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Development and laboratory evaluation of a do-it-yourself (DIY) filtration solution for residential evaporative coolers to reduce indoor wildfire smoke exposure

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Abstract

This work describes the development and laboratory evaluation of a do-it-yourself (DIY) filtration solution for residential evaporative coolers (ECs), which bring in large amounts of outside air during their operation, to reduce the infiltration of ambient pollutants during wildfire smoke events. We sought to identify an air filtration solution that could fit most residential ECs in the field; be relatively low-cost (under $100 USD); meet prevailing recommendations for wildfire smoke particle removal while not excessively restricting airflow; potentially remove gas-phase compounds in wildfire smoke; and be deployed for typical wildfire durations of a few days to weeks. We characterized the baseline performance of three common residential ECs in a laboratory setting and tested over 15 filters and media with different combinations and attachments. Our testing identified a simple DIY solution that involves direct attachment of filters to the exterior intakes of ECs using bungee straps. Our recommended DIY filtration solution that met performance goals uses 10-cm thick carbon-impregnated filters with a minimum efficiency reporting value (MERV) of 13, but cost goals are exceeded. Our recommended DIY solution that met goals for costs, particle removal, and airflow resistance, but not for VOC removal, uses 10-cm thick MERV 13 filters without carbon-impregnation. Other alternative solutions include locally available lower-efficiency media or flat sheet media, albeit each with some drawbacks. Future work will evaluate the DIY solution in field settings to better understand in-situ performance and impacts on indoor particulate matter concentrations.

Keywords: air filtration, residential buildings, evaporative cooling, laboratory measurements, MERV

1. Introduction

The increasing frequency and severity of wildfires is a growing threat to public health worldwide. Wildfires are a major source of ambient air pollution in many regions of the world, leading to excess morbidity and mortality (G. Chen et al., 2021; Reid et al., 2016; Roberts and Wooster, 2021), particularly in vulnerable, lower socioeconomic status communities (Jones et al., 2020). The threat of wildfires to public health continues to increase with increasing frequency of drought (Richardson et al., 2022; Williams et al., 2019) and is expected to be exacerbated by climate change in the coming decades (Burke et al., 2023; Fadadu et al., 2024; Park et al., 2024). In the U.S., climate change is expected to result in a doubling of the number of premature deaths attributable to exposure to fire-related fine particulate matter ($PM_{2.5}$) by the end of the century (Ford et al., 2018).

Commonly recommended interventions for reducing exposure to wildfire smoke include providing the public with information on smoke events; reducing outdoor activities; using personal protective equipment (e.g. respirators); and using indoor air filtration devices (Hadley et al., 2022). Because people often shelter indoors during wildfire events and outdoor air pollutants can infiltrate and persist in buildings, much of their exposure to elevated levels of wildfire smoke occurs indoors, especially at home (Liang et al., 2021; O'Dell et al., 2023; Reisen et al., 2019). Indoor air filtration – including portable air cleaners (PACs) with high efficiency particulate air (HEPA) filters, in-duct central air filtration, and, more recently, do-it-yourself (DIY) fan and filter combinations with filters achieving a minimum efficiency reporting value (MERV) 12 or higher – has been shown to be effective in reducing indoor pollutant concentrations during wildfire smoke events, especially for fine particulate matter, or $PM_{2.5}$ (Antonopoulos et al., 2024; Barn et al., 2016; Fisk and Chan, 2017; Henderson et al., 2005; Laumbach, 2019; Prathibha et al., 2024; Stinson et al., 2024; Stinson and Gall, 2024). However, the effectiveness of indoor air filtration can be limited in homes that have high air exchange with outdoors due to high infiltration rates through leaky building envelopes (Rajagopalan and Goodman, 2021), through natural ventilation with open windows (Barn et al., 2008; Kirk et al., 2018; May et al., 2021), or through the use of mechanical ventilation systems (Shrestha et al., 2019).

Many homes in hot and dry climates globally use evaporative coolers (ECs), also commonly referred to as “swamp coolers”, to provide cooling (Karpiscak et al., 1998). ECs are particularly common in arid lower-income areas because they cost about one-half as much and use about one-quarter of the electricity as central vapor compression based air-conditioners (U.S. Department of Energy). According to the 2020 U.S. Residential Energy Consumption Survey (RECS), nearly 1 million homes in the U.S. use ECs as their primary air-conditioning equipment and another 400,000 homes use ECs as secondary air-conditioning equipment (US EIA, 2023).

Residential ECs use a fan to draw large amounts of outdoor air into the home through moist pads made of cellulose or aspen wood. Nominal airflow rates of residential ECs reported by manufacturers are commonly 5,000 m^3/h (3,000 ft^3/min) or higher. When operating, the moist, cool air supplied by ECs mixes with the hotter, drier indoor air in the home to reduce the overall temperature; the mixed air then exits through cracks/leaks in the building envelope and through any open windows or doors (manufacturers typically recommend opening some windows and/or doors during EC operation). Because wildfire events often also coincide with heat events, ECs are needed for cooling, but they present a challenge for wildfire smoke, as they draw in large amounts of outside air and thus can be a major source of pollutants during wildfire smoke events (Sonntag et al., 2024). EC pads are understood to have relatively low inherent filtration efficiency for fine particles and gasses from wildfire smoke (ASHRAE, 2011). We were able to identify only two prior studies on the penetration of particulate matter through EC pads. Paschold et al. (2003) reported that the passage of air across the moist pads of ECs reduced indoor PM_{10} in a chamber by up to 50% and $PM_{2.5}$ by 10-40% in a laboratory setting (Paschold et al., 2003). A short-term field study in 10 Texas homes with ECs each found that the use of ECs provided significant dilution of indoor air, leading to indoor PM_{10} and $PM_{2.5}$ concentrations that were approximately 40% and 35% of outdoor concentrations, respectively (Li et al., 2003). However, these studies did not provide single-pass particle removal efficiencies of EC pads and suggest that typical EC media have only modest filtration ability for $PM_{2.5}$, which would lead to extensive migration of ambient $PM_{2.5}$ indoors when outdoor levels are elevated. In fact, a recent survey of residents of homes in northern Nevada with ECs indicated that the concurrent need for cooling but the lack of filtration from ECs during wildfire smoke episodes left occupants needing to choose between minimizing air pollution by not operating ECs (but increasing heat exposure) and minimizing heat exposure by operating ECs (but increasing air pollution exposure) (VanderMolen et al., 2024).

Despite this limitation, because ECs draw outside air through a known air intake location and can positively pressurize a home, they may also present an opportunity to filter wildfire smoke constituents at the source of entry before pollutants enter the home, similar to an ASHRAE recommendation to “add additional filtration at the intake air vent” for commercial buildings during wildfire events (ASHRAE, 2021) and EPA’s more recent recommendations to cover any home outdoor air intakes with MERV 13 filters during wildfires (US EPA, 2024). However, to our knowledge, there are no known commercially available high efficiency filtration options for residential ECs. Therefore, this work describes the development and laboratory evaluation of a do-it-yourself (DIY) filtration solution for residential ECs to reduce residential indoor wildfire smoke exposure. This effort is part of a larger field intervention study entitled Filtration for Respiratory Exposure to Wildfire Smoke from Swamp Cooler Air (FRESSCA).

2. Methods

2.1. Pilot Field Survey of Residential Evaporative Coolers (ECs)

The FRESSCA study focuses on agricultural worker communities in Fresno and Kern Counties in California’s Central Valley (PHI IRB #I22-002). A Community Advisory Group (CAG) comprising farmworkers and representatives from local communities was first convened in 2022 to recruit participants, which led to a smaller group of homes that participated in a pilot study in 2022 and a larger group of homes that participated in an intervention study in 2023. This manuscript focuses only on the pilot year field survey. A total of 30 homes with ECs were initially recruited in 2022 for pilot testing of filtration solutions, with approximately half of homes located in Arvin and Lamont (Kern County) and half located in Coalinga (Fresno County). The recruited homes were visually surveyed by the project team to document the types, dimensions, and conditions of ECs in use in each location. Across both locations, the majority of homes (~85%) were served by a through-the-wall or through-the-window (horizontal-flow) EC unit, whereas the remainder were served by a rooftop (downflow) EC unit. ECs from at least seven different manufacturers were observed in the field survey, including, ranked from most to least prevalent: Champion, Brisa, Phoenix, Bonaire, MasterCool, Adobe Air, and Tradewinds. **Figure 1** shows a sample of EC units observed in the field in the study location during the pilot survey.

