One such option is via the use of non-thermal plasma air purification devices. In this article, the authors aim to provide experimental measurements demonstrating the efficacy of a plasma filtration system (PFS) under various conditions relevant to HVAC systems.

It is now well established that inhalation of small solid or liquid particles, particularly those around the 0.1 µm to 3 µm range, can have significant adverse impacts on human health, both short and long term.[1] For example, estimates are that more than 4 million people die prematurely each year alone due to the effect of atmospheric particles smaller than 2.5 µm ($PM_{2.5}$).[2]

Additionally, the transport of airborne droplets is also a likely mode of airborne pathogen transmission. In particular, respiratory pathogens such as the coronaviruses responsible for the SARS, MERS and recent COVID-19 outbreaks are likely to spread via transmission of liquid particles.[3]

Therefore, an urgent and important need exists for effective methods to remove and filter particles from airstreams, particularly within confined environments

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such as those serviced by mechanical ventilation.

The importance of maintaining healthy indoor air quality (IAQ) within buildings is well established, with building rating schemes such as the U.S.'s LEED, United Kingdom's BREEAM and Australia's Green Star rating systems acknowledging the importance of indoor environmental quality. One method to improve IAQ is through supplying a conditioned space with outdoor air in excess of the minimum requirements (i.e., over-ventilation). However, this may have a significant penalty on energy consumption, as the outdoor air is typically conditioned when brought into the building where the outdoor air is intemperate. Furthermore, this may require larger fans and ductwork, which in turn may significantly increase capital cost, particularly for larger buildings where long duct runs may be required.

Another method to improve IAQ is to use high efficiency filtration systems. A commonly used classification for high efficiency filters is HEPA, which is defined slightly differently for different standards (*Online Table 1,* http://tinyurl.com/JournalExtras).[4,5] In most cases, true HEPA-rated filters should have a minimum particle collection efficiency of 99.95% (or 99.97% according to some standards, e.g., U. S. Department of Energy[6]) for the most penetrating particle size (see Background section).

HEPA filters are typically made of tightly woven, random arrangement of fibers or porous materials, which allows them to capture small particles much more efficiently than conventional filters. However, the disadvantage of using HEPA filters is that they introduce a significant pressure drop within the mechanical ventilation system, which significantly increases fan energy consumption and potentially fan size and cost. For this reason, HEPA filters are typically only used for specific applications where the removal of PM is paramount (e.g., intensive care units).

The new generation non-thermal plasma air purification devices typically rely on passing the particle-laden airstream through a high intensity electric field generated by applying a high voltage between discharge and ground electrodes, separated by a small gap of dielectric material.[7] The electric field can generate a large volume of high-speed, low-energy electrons, which are then introduced into the airflow.

Recently this technique has been used to remove PM, as the free electrons can increase the propensity of the particles to agglomerate or to stick to other surfaces.[8] This technology is similar to electrostatic precipitators (ESPs), with the major difference being that in ESPs particles are collected on collection plates within the device, while plasma purification systems typically use porous media filters in conjunction with the plasma field to collect the particles.

In the latter, the plasma field can potentially increase overall particle collection efficiencies by causing the particles to stick to the post-filter or to increase the effective particle size so they are more easily captured by the post-filter. The advantage of this method relative to HEPA filters is that it potentially reduces harmful particles from the airstream with significantly less pressure drop and with only minimal electricity input.

However, while this technology offers significant advantages as a potential replacement for porous media filters in ducted HVAC systems, it has not been widely used because there is a lack of data clearly demonstrating its efficacy under practical settings.

Background

The efficiency and effectiveness of filtration systems can be classified and/or rated in different ways, depending on the application. Arguably the most straightforward method to rate a filter is through its single-pass particle collection efficiency, defined as

$$\eta = \frac{C_o - C_i}{C_i}$$

where C_i and C_o are the particle concentration (count per unit volume) upstream and downstream of the filter, respectively. The collection efficiency not only depends on filter characteristics, but may also be a function of particle diameter and flow conditions, such as face velocity. Therefore, collection efficiency is usually specified either at a specific set of conditions or as an average value.

Filter efficiencies can also be measured by introducing instantaneous particulate matter load in the room and measuring the time it takes to return the PM levels to a specified level based on the preload conditions. Using this method, we can define the particle removal efficiency, ρ, defined as

$$\rho(t) = C(t)/C_{init}$$

where $C(t)$ is the PM concentration after a certain time, t, and C_{init} is the initial PM concentration.