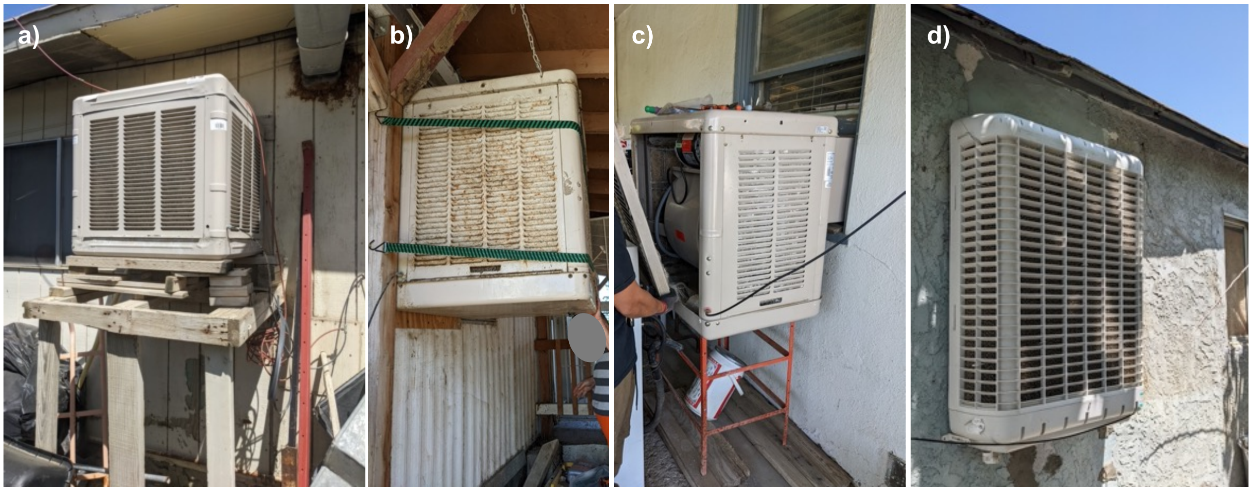

Figure 1. Sample of EC units observed in the study location during the pilot study: a) horizontal-flow unit installed on a platform, b) horizontal-flow unit suspended by bungee straps, c) through-the-window unit on stand with cover removed, and d) narrow dimension through-the-wall unit.

Most ECs were approximately cubic in their dimensions (e.g., similar to **Figure 1**a-c) with air intakes on three sides, while several were thinner units with narrower dimensions on two of their sides (e.g., **Figure 1**d). Within the cubic dimensioned units, there was a mix of smaller and larger unit sizes. The smaller units generally had overall EC dimensions of less than approximately 91x91x76-cm (36x36x30-inches), with air intake sizes as small as 50x50-cm (19x19-inches). The larger units generally had overall EC dimensions of greater than 101x89x89-cm (40x35x35-inches), with air intake sizes as large as 76x89-cm (30x35-inches). Given the logistical and safety challenges of accessing rooftops in the field and the predominance of horizontal-flow through-the-window/wall units in the study location, the study team decided to focus on devising a filtration solution primarily for the types of horizontal-flow units observed in the field survey.

2.2 Residential EC Filtration Concept and Design Goals

EC filtration concepts and design decisions were informed by conversations with collaborators in the field and the project's CAG and Design Advisory Group (DAG), with the goal of devising cost-effective solutions for implementation in homes during wildfire smoke events. The team decided to pursue a do-it-yourself (DIY) solution that involved attaching media filters directly to the air intakes of residential ECs, with goals of (1) comprising readily accessible, off-the-shelf, commercially available components, (2) being customizable to fit most residential ECs, (3) being able to be rapidly deployed in just a few minutes by homeowners and occupants, and (4) being cost-effective to consumers (e.g., ideally under $100 USD). The concept was inspired by recent developments in low-cost DIY air filtration solutions such as singular box-fan filters and Corsi-Rosenthal boxes that combine media filter(s) (typically MERV 11 or MERV 13) of various dimensions and a standard box fan to cost-effectively deliver large amounts of particle-free air (Dal Porto et al., 2022; Derk et al., 2023; Dodson et al., 2023; May et al., 2021). However, for such a solution to be effective on the types of residential ECs observed in the field location, the project team decided to investigate (i) what types of filter media would be appropriate for such an installation, (ii) realistic approaches to attaching filters to ECs, (iii) how different filters and configurations of filters affect the performance of ECs, and (iv) how well such a solution might filter pollutants in wildfire smoke. Laboratory testing was first conducted to investigate these factors.

2.3 Laboratory Testing of DIY EC Filtration Solutions

Three residential ECs were purchased for laboratory testing on the campus of Illinois Institute of Technology (IIT) in Chicago, IL (**Figure S1**). The selection of the three ECs was informed by the pilot survey of ECs in the field study location, with the goal of acquiring EC units that were similar to several of the side-mounted units observed in the study communities. The chosen horizontal-flow units for testing were: (1) an Essick RN35W with exterior dimensions of approximately 80-cm (31.5-inches) width, 68-cm (34-inches) depth, and 77-cm (30.5-inches) height and a manufacturer-reported nominal flow rate of 5,600 m^3/h (3,300 ft^3/min) (the Essick family of products also includes Champion, MasterCool, Ultracool, and Aircare), (2) a Phoenix/Brisa BW4002 with exterior dimensions of approximately 71-cm (28-inches) width, 71-cm (28-inches) depth, and 91-cm (36-inches) height and a manufacturer-reported nominal flow rate of 6,800 m^3/h (4,000 ft^3/min), and (3) a narrower MasterCool MCP44 with exterior dimensions of approximately 86-cm (34-inches) width, 56-cm (22-inches) depth, and 117-cm (46-inches) height and a manufacturer-reported nominal flow rate 5,440 m^3/h (3,200 ft^3/min). Each unit was mounted on a custom wood frame in a laboratory space and connected to a tap water source with spigot for testing during both wet and dry pad conditions. The Essick and Brisa units both utilize a centrifugal fan for air movement and an aspen pad for the cooling pad; the MasterCool unit utilizes an axial fan for air movement and rigid cellulose for the cooling pad.

2.3.1 Design Goals and Performance Targets for Lab Testing

The overarching design goal was to outfit each of the residential ECs in the laboratory with filter media that could remove pollutants in wildfire smoke with acceptable efficiency, while not excessively restricting airflow to avoid reducing cooling capacity and potentially worsening thermal comfort. Additionally, the solution should be able to be installed without the need for specialized training and should be able to last the duration of a typical wildfire smoke event in the field (i.e., up to about a month). While quantitative targets for these measures were not objectively well known or defined at the outset, the design team, using a combination of past experiences, knowledge of existing literature, and engineering judgement, generally agreed that a target single-pass $PM_{2.5}$ removal efficiency for ambient PM should be a minimum of approximately 50% – consistent with approximately MERV 13 or higher (Azimi et al., 2014; Fazli et al., 2019). The design team also generally agreed that a target reduction in airflow due to the installation of a filtration solution should be less than approximately 20% to avoid potential cooling performance issues. While the approximately 20% maximum airflow reduction target was chosen by consensus among the design team, it is consistent with prior literature showing that, for example, thermal comfort could still be maintained in an office building after reducing supply airflow rates by up to ~12% (Ghahramani et al., 2014).

Since wildfire smoke is a mixture of particulate pollutants, including fine organic carbon and trace metals, and gaseous pollutants, including carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and semi-volatile organic compounds (SVOCs) (Boaggio et al., 2022; H. Chen et al., 2021; Holder et al., 2023; Sparks and Wagner, 2021; U.S. EPA, 2023), our ideal filtration solution would be able to remove both particles (especially $PM_{2.5}$) and gases. Therefore, understanding the nature of particles and gases in wildfire smoke is an important first step in establishing performance targets.

The literature on particles resulting from wildfires and biomass burning suggests that peak $PM_{2.5}$ concentrations can increase to well above 100 μg/m^3 during smoke events (Aguilera et al., 2023; Heaney et al., 2022; Selimovic et al., 2019) and that wildfire smoke fairly regularly leads to $PM_{2.5}$ concentrations above 35 μg/m^3 in the U.S. (Burke et al., 2023). Much of the $PM_{2.5}$ mass in wildfire/biomass smoke exists in the accumulation mode between 0.1 and 1 μm in diameter, with number and mass distributions peaking around 0.05-0.2 μm and 0.2-0.4 μm, respectively, which is larger than combustion-related peaks in typical urban air (Niemi et al., 2005; Okoshi et al., 2014; Phuleria et al., 2005; Sillanpää et al., 2005; Sparks and Wagner, 2021).

The literature on VOCs resulting from wildfires is somewhat mixed, with specific VOCs influenced by the age and transport distance of wildfire smoke (O'Dell et al., 2020). A study of two aged wildfire smoke events in Colorado in 2015 found significant increases in ethyne and benzene and no significant increases in toluene, *o*-xylene, or ethyl benzene (Lindaas et al., 2017). An investigation of VOCs in wildfire smoke in Idaho and Washington in 2019 observed elevated levels of benzene, toluene, ethylbenzene, xylenes, butenes, phenol, isoprene, and pinenes (Dickinson et al., 2022). Benzene and toluene were both elevated over 100 times higher than background levels during some of the monitored fires. Benzene, toluene, xylenes, and ethylbenzene, among others, were also enriched in the urban Richmond, California area during the 2018 Camp Fire wildfire event, despite being located over 200 km away from the fire (Wang et al., 2024). An investigation of indoor and outdoor VOCs during wildfire conditions in the Pacific Northwest in the U.S. noted that elevated outdoor benzene concentrations also manifested in elevated indoor benzene concentrations in at least one home (Kirk et al., 2018). Wildfire smoke also contains many SVOCs – including polycyclic aromatic hydrocarbons (PAHs) – that may be simultaneously in both the gas-phase and condensed particle-phase (Lei et al., 2024; Liang et al., 2023).

Wildfire duration is also an important factor to understand. In the abovementioned studies, one of the 2015 Colorado fires lasted 4 days and the other lasted 14 days (Lindaas et al., 2017), while the four fires in Idaho and Washington in 2019 lasted from 4 days to 31 days (Dickinson et al., 2022). More specifically to our field study location, early in the project (2021) we calculated the duration of large fires (300 acres and greater) reported in the California Department of Forestry and Fire Protection's 2020 Wildfire Activity Statistics report (see Table 5 of the report) by subtracting the start date from the date of containment (CAL FIRE, 2021). Among 62 large fires reported in 2020, the median duration was 6 days, ranging from less than 1 day to as much as 110 days. Approximately 70% of fires were less than 12 days in duration and approximately 15% of fires were longer than 30 days in duration.

Therefore, the combination of our design goals and the existing literature suggested that a filtration solution should be able to (1) at minimum, remove accumulation mode particles between about 0.1 and 1 μm in diameter with acceptable single-pass efficiency, (2) ideally, remove a wide range of VOCs, and (3) be deployed for as little as a few days to as long as about a month to offer protection throughout a range of wildfire smoke events.

2.3.2 Filter Media Selection and Filter Attachment Methods for Lab Testing

To address target #1 in Section 2.3.1, the team hypothesized that deep bed MERV 13 residential filters of at least 5-10 cm (2-4 inches) could achieve ~50% removal of $PM_{2.5}$ while minimizing airflow restrictions (Fazli et al., 2019). This choice is also consistent with the U.S. EPA's recommendation to "choose [a high-efficiency HVAC filter] with a MERV 13 rating, or as high a rating as your system fan and filter slot can accommodate" (US EPA, 2023) and ASHRAE's recommendation to employ MERV 13 filters in HVAC systems in their recently published Guideline 44 (ASHRAE, 2024). Target #1 was our primary initial target given the importance of PM exposure for health. To attempt to address target #2, the team hypothesized that particle media filters that achieve MERV 13 but are also impregnated with activated carbon could likely provide some level of removal of a broad range of VOCs (Sidheswaran et al., 2012). Finally, to address target #3, a short-term application period was envisioned, whereby an occupant could keep their high efficiency filters in storage until a wildfire smoke event, at which point they could then install the filters on their EC to achieve desired pollutant removal, and they could remove them when the smoke event dissipated (e.g., after a few days or weeks).

With these objectives in mind, we consulted with several filter and filter media manufacturers to explore commercially available solutions that could feasibly provide low resistance to airflow (i.e., low pressure drop), high removal efficiency (e.g., MERV 13), some level of VOC removal (via carbon), and some level of moisture resistance given that the filters would likely be in close proximity to active water sources within the ECs. Informed by these conversations and by an investigation of locally available products, we tested several filtration products from a variety of manufacturers to explore solutions that could meet some or all of the abovementioned design goals, including a limited number of carbon-impregnated MERV 13 filters and a range of conventional media filters (i.e., without impregnated carbon) with depths from 2.5 cm (1 inch) to 10 cm (4 inch) and efficiencies from MERV 8 to MERV 13, as well as rolls of flexible, thin, flat sheet media that could conform to EC dimensions more so than standard rigid frame filters.

A variety of filter attachment methods were also explored in the laboratory, including multiple direct attachment methods and an attachment where the filters could be offset from the ECs using a larger surrounding structure to act as a plenum and filter housing. Direct attachment methods, including tie-down ratchet straps (**Figure 2**a), bungee cords (**Figure 2**b), and bungee straps (**Figure 2**c), were the most cost effective and straightforward to install. We found that bungee straps (also called "flat bungee cords", approximately $5 USD per pair) were ideal among these three attachment methods because the tension provided by the bungee's elastic helped to adhere the filters close to the ECs while the extra width of the flat strap compared to a typical narrow cord spread the force of the bungee out more widely across the filter frame to avoid crushing it by compression. The larger plenum-like structure (**Figure 2**d) was investigated for its ability to provide greater protection for filter media from the high moisture environment immediately adjacent to the ECs for potentially longer-term deployments and to explore whether a smaller number of filters could be used for an installation than direct attachment methods. Direct attachment methods were tested with and without foam gasketing between the EC and filters, but gasketing adversely affected the ability of some of the filters to remain secured to the test EC units, so subsequent direct attachment tests did not utilize foam gasketing. Overall, the custom plenum-like intake and housing solution for filters is difficult to replicate in the field due to limitations in physical space, costs, construction time, and availability of materials.

These filters, filter media, and different attachment methods were explored iteratively to test the bounds of performance and inform a solution for eventual selection and deployment in the field study location. For direct attachment methods, we tested combinations of quantities and dimensions of filters that could cover the entire air intake areas of the ECs, including beginning with custom dimensions (i.e., 46x61-cm [18x24-inch]) that ideally fit the ECs, followed by more standardized dimensions (i.e., 51x51-cm [20x20-inch], 41x63-cm [16x25-inch], and 61x76-cm [24x30-inch]) that are more prevalent in the commercial marketplace and therefore are more likely to be readily available. The Brisa unit required three custom 46x61-cm (18x24-inch) filters or four 41x63-cm (16x25-inch) filters to fully cover its intake areas. The Essick unit required either two custom 46x61-cm (18x24-inch) filters on its side intakes and one 51x51-cm (20x20-inch) filter on its back intake, or six 41x63-cm (16x25-inch) filters, or four 41x63-cm (18x24-inch) filters and three 61x76-cm (24x30-inch) filters to fully cover its intakes. The MasterCool unit required two 61x76-cm (24x30-inch) filters on its large primary intake while either blocking the narrow curved side intakes entirely or covering them with flat sheet media.

Figure 2. Filter and filter media attachment methods tested in the laboratory: (a) tie-down ratchet straps, (b) bungee cords, (c) bungee straps, and (d) custom plenum-like intake and housing for filters.

2.3.3 Laboratory Measurements of EC Performance

Five key parameters were assessed in laboratory measurements of EC performance with and without various configurations of potential filtration solutions: airflow rate, power draw, pressure drop, sensible and latent cooling capacity, and pollutant (i.e., particulate matter or VOC) removal efficiency. Each measurement approach is described briefly below and in more detail in the SI. Not every measurement was conducted with every test condition/configuration, but the list below is exhaustive to encompass the range of laboratory tests that were conducted. Measurements were conducted on the highest fan speed settings on each test EC unit unless otherwise noted.

Airflow Rates. A velocity traverse was used to measure the airflow rates of the ECs at each test condition, closely following the National Comfort Institute's (NCI) *Measuring System Airflow From Grilles and Registers* guidance document (NCI, 2015).

Power Draw. Instantaneous power draw of the ECs was measured at each test condition by plugging the ECs directly into a Kill-A-Watt P4400 Power Meter. This measurement of power draw accounts for both the fan power of the EC (the largest contributor to power draw) and the power draw of the water pump used to circulate water across the EC pads (the smallest contributor).

Pressure Drop. The differential pressure across the EC intake, which included the cooling pads, intake grilles, and any filters or blockages installed for a given test condition, was measured using a static pressure pitot tube inserted in a small hole on the exterior enclosure of the ECs and connected to an Energy Conservatory DG-700 digital manometer.

Sensible and Latent Cooling Capacity. The impact of a subset of test conditions and corresponding airflow rates on sensible and latent cooling capacity of the ECs was evaluated by measuring the temperature and relative humidity (RH) upstream and downstream of the ECs. Temperature and humidity ratio differences across the ECs were used to investigate whether flow reductions introduced by various filter attachments also led to changes in EC performance similar to how flow restrictions affect sensible and latent capacity in typical vapor compression cooling systems (Proctor, 1998; Rodriguez et al., 1996; Stephens et al., 2010b, 2010a).

Particle Removal Efficiency. For all lab tests of particle removal efficiency, two MetOne GT-526 optical particle counters (OPCs) were used to measure particle concentrations from 0.3 to 10+ µm in bins of 0.3-0.5 µm, 0.5-1 µm, 1-2.5 µm, 2.5-5 µm, 5-10 µm, and 10+ µm. One OPC was used to measure particle concentrations immediately upstream of the EC air intake ($C_{upstream}$) and another OPC was used to measure particle concentrations immediately downstream of the EC supply air outlet ($C_{downstream}$). Both OPCs logged at 1-minute intervals and tests were run for a minimum of 30 minutes, and typically a maximum of 2 hours. The removal efficiency of the EC and any filter attachments for each particle size bin ($\eta(d_p)$) was calculated using Equation 1.

$$\eta(d_p) = \left[1 - \frac{C_{downstream}(d_p)}{C_{upstream}(d_p)}\right] \times 100\% \tag{1}$$

The average efficiency over the duration of a test period was used to characterize filtration efficiency for a particular size bin. The uncertainty in removal efficiency for each particle size bin was estimated using the standard deviation of the set of readings over the test period. Additionally, for a subset of filter efficiency tests, a TSI NanoScan Scanning Mobility Particle Sizer (SMPS) Model 3910 was used to measure filtration efficiency for smaller particles 0.01-0.4 µm in mobility diameter. The SMPS was connected to an automated switching valve (Swagelok Model SS-43GXS4-42DCX electrically actuated three-way ball valve; Swagelok, Solon, OH USA) to alternately measure concentrations upstream and downstream of the EC and any filter attachment. The switching valve was controlled automatically by an electronic timer (Sestos B3S-2R-24; Hong Kong) set to switch upstream/downstream every 4 minutes. Data from each 1-minute period associated with the switch was excluded from analysis.