As previously noted, all these measures of efficiencies can significantly depend on the particle size ranges. This is because the physical mechanisms in which particles are collected in dense media filters (e.g., cloth filters, HEPA filters) depend on the particle size. For very small particle sizes (0.1 µm), particles are generally small enough such that they are significantly affected by Brownian motion (due to random collisions by atoms and molecules). Particle trajectories therefore have a significant random component and through this random motion may collide and stick with filter fibers. This is called the diffusion regime.

For large particles (3 µm), the particles have significant inertia and will typically directly impact on the fibers and stick. This is called the impaction and interception regime. However, for intermediate particle sizes, particles tend not to have significant random motion nor have significant inertia. As a result, porous media filters are typically at their lowest collection efficiencies at these intermediate particle sizes.[9]

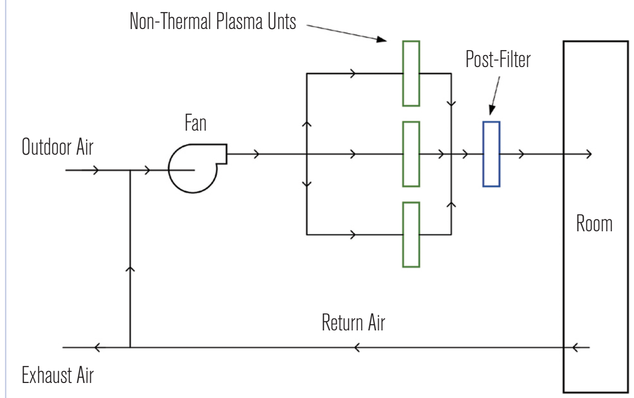
The particle size corresponding to the lowest filter efficiency is called the most penetrating particle size (MPPS). The efficiency of HEPA filters is usually rated at the MPPS; however, a MPPS of 0.3 µm is sometimes assumed as this is the typical mass-median diameter of the dispersed oil particulates used in testing of HEPA filters.[5] Therefore, to compare the efficacy of plasma filtration technology and conventional dense media filtration, the present study will also focus on measurements with particle sizes that have a diameter of approximately 0.3 µm.

Experimental Setup

Experiments were conducted of a non-thermal plasma filtration system comprised of three separate in-duct plasma units configured to run simultaneously in parallel within the ductwork, with a provision for a separate post-filter downstream of these (*Figure 1*). These plasma units also contain internal class G2 porous media filters at the exit, which primarily act as flow homogenizers. These units were chosen on the basis that they produced negligible amounts of ozone[10] and were designed for servicing ducted airflows, and hence are widely relevant to the HVAC sector. For the base case measurements, a single MERV 13 (particle collection efficiency for 0.3 µm to 1.0 µm particles = 50% to 75%) post-filter was used.

Two separate experiments were conducted within an unused cleanroom facility. These experiments were comprised of a) single-pass measurements and b) smoke recovery tests. They were conducted across two separate rooms with a volume of 41.25 m^3 (1,457 ft^3) and 23.26 m^3 (821 ft^3), respectively. The general ductwork arrangement for these experiments is shown in *Figure 1*.

FIGURE 1 General duct arrangement of the plasma filtration system (PFS). The fraction of outdoor air and return air are different for the different experiments.

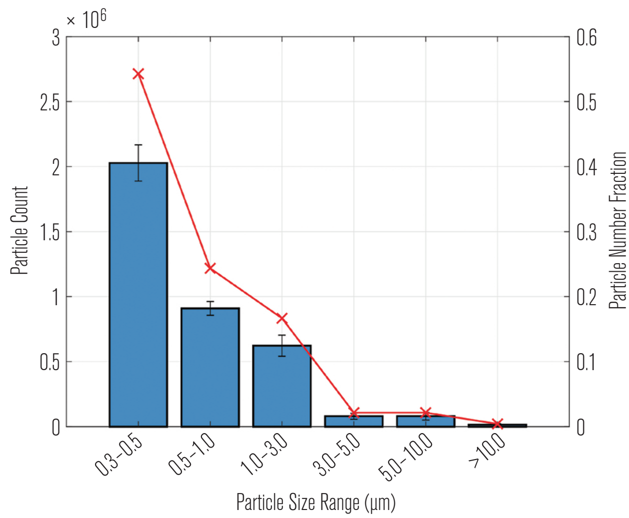


For the single-pass measurements, the mechanical ventilation system operated using 100% outdoor air with the flow rates varied within the range of 84 L/s to 217 L/s (178 cfm to 460 cfm), resulting in face velocities of 0.62 m/s to 1.6 m/s (122 fpm to 315 fpm). These face velocities are lower than the typical maximum face velocities (≈2.5 m/s [500 fpm]) used in porous media filters within commercial HVAC systems. The flow rates through the PFS could potentially be increased by increasing the number of non-thermal plasma units, and/or through using larger units.