VOC Removal Efficiency. A single set of VOC removal efficiency measurements was conducted on a single 10 cm (4 inch) depth MERV 13 impregnated-carbon filter in a test chamber at Portland State University (interior volume 17.8 m^3) to explore the feasibility of the media for reducing VOCs commonly present in wildfire smoke. A new 61x76x10-cm (24x30x4-inch) filter was placed into a custom cardboard housing and connected to an Energy Conservatory DuctBlaster to induce airflow through the filter (**Figure S2** and **Figure S3**). These tests were conducted similar to clean air delivery rate (CADR) tests on portable air cleaners in which pollutant concentrations are elevated by a source, the source is then extinguished, and the subsequent decay of concentrations to background levels is measured over time, repeated both with and without the filter/fan combination operating in the chamber (ANSI/AHAM, 2020; Offermann et al., 1985; Shaughnessy and Sextro, 2006; Stephens et al., 2022). A mixture of VOCs was introduced into the chamber by burning pine needles to mimic a small biomass fire and resultant smoke. Real-time VOC concentrations were measured using proton transfer reaction – time of flight – mass spectrometry (PTR-ToF-MS). The clearest signals for VOC production and subsequent decay were for benzene and toluene. Tests with the filter/fan combination operating were conducted at three fan speed settings to achieve face velocities through the test filters that encompass a range of face velocities measured in the laboratory tests on the test ECs at various conditions at IIT: approximately 0.3, 0.55, and 1.05 m/s (i.e., 60, 110, and 210 ft/min), representing low, medium, and high face velocities. Each face velocity condition was repeated in triplicate and background loss rates were tested once for each condition. Single-pass VOC removal efficiencies were back-calculated from CADR measurements following a method described in the SI.

Wildfire Event in Chicago, IL. On June 26 and 27, 2023, wildfire smoke from fires across Quebec and Ontario in Canada enveloped much of the Great Lakes region of the U.S. and Canada, including Chicago. In fact, Chicago air quality was ranked by some measures as the worst in the world among major cities at that time (Livingston, 2023). On these two days, one of the test ECs (Brisa BW4002) was rapidly deployed just outside a set of exterior doors of their laboratory building on campus and fabricated a sheath to mimic a through-the-wall installation of an EC (**Figure S4**). The dual OPCs and single SMPS with switching valve were deployed to measure ambient particle size distributions and particle removal efficiencies of the EC with and without filters attached to capture performance during realistic wildfire smoke conditions caused by long-range transport over Chicago. Ambient (outdoor) size distributions were measured for a brief period of ~30 minutes with the SMPS and size-resolved particle removal efficiencies of the EC without a filter and the EC with three different 10-cm (4-inch) depth filters, including two carbon-impregnated and one without carbon, were measured over consecutive periods of ~30 minutes each.

3. Results

3.1 Airflow, pressure, and power draw of the test ECs without filtration

The three acquired test ECs that were installed in the laboratory at IIT were first characterized to establish baseline performance curves in the absence of any filtration (i.e., with only the cooling pad from the manufacturer). Wet and dry conditions were initially evaluated on each EC, and since minimal differences in performance were observed, subsequent testing was conducted either in wet conditions to resemble normal operation more closely in the field or in dry conditions when a water source was not available (but seldom both wet and dry beyond initial testing). To ensure that the cooler pads were fully wet during wet condition tests, the ECs and pumps connected to a tap water source were allowed to operate for 5-10 minutes prior to conducting any measurements. Baseline performance characterizations included measuring the supply airflow rate, pressure drop across the air intake, and power draw while progressively blocking the air intakes of the ECs with cardboard to establish EC performance curves (i.e., relationships between flow and pressure/power) that is distinct and separate from any impact of installation filters. Progressive blocking of the EC intakes on the Essick and MasterCool ECs began with no blockage (0%, ideal condition), followed by fractional area blockages of 25% blockage, 50% blockage, 75% blockage, and 100% blockage, whereas for the larger Brisa EC, fractional area blockages of approximately 0%, 33%, 66%, and 100% were used.

Figure 3 shows results of these experiments without filtration attachments. Polynomial curves are fit through the data points for each EC to establish empirical fan performance curves. Each EC unit followed a generally similar trend in that increased blockage led to increased return pressure and decreased flow following an approximately polynomial relationship. However, the magnitude of flow reduction introduced by progressive blocking varied by unit, with the larger Brisa unit showing the flattest decrease in flow as blocking (and return pressure drop) increased and the smaller MasterCool unit following the steepest decline in flow with increasing pressure. To achieve a design target of no more than approximately 20% reduction in airflow with a filtration solution, the resulting performance data suggest that the return pressure should increase from ~29 Pa to no more than ~50 Pa on the Essick, from ~13 Pa to no more than ~40 Pa on the Brisa, and from ~24 Pa to no more than ~35 Pa on the MasterCool.

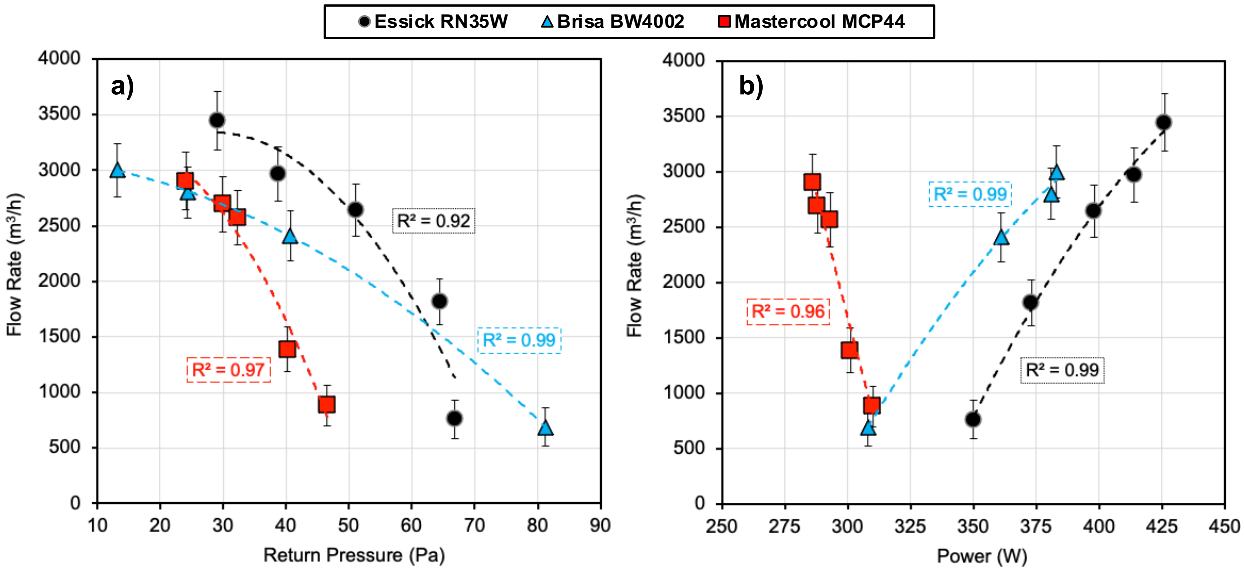

Figure 3. Performance curves for three test ECs in the lab under wet pad conditions: (a) airflow rate vs. return pressure and (b) airflow rate vs. power draw.

Figure 3b shows that the power draw of the Brisa and Essick units increased with increasing airflow rate following an approximately polynomial relationship, while the power draw of the MasterCool unit decreased with increasing flow following an approximately linear relationship.

These patterns are typical of centrifugal and axial fans, respectively. Since the approximations of performance curves for airflow rate versus both pressure and power were relatively consistent ($R^2 > 0.9$ for all comparisons), these data also suggest that all three metrics can be useful for characterizing operational points of these EC units.

Also worth noting is that even with brand new cooling pads and no additional resistance from blockages or filtration attachments, none of the three EC units was measured to deliver the nominal airflow rates reported by the manufacturer. As mentioned, the nominal airflow rates of the Essick, Brisa, and MasterCool units were 5,600 m^3/h, 6,800 m^3/h, and 5,440 m^3/h, respectively. The maximum airflow rates measured without filters and in wet pad conditions for these units were approximately 3408 ± 241 m^3/h, 3000 ± 189 m^3/h, and 2900 ± 207 m^3/h, respectively, which corresponds to flow rates that were approximately 39%, 56%, and 47% lower than nominal flow rates reported by the manufacturer. Such deviations were also described by Watt (1986), attributable to manufacturers using bare-fan flow ratings as performance metrics for ECs, which “ignored airflow resistances in louvers, pads, pad bindings, and retainers, and so gave inflated values” (Watt, 1986). Moreover, our observed relative differences in measured versus nominal flow rates were similarly in line with performance data reviewed by Watt (1986).

3.2 Airflow, pressure, and power draw of the test ECs with filtration attachments

Next, we investigated the impact of a variety of filters and combinations of filters on the test EC performance when attached directly. We used airflow rate and pressure drop as our primary performance metrics, seeking solutions that reduced airflow rates by less than approximately 20% to minimize impacts on cooling capacity in the eventual field deployments. We tested the widest range of filters and filter combinations on the Essick and Brisa units since they performed somewhat similarly in response to flow blockages (due to their use of centrifugal fans) and since their cubic structure was representative of the majority of ECs observed in the pilot field survey. The MasterCool EC unit was tested with a different set of filters and attachments in large part because its dimensions did not allow for testing of assembled filters by themselves without also blocking off the side intakes or wrapping them with flexible flat sheet filter media, and also because its use of an axial fan led to it performing very differently than the Essick and Brisa units.

We initially investigated the potential for attaching a filter solution to the supply side (i.e., outlet) of the ECs, which could minimize the number of filters needed, but it turned out to be unfavorable for several reasons including: (1) the same filter led to higher pressure drops and lower airflow rates due to the smaller area of filter media compared to an intake-side solution, (2) it would be prone to leaks and would likely lead to attachment problems over time since the filter would need to resist a large amount of force from the supply air, (3) the filter would be at risk for moisture damage from continuous supply of high RH air, and (4) the rate of dust loading would be higher given the concentrated smaller area. These drawbacks encouraged us to align our design to the air intake sides of the EC rather than the supply side.

Table 1 summarizes the different quantities and dimensions of filters that were tested for direct attachment solutions on the three test ECs in the lab, as well as some of their advantages and disadvantages as potential solutions with respect to filter costs, commercial availability, material efficiency, installation effectiveness, and other factors. Early testing involved mixing and matching filters of different dimensions for each EC to try to optimize intake area coverage while minimizing excess filter media area, but later we standardized as much as possible to the most commercially prevalent filter dimensions that could fit each EC. For example, custom filter dimensions of 46x61-cm [18x24-inch] best matched the intake areas of the Brisa and Essick units, but such dimensions are not widely available for purchase. Instead, we later decided to use more standardized filter dimensions (i.e., 41x63-cm [16x25-inch] and 61x76-cm [24x30-inch]) to ensure commercial availability would not be a major limitation to the solution. While any combination of quantities and dimensions of filters in Table 1 could work, most of our subsequent testing described below was conducted with four 41x63-cm [16x25-inch] filters on the Essick EC and three 61x76-cm [24x30-inch] filters on the Brisa EC. The MasterCool unit was always tested with two 61x76-cm [24x30-inch] filters on its large primary intake while either blocking the narrow curved side intakes entirely or covering them with flat sheet media. This standardization allowed us to better plan and procure filters for subsequent field testing.

Table 1. Summary of quantities and dimensions of filters tested on each EC unit in the lab.

Test EC Unit	Dimensions	Quantity	Advantages	Disadvantages
Brisa	46x61-cm [18x24-inch]	6	Excellent fit with minimal wasted filter area	Nonstandard dimensions limits commercial availability
	61x76-cm [24x30-inch]	3	Minimized filter quantities	Higher cost due to unique sizing; difficult to source 4-inch depth in this size
	41x63-cm [16x25-inch]	6	Highly standard dimension, thus readily available; very good fit	Largest number of filters can make installation challenging
Essick	46x61-cm [18x24-inch] and 51x51-cm [20x20-inch]	2 1	Good fit with minimal wasted filter area	Some nonstandard dimensions limits commercial availability; requires two different filter dimensions
	61x76-cm [24x30-inch]	3	Consistent dimensions simplifies procurement and installation	Filter extends beyond EC intake, wasting filter area; higher cost due to unique sizing; difficult to source 4-inch depth in this size
	41x63-cm [16x25-inch]	4	Highly standard dimension, thus readily available	Larger number of filters can make installation challenging
MasterCool	61x76-cm [24x30-inch] and sides with flat sheet media (or blocked)	2	Excellent fit on large intake; sheet media provides for the easiest and most flexible installation	Sheet media loads quickly and restricts airflow

Figure 4a shows results of airflow rates versus return pressure drop measured with different filters directly attached on the intake sides of the Brisa and Essick units. **Figure 4**b shows the same for the MasterCool unit; both figures also maintain the polynomial curve fit through progressively blocked intakes from **Figure 3**. Most of the test results shown in **Figure 4** and subsequent figures are based on testing with four 41x63-cm [16x25-inch] filters attached to the Essick EC and three 61x76-cm [24x30-inch] filters attached to the Brisa EC. The only exceptions were the 3M and HDX filters which were tested using only standard dimensions of 41x63-cm [16x25-inch], including four on the Essick and six on the Brisa EC.

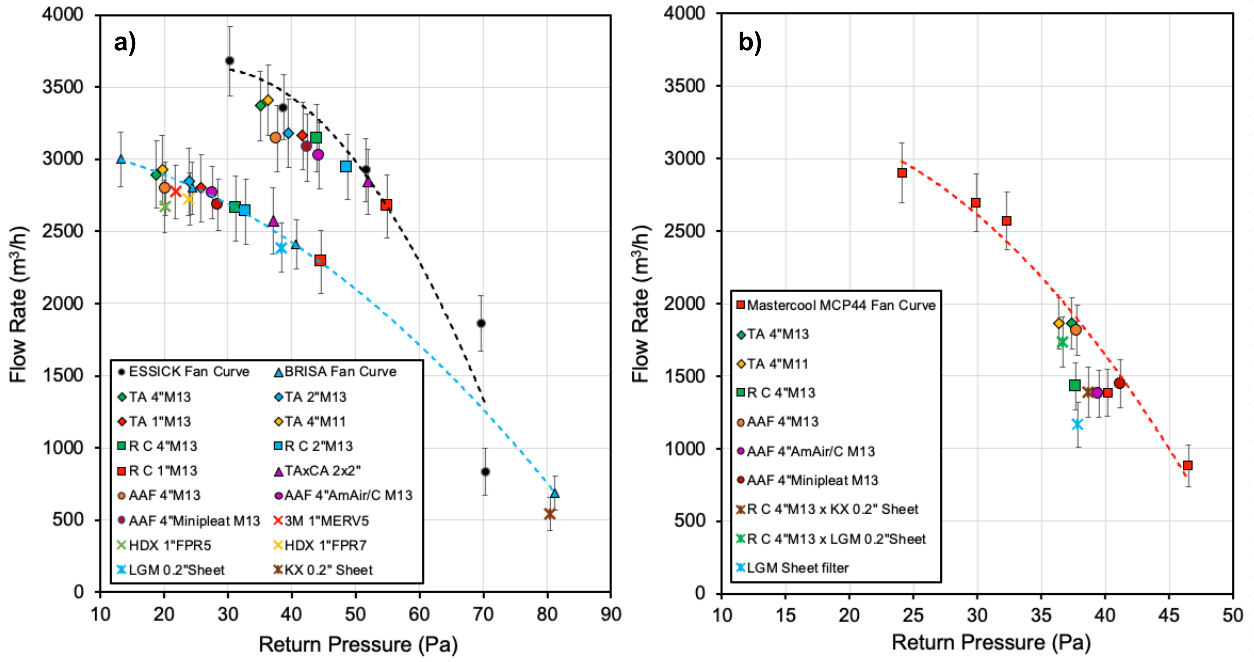

Figure 4. Airflow versus pressure drop for test filters overlaid with polynomial fan performance curves for the (a) Essick and Brisa unit and (b) MasterCool unit with narrow sides fully blocked or covered with flat sheet media.

Measured airflow rates from filters and combinations of filters generally followed the fan curves established by progressively blocking the intakes, which suggests that the blockage approach is useful for identifying target pressure drops that can meet our defined maximum flow reduction criteria. In each test shown, filters were attached directly to the ECs using two bungee straps; two ~200-cm (80-inch) bungee straps were sufficient to securely attach all filters on all three ECs with minor adjustments. Several generalizations can be inferred from these data. First, as expected, deeper bed 10-cm (4-inch) depth filters (green solid symbols) lead to lower flow reductions than 2.5-cm (1-inch) filters (red solid symbols) and 5-cm (2-inch) filters (blue solid symbols) of the same or similar MERV (or equivalent) rating, whereas thinner filters with lower efficiency also lead to smaller flow reductions (but will not achieve sufficient particle removal efficiency). In fact, the Tex-Air 10-cm (4-inch) MERV 13 (green diamond), the Rensa 10 cm (4-inch) carbon-impregnated CA13 (green square), the AAF 10 cm (4-inch) MERV 13 (orange circle), the AAF AmAir/C 10-cm (4-inch) M13 (purple circle) filter, and the AAF 10-cm (4-inch) Minipleat M13 (red circle) filters all met our design goal of reducing flow by less than approximately 20% on the Essick and Brisa units while also achieving MERV 13 filtration for particles. Therefore, these deep-bed (10-cm, 4-inch) MERV 13 filters were generally prioritized for subsequent testing and pilot field deployments more so than other solutions. And given that our secondary goal is to ideally remove some VOCs, the deep-bed (10-cm, 4-inch) MERV 13 filters impregnated with activated carbon were further prioritized for additional testing. We also tested a combination of 5-cm (2-inch) Rensa CA-13 filter in series with a 5-cm (2-inch) Tex-Air MERV 13 filter as a pre-filter, with the logic that the less expensive Tex-Air filter could protect the more expensive Rensa CA-13 filter, but the excess pressure drop of the two 5-cm (2-inch) filters led to an excessive reduction in airflow.

Second, the MasterCool unit with axial fan behaved quite differently from the Essick and Brisa units with centrifugal fans, with none of the filtration attachments being capable of meeting design goals for flow rate reduction. In fact, even the least restrictive (lowest pressure drop) filtration solution tested on the MasterCool (the 10-cm, 4-inch TexAir MERV 11) resulted in an airflow rate reduction of approximately 40%. Most of the MERV 13 solutions led to greater than 50% airflow rate reduction. This is due to the much steeper fan curve for this EC, which is attributable to a combination of its axial fan characteristics and a much smaller intake area over which filtration pressure drop occurs.

Third, the thin sheet media, while having advantages for ease of attachment, severely restricted flow, in some cases nearly completely restricting flow in a manner similar to the 100% blockage test condition. However, some of this excess restriction was since approximately 40% of the opening/intake area was through curved openings on the side, which do not accommodate rigid filters without significant gaps and bypass airflow. Therefore, the curved sides were simply blocked with duct tape and the filter was installed only on the large intake (i.e., the remaining ~60% of the intake area). This approach, while necessary to obtain a decent filter fit, negatively impacts flow. Some improvement in flow reductions was possible by combining a 10-cm (4-inch) depth MERV 13 filter (e.g., Rensa CA13) on the main intake side with thin flat sheet media (rather than full blockage) on the narrow, curved side intakes, but still did not meet design targets for flow reductions (see green and blue 'x' symbols).