During the experiments, the outside air temperature and relative humidity were 21.5°C (71°F) and 30.8%, respectively. The use of outdoor air introduced ambient levels of PM into the filtration system, with the particles having a particle size distribution consistent with typical mechanical ventilation systems. Instantaneous particle count measurements were conducted simultaneously at the centers of the outdoor air intake and outlet register (the latter within the room). The measurements were repeated four to six times for each flow rate, achieving a variation in measurement for each case of <±7% (±1 standard deviation).

For the smoke recovery experiments, the mechanical ventilation system operated using 100% return air. A 60 W, 0.4 m (1.3 ft) pedestal fan was used continuously within the room for the entire duration of the test to improve internal mixing. The flow within the duct

FIGURE 2 Particle size distribution measured at the inlet of the outdoor air duct used in the single-pass experiments. The bar chart denotes particle count, while the red crosses denote the particle number fraction (of the total).



(and through the de-energized PFS) was operated for two hours prior to the measurements to achieve a "baseline" PM concentration within the room. Then, the flow into the room was turned off for two minutes, before a lit cigarette was introduced in the middle of the room. After a few puffs of smoke were generated, the cigarette was removed from the room. After a further three minutes, the flow into the room and the PFS were turned on. Then particle count measurements were made at regular time intervals for 20 minutes. The flow rate of the mechanical ventilation system was fixed at 193 L/s (409 cfm, equivalent to 30 air changes per hour).

For all experiments, particle counts were measured for six different size ranges from 0.3 µm to >10 µm using handheld particle counters (mounted with isokinetic probes).

Results

Steady-State Single-Pass Measurements

Figure 2 presents the particle size distribution measured at the inlet to the outdoor air duct (i.e., before any filtration). The results show that there are significantly more small particles than larger ones, with >78% of particles having a diameter of 1 µm or less. Importantly, the number of particles in the range close to the expected MPPS, 0.3 µm < d_p < 0.5 µm, is significantly greater than all other particle size ranges, with the number of particles within this small range in excess of 100 times the total number of all particles above 10 µm. This highlights the importance of designing filtration systems that are effective at these small size ranges.

Single-pass particle collection efficiencies, η, for the PFS with the MERV 13 post-filter are shown in *Figure 3* as a function of five different face velocities (corresponding to five different flow rates). The results for d_p >5 µm are not shown here because values of η for these cases were close or equal to 100% for all investigated face velocities. Results here show η decreases as the face velocity increases. This is to be expected because a higher face velocity results in a decreased particle residence time within the filter plasma chamber, which in turn results in a lower probability that a particle will be influenced by the plasma field.

Furthermore, an increase in face velocity is also known to result in decreased collection efficiencies in porous media filters due to the reduction in the opportunity for the particle to undergo Brownian motion and the increased particle inertia relative to the attraction forces between the particles and the porous media fibers.[11]

The results also show that particle collection efficiency decreases as particle size decreases, with η being the lowest for the 0.3 µm to 0.5 µm particles, as expected. Nevertheless, the PFS system with MERV 13 post-filter is shown to be highly efficient at removing all measured particle sizes, with efficiencies of η >99.95% (similar to a HEPA H13 filter) for face velocities <1 m/s (<197 fpm). At the highest tested face velocity (1.6 m/s [315 fpm]), the efficiencies decrease slightly to η >99.72%.

Figure 4 presents the single-pass particle collection efficiencies for cases with and without the use of a MERV 13 post-filter. Also shown are the results for the case where a MERV 13 post-filter was used, but the PFS was turned off. In each of these cases, a G2 internal porous media filter was used in each plasma unit as part of the default unit configuration. The results show that with the post-filter installed, the particle collection efficiencies approach 100% for all particle sizes, consistent with the data presented in *Figure 3*.

However, when the post-filter is removed, there is a decline in the values of η, particularly for the smaller particle sizes. This is consistent with the hypothesis that the non-thermal plasma causes particles to more likely agglomerate to other particles (resulting in larger particle sizes) and to stick to the post-filter. This provides evidence that it is the combination of non-thermal

FIGURE 3 Single-pass particle collections efficiencies of the plasma filtration system (with a MERV 13 post-filter) as a function of face velocity. Note that the data for particle sizes larger than 5 µm are not shown here because the values of η were close to 100% for all face velocities.

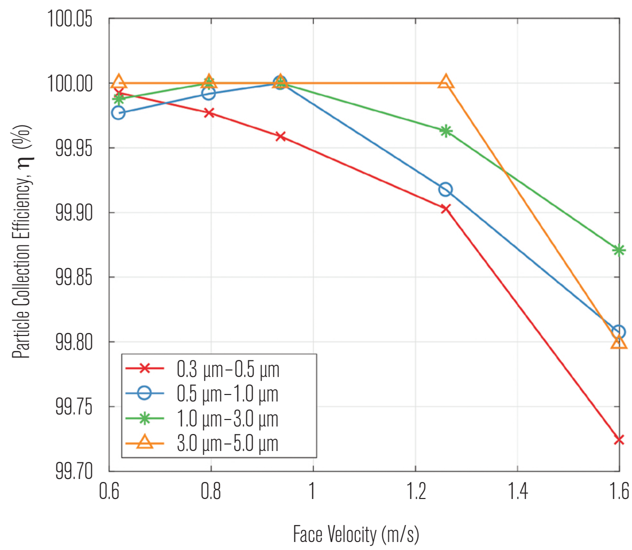
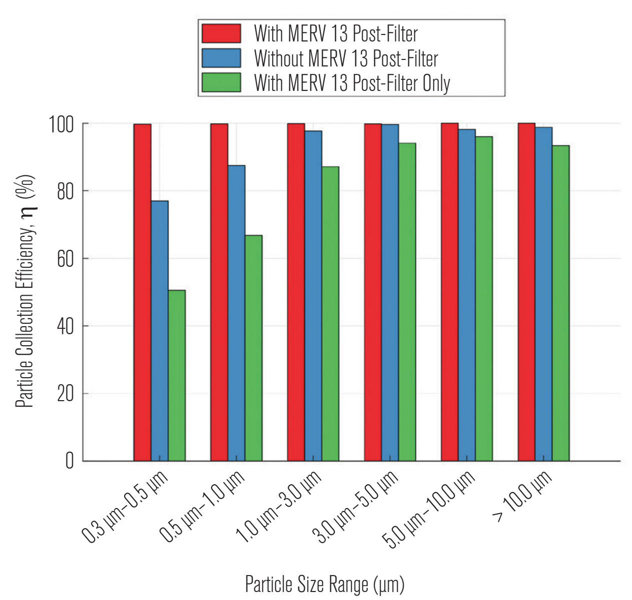


FIGURE 4 Particle collection efficiencies across different particle size ranges for cases with and without the MERV 13 post-filter, together with the case where only a MERV 13 post-filter was used (i.e., with the PFS turned off). In this case, the flow rate was fixed at 2099 L/s (44,319 cfm). In all cases, a G2 internal filter was used within each plasma unit.



plasma with conventional porous media filters that provides the highest particle collection efficiencies. Nevertheless, even without a post-filter, the PFS still has a minimum efficiency of η >76.98% across all measured particle sizes and an efficiency of 82.2% for 0.3 µm to 1.0 µm particles, which is similar to a conventional MERV 14 filter.[12]

Results also show that the particle collection efficiency of the MERV 13 post-filter alone (with the PFS turned off) has a minimum value of 50.6%, significantly lower than with the PFS turned on. In fact, the MERV 13 post-filter alone has a lower value of η than the case where the post-filter is used in combination with the energized PFS for all measured particle size ranges. This demonstrates that the PFS can significantly augment the collection efficiencies of porous media filters, particularly for small particle size ranges (0.3 µm to 1.0 µm).

Smoke Test

Figure 5 presents the time-series of particle count for six different particle size ranges between 0.3 µm to 10 µm for smoke tests where the PFS operated with a MERV 13 post-filter. The results at time t = -1 min were the "baseline" measurements made before smoke was introduced into the room. As can be seen from the results, the introduction of smoke significantly increases the number of particles, particularly those within the 0.3 µm to 1.0 µm range. This is expected because smoke particles tend to have diameters that are on the order of ≈0.5 µm. The increase in the number of small particles at time t = 0 min, in particular the number of 0.3 µm particles, which increases from 2.2×10^5 to 6.1×10^8 (i.e., more than a 2,700 fold increase), shows the introduction of a few puffs of a cigarette introduces a sufficient number of particles into the room for the tests.