Fourth, results suggest that reliance on a locally available solution is unlikely to be successful. For example, the team conducted a survey of filters that were locally available in stores in the San Joaquin Valley, and then a sample of those filters were acquired for testing in the laboratory at IIT. These included a 3M 2.5-cm (1-inch) MERV 5 (red cross), an HDX 2.5-cm (1-inch) FPR 5 (MERV 8 equivalent, green cross), and an HDX 2.5 cm (1-inch) FPR 7 (MERV 11 equivalent, yellow cross). These filters showed similar performance to deeper bed 5 and 10-cm filters in terms of airflow and pressure drop, but their much lower filtration efficiency rating means they will not meet design goals for removal efficiency.

3.3. Particle removal efficiencies

Figure 5 shows results from measurements of size-resolved particle removal efficiency for 0.3-10 µm particles, measured using OPCs upstream and downstream of the EC units in the lab, of the five 10-cm (4-inch) MERV 13 (with or without carbon) filters that were identified from flow and pressure drop testing. **Figure 5** also shows measurements of removal efficiency of the EC operating in wet conditions without a filter (all operating conditions include a wet cooling pad). As expected, the no filter condition led to minimal particle removal for most particle sizes, especially below 5 µm, on all three EC units, which further justifies the need for an EC filtration solution to protect against wildfire smoke.

Understanding from our literature review that the mass distribution of wildfire/biomass smoke appears to exist in the accumulation mode between 0.1 and 1 µm in diameter, with number distributions peaking around 0.05-0.2 µm (Niemi et al., 2005; Okoshi et al., 2014; Phuleria et al., 2005; Sillanpää et al., 2005; Sparks and Wagner, 2021), it is most useful to focus on removal efficiency measurements for submicron particles, especially ~0.3 µm particles, which tends to be the most penetrating particle size (MPPS) for fibrous media filters. Each of the five deep-bed MERV 13 filters tested showed a removal efficiency of at least 40% for the 0.3-0.5 µm size bin when tested on all three EC units. Size-resolved results generally followed expected patterns from ASHRAE Standard 52.2 testing (ASHRAE, 2017) in that efficiency increased with increasing particle size, except for on the MasterCool unit (although uncertainties on the MasterCool unit were much larger). Worth noting is that the same filters tested on the Brisa unit led to higher removal efficiencies than on the Essick and MasterCool, likely due in part to differences in face velocities among the two units. For example, the average face velocity for the Brisa and Essick EC units with the Rensa CA13 filter attached to the intake was measured to be approximately 0.57 m/s (112 ft/min) and 0.73 m/s (144 ft/min), respectively, and lower face velocities are known to lead to higher particle removal efficiencies for fibrous media filters, holding other factors constant (Chen et al., 2019; Hanley et al., 1994; Hinds, 1999; Lee and Liu, 1981; Yit et al., 2023). Additionally, the MasterCool EC was tested with its narrow, curved intake sides sealed with duct tape.

The highest performing filter was the AAF 10 cm (4-inch) MERV 13 (orange line in **Figure 5**), with minimum removal efficiency over 60% for 0.3-0.5 µm particles on the Essick and MasterCool units and as high as >80% on the Brisa unit. This level of performance is likely attributed to the media being highly electrostatically charged, which yields high initial filtration efficiency that would likely decline over time with loading (Hanley et al., 1994; Lehtimäki et al., 2002; Owen et al., 2013). As such, it is likely that the progressive dust loading procedures in ASHRAE Standard 52.2 captured this reduction over time and led to the designation of MERV 13 rather than MERV 14 or higher that might be suggested by only initial efficiency testing. Although such high initial efficiency might be preferred for short-term installations, the filter has the disadvantage of not having any carbon media impregnated for VOC removal. The two MERV 13 filters with carbon (Rensa CA13 and AAF AmAir/C) both performed similarly well in particle removal testing. Thus, these results gave confidence in our recommendation of MERV 13 filters impregnated with carbon media to meet both particle and VOC removal design goals, or only MERV 13 filters without carbon to meet only the particle removal design goals.

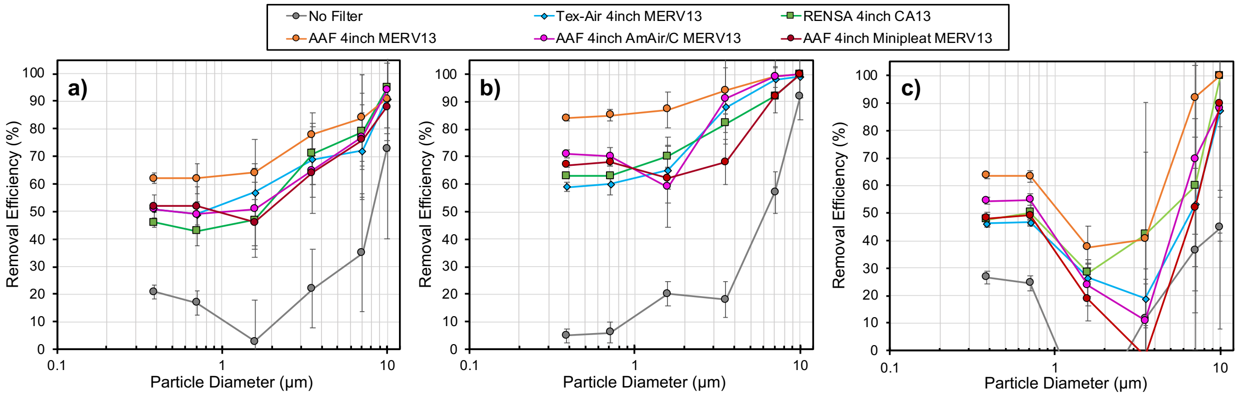

Figure 5. Lab tests of size-resolved filter removal efficiency for 0.3-10 µm particles for five deep-bed 10 cm (4-inch) filters compared to no filter conditions on the (a) Essick, (b) Brisa, and (c) MasterCool MCP44.

Figure 6 shows results for size-resolved particle removal efficiency testing on several filters found locally and commercially available in the San Joaquin Valley region, as well as flexible flat sheet media that can be purchased in rolls in a variety of online marketplaces. Two of our five 10 cm (4-inch) MERV 13 filters (Rensa CA13 and Tex-Air MERV 13) are also shown for direct comparison to our deep-bed filters. As expected, the locally available filters, each with MERV or MERV-equivalent lower than MERV 13, had lower removal efficiency for all particle sizes than the MERV 13 filters (e.g., 0.3-0.5 µm particle removal efficiency was <30%). However, they could potentially still be beneficial for modest fine particle removal and greater dust control (e.g., >5 µm) if deep bed MERV 13 filters are not locally or readily available.

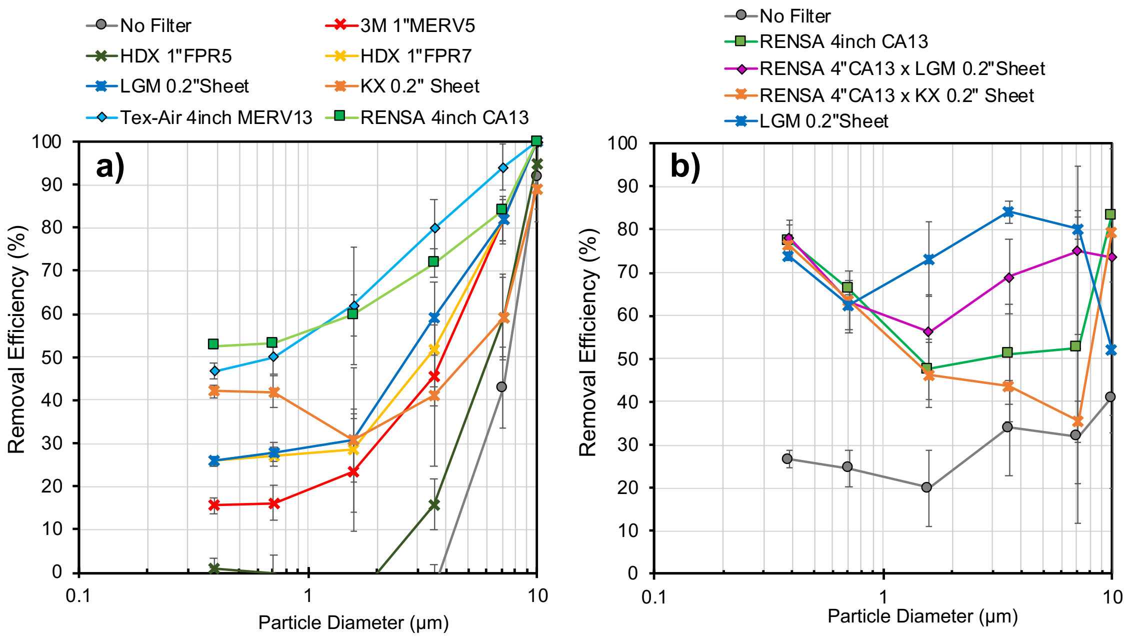

Figure 6. Removal efficiencies of locally available filters and sheet filters tested on: (a) Brisa and (b) MasterCool EC units

The removal efficiencies of the KX and LGM 0.5-cm (0.2-inch) flat sheet media (orange and blue 'x' in **Figure 6**, respectively) were relatively high on both EC units, performing at least similar to FPR 7 (approximately MERV 11 equivalent) on the Brisa and even higher than MERV 13 on the MasterCool. However, as was shown in **Figure 4**, the thin sheet media, especially KX but less so for LGM on the Brisa, severely restricted flow. Despite these disadvantages, the thin sheet media does have some potential for exploring for emergency use, and/or in combination with other filters. For example, **Figure 6**b also shows combinations of rigid filters and flat sheet media tested on the narrow dimensioned MasterCool unit, including with a Rensa CA13 10 cm (4-inch) filter installed on the primary air intake and flat sheet LGM or KX media wrapped around the intakes on the two narrow, curved sides. These combination solutions achieved removal efficiency similar to or higher than the Rensa CA13 with side intakes fully blocked and led to less severely restricted flow that was more similar to a 10 cm (4-inch) MERV 11 or 13 with sides fully blocked on this unit. Since the flat sheet media is highly electrostatically charged, it is not expected to maintain performance for long periods of time, but these results demonstrate that it could be useful for various short-term configurations.

Last, because the OPC measurements and also conventional ASHRAE Standard 52.2 testing do not evaluate removal efficiency for filters below 0.3 µm (Hecker and Hofacre, 2008; Stephens, 2018; Stephens and Siegel, 2013) but such sized particles are present in wildfire smoke, a subset of two 10 cm (4-inch) MERV 13 filters – a Rensa CA13 (with carbon) and Tex-Air (without carbon) – were tested for ultrafine particle removal efficiency using the combination of alternately sampling by the NanoScan on just the Brisa unit, this time operating with a dry pad. **Figure 7** shows the Rensa CA13 achieved a removal efficiency of at least 50% for all particle sizes smaller than 0.3 µm and the Tex-Air MERV 13 achieved a removal efficiency of at least 35% for the same sizes. The no filter condition with only the cooling pad had less than 20% removal efficiency for all sizes in this range (and 10% or less for most sizes). These results are consistent with other recent measurements of MERV 13 filters in that they do tend to achieve some level of removal efficiency for ultrafine particles even though they are not typically tested in this range.

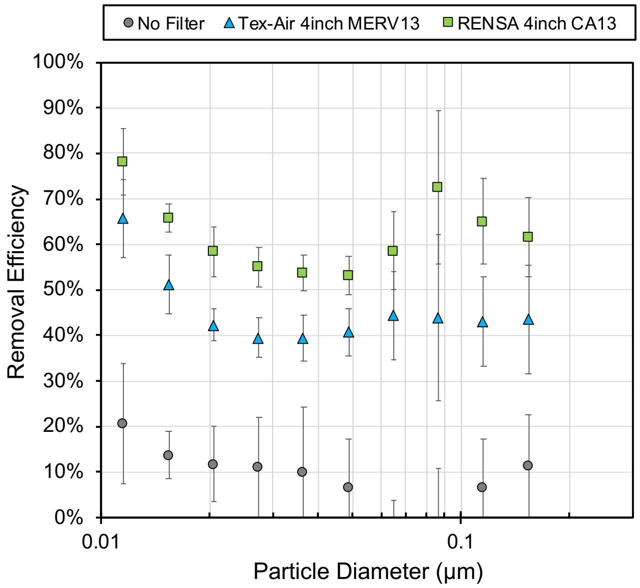

Figure 7. Size-resolved particle removal efficiency measured by alternately sampling with the NanoScan SMPS for three filter conditions on the Brisa EC unit with dry pad.

Figure S5 also shows results from testing a custom surrounding structure that could act as a plenum and filter housing and allow for filter(s) to be offset from the ECs, potentially reducing moisture issues and leading to longer filter lifespans. Briefly, while the use of the structure showed better flow performance when all three sides had filters installed than when the same number of filters were directly attached to the unit, and even the potential for just 2 of 3 sides with filters to still meet airflow design goals, the particle removal efficiency was consistently lower than for the direct attachment solution. These effects are likely attributable to a significant amount of leakage through the DIY structure, as even a small amount of bypass airflow around filters, especially higher pressure drop filters like those tested here, will significantly reduce efficiency (Chojnowski et al., 2009; VerShaw et al., 2009; Ward and Siegel, 2005). Given the complexity of installing such a structure not only in the lab but especially in the field, combined with these poor results, we did not pursue this option further for subsequent testing.

3.4 Cooling capacity

Tables S1 and S2 show results for cooling capacity from measurements of temperature and relative humidity (RH) measured upstream before the EC air intakes and downstream after the EC supply with the EC operating at approximately steady-state wet conditions under four filter configurations for the Brisa and MasterCool, respectively. The goal was to test the impact of a wide range of filter attachments and associated airflow rates on EC cooling performance to determine whether decreased airflow rates from filter attachments have a linear, sub-linear, or supra-linear relationship with delivered sensible or latent cooling capacity, motivated by past research that has shown that reductions in airflow rates due to increased pressure drop filtration in residential vapor compression air-conditioning systems does not have a linear relationship to cooling capacity because the increased contact time of air with the cooling coil leads to greater differences in temperature and humidity ratio delivered to the space (Stephens et al., 2010a). Results from the Brisa show that cooling capacity varied approximately linearly with flow rate, as temperature and humidity ratio differences across this EC did not clearly vary at different airflow rates. Results for the MasterCool were not as clear but suggested that cooling capacity varied approximately sub-linearly with flow rate, as temperature and humidity ratio differences across this EC were slightly greater with filter attachments than without a filter. In both cases, it appears that flow rate reductions due to filter attachments can be the primary indicator of potential cooling capacity impacts.

3.5 VOC removal efficiencies

Figure S3 shows an example of time-resolved benzene concentrations measured by the PTR-ToF-MS during chamber testing of a 61x76-cm [24x30-inch] 10-cm [4-inch] depth Rensa CA-13 carbon-impregnated MERV 13 filter and fan combination. **Figure 8**a shows an example of first order loss rate estimates for benzene decay made (i) with the fan/filter combination switched off (‘air cleaner off’) and (ii) with the fan/filter combination operating (‘air cleaner on’) at the highest fan speed test condition (face velocity of 1.05 m/s), tested over 3 replicates. **Figure 8**b shows resulting estimates of single-pass removal efficiencies of the Rensa CA-13 filter for benzene and toluene from three replicate tests at three face velocities each (1.05, 0.55, and 0.3 m/s). VOC removal efficiency estimates were similar for both benzene and toluene, and were influenced by face velocity, ranging from ~20% at the highest face velocity to ~35% at the medium face velocity and ~40% at the lowest face velocity. This inverse relationship between VOC removal efficiency and face velocity was expected due to lower residence times of air in the filter media matrix at higher face velocities. While these tests are not inclusive of other VOCs commonly present in wildfire smoke, they suggest that moderate VOC removal is possible using the Rensa CA-13 carbon-impregnated MERV 13 media filters.

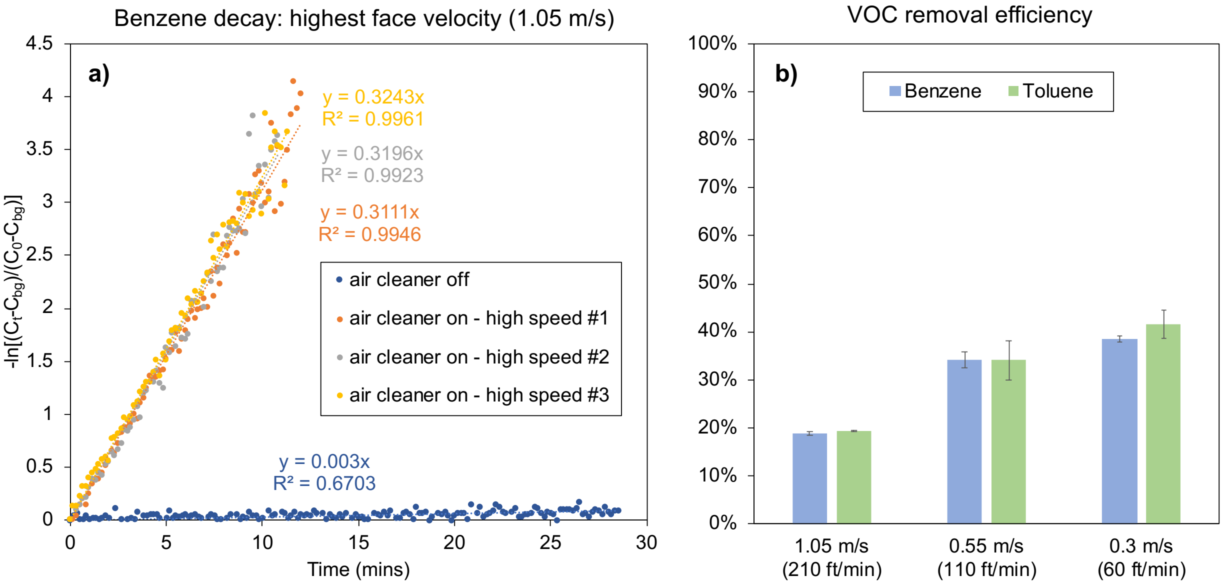

Figure 8. Estimated VOC removal efficiencies of a 10-cm (4-inch) Rensa CA-13 carbon-impregnated MERV 13 filter measured by PTR-ToF-MS during testing at Portland State University: a) example of first order loss rate estimation for benzene decay during air filter and fan combination (i.e., "air cleaner") off and on periods from the highest fan speed test condition (face velocity of 1.05 m/s), and b) estimated single-pass removal efficiencies of the filter for benzene and toluene from three replicate tests at three face velocities.