After the PFS is turned on (t = 0 min), there is a steady decline in the number of smoke particles, particularly those below 1.0 µm. The trend of this reduction is approximately exponential, with the most significant reduction occurring in the first 10 minutes or so. By ≈15 minutes after the PFS is turned on, the number of particles is reduced close, but not exactly, to the baseline. *Figure 6* presents the particle removal efficiency, ρ, as a function of time for the smoke tests. Only the results for the three smallest particle size ranges are presented here because the number of large particles introduced by the smoke was relatively small, resulting in noisy data. The results show that more than 85% of the smoke particles of all sizes are removed by the PFS within the first five minutes. By 15 minutes, this increases significantly, with 99.8% (i.e., >2 $\log_{10}$ reduction) of smoke particles removed (see *Figure 6* inset). Results also show particle removal efficiency seems to asymptote to 99.8%. The reason is unclear, but

FIGURE 5 Particle count measurements versus time for the smoke test. Note that the data point at t = 5 min for the 0.5 µm – 1.0 µm diameter particles was removed because it was deemed as unreliable.

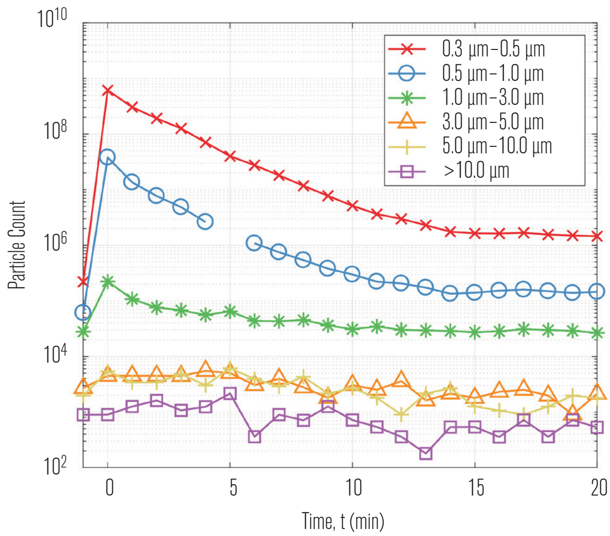
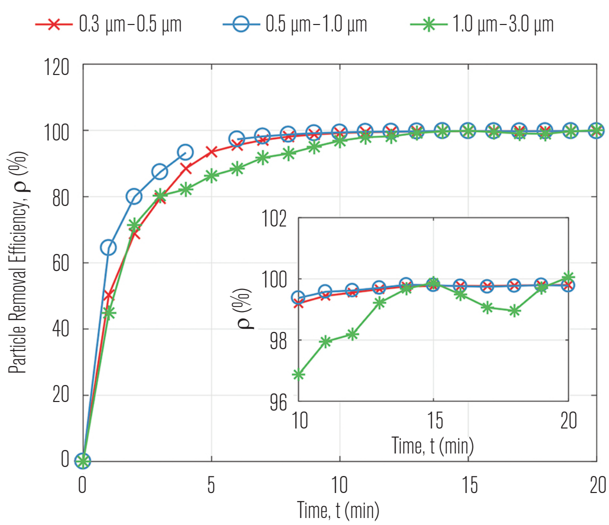


FIGURE 6 Particle removal efficiency versus time for the smoke test. Note that the data point at t = 5 min for the 0.5 µm – 1.0 µm diameter particles was removed because it was deemed as an outlier. The inset is a zoomed-in view of the main figure, focusing only on the 0.3 µm to 3.0 µm particles.



is likely due to outdoor air leakage into the room.

Conclusions

Experiments of PM count have revealed a non-thermal plasma air purification system can achieve single-pass particle collection efficiencies in excess of 99.95% (similar to a H13 HEPA filter) across all measured particle sizes between 0.3 µm and 10 µm where filter face velocities are <1 m/s (<197 fpm) and a MERV 13 post-filter is used. At greater face velocities (1.6 m/s [315 fpm]), the minimum efficiency decreases slightly to 99.72%. Where a post-filter is not used, the minimum efficiency further decreases to 76.98%, with an efficiency of 82.2% for particles in the 0.3 µm to 1.0 µm range (approximately equivalent to a MERV 14 filter). The results here therefore highlight that while a non-thermal plasma system can operate as an efficient particle removal device in itself, its performance can be raised to a HEPA-like filter when used in combination with an appropriate porous media post-filter.

Results from a smoke test have also shown that the PFS is able to remove 99.8% of smoke particles introduced into the room (i.e., greater than a 2 $\log_{10}$ reduction) within 15 minutes of operating in a room at a flow rate equivalent to 30 air changes per hour.

While the results show that non-thermal plasma air purification systems are capable of removing PM at HEPA-like levels with significantly less pressure drop, further research and development is currently underway to further optimize these systems under a broader range of operating conditions.

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