3.6 Chicago wildfire event

Figure 9 shows results from particle measurements conducted upstream and downstream of the Brisa EC unit operating in dry conditions during long-range transport of Canadian wildfire smoke into Chicago on June 26-27, 2023. Four filtration conditions are tested, each for approximately 30 minutes: no filter (dry pad) and three of the 10-cm (4-inch) depth MERV 13 filters including the Rensa CA-13, AAF AmAir/C, and AAF MERV 13.

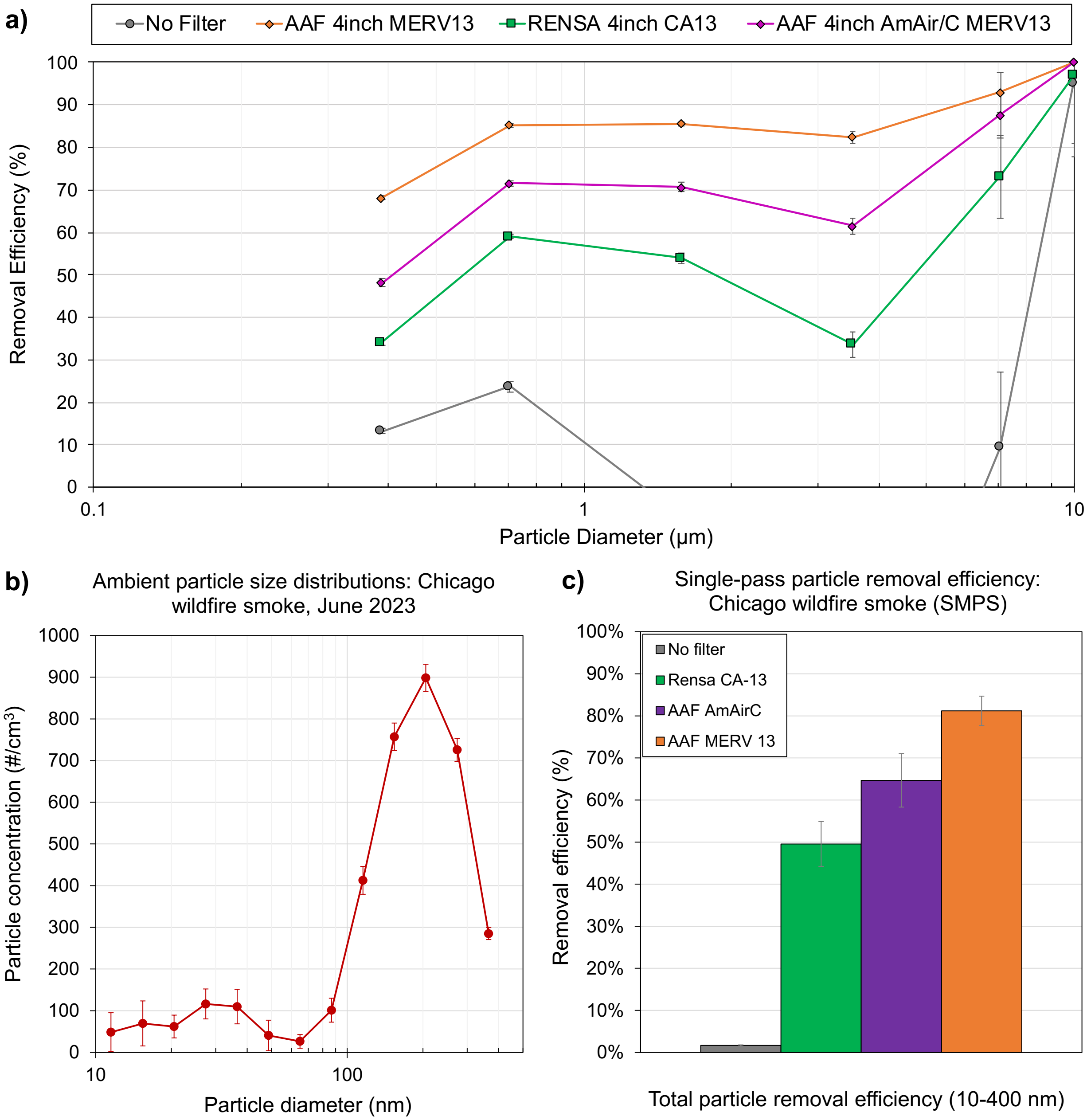

Figure 9. Particle measurements conducted on the Brisa EC operating in dry conditions without a filter and with three different 10-cm (4-inch) MERV 13 filters in Chicago during long-range transport of Canadian wildfire smoke, June 26-27, 2023: a) single-pass removal efficiency for size-resolved particles measured by two OPCs (0.3-10 µm) for the same four test conditions, b) ambient (outdoor) particle size distributions measured by the NanoScan SMPS (10-400 nm), and c) single-pass removal efficiency for total particle number concentrations measured by the NanoScan SMPS (10-400 nm).

Figure 9a shows mean (SD) size-resolved removal efficiencies for 0.3-10 µm particles measured during these tests using two OPCs installed upstream and downstream of the EC. Results are fairly consistent with measurements during typical conditions in other lab measurements in the absence of wildfire smoke, suggesting that our earlier approaches to evaluate size-resolved performance in the absence of wildfire conditions can be useful for informing likely performance during wildfire conditions. The EC with cooling pads alone (dry conditions) had minimal removal efficiency for most particle sizes.

Figure 9b shows ambient (outdoor) particle size distributions measured by the NanoScan SMPS, which measures particle number concentrations in 13 size bins in the range of approximately 10-400 nm (assigned bins range from 11.5 nm to 365 nm). Consistent with the existing literature (Niemi et al., 2005; Okoshi et al., 2014; Phuleria et al., 2005; Sillanpää et al., 2005), particle number concentrations in this aged, long-range transported smoke peaked around ~150-275 nm, with the largest peak in the size bin assigned to 205 nm in mobility diameter. This distribution is indeed shifted towards larger particle sizes than typical urban air in the Chicago area. For example, in a prior study in the same geographic location in Chicago, we measured an average geometric mean diameter of ambient air to be ~42 nm across several repeated tests; see Table S1 in (Zhao and Stephens, 2017). Also worth noting is that in prior investigations of ambient and indoor air with the NanoScan SMPS, we and others have excluded number concentrations above ~100 nm because of known issues due to the method of fitting distributions, which, according to the manufacturer, is required because of the instrument's unipolar charger (Stephens et al., 2013; Zeng et al., 2022a, 2022b, 2021; Zhao and Stephens, 2017). The issue is particularly apparent when concentrations of particles above ~100 nm are low relative to the total number concentration (Yamada et al., 2015), which is usually the case in urban air. However, this issue was not apparent during sampling in these wildfire smoke conditions because of the shifted size distribution towards larger particles.

Figure 9c shows single-pass particle removal efficiencies for the sum of all particle sizes measured by the NanoScan SMPS alternately sampling upstream and downstream of the Brisa EC during the same filter conditions on the same day. Notably, the EC operating with AAF non-carbon MERV 13 media had the highest filtration efficiency for wildfire smoke in both the OPC and SMPS particle size ranges, removing 80% or more of most particle sizes. This level performance, especially in the sub-micrometer size range, is more similar to MERV 14 or even MERV 15 performance, similar to prior observations in the lab during non-wildfire conditions. The

EC operating with Rensa CA-13 filters performed similarly to other test conditions, with a total particle removal efficiency measured by the SMPS of ~50%, and the EC operating with AAF AmAir/C filters had a total particle removal efficiency measured by the SMPS of ~65%, approximately halfway between the Rensa CA-13 and the AAF electret MERV 13. These results demonstrate the viability of any one of these filtration solutions attached to an EC could achieve at least 50% removal efficiency for wildfire smoke, which is consistent with overall design goals and consistent with laboratory tests during non-wildfire conditions.

4. Discussion and Conclusions

We sought to identify an air filtration solution for residential ECs that could meet design goals of being cost effective (i.e., under $100 USD), being flexible for attaching to most residential ECs (especially horizontal-flow units), providing a level of particle filtration that is consistent with prevailing recommendations (e.g., MERV 13), potentially providing some gas-phase filtration, while not excessively restricting airflow. We characterized the baseline performance of three residential ECs in a laboratory that are typical of many of those observed in a pilot field survey in our study region. We tested over 15 filters and filter media in a variety of configurations and attachments and evaluated their impacts on a range of performance metrics. The testing identified a DIY solution that involves direct attachment of filters to the exterior intakes of ECs using bungee straps, such that a moderately handy individual could deploy for relatively short periods of time during wildfire smoke conditions. Our recommended DIY filtration solution that met all goals of removing more than 50% of relevant particle sizes, providing at least some VOC removal, and not diminishing airflow more than 20% is deep bed 10-cm (4-inch) carbon-impregnated MERV 13 filters. Our recommended DIY solution that met goals for particle removal and airflow resistance but that did not remove VOCs is deep bed 10-cm (4-inch) MERV 13 filters without carbon-impregnation. Other backup/alternative solutions include locally available FPR 7 media or equivalent or even flat sheet media, albeit with some drawbacks. Our primary recommendations are thus consistent with the U.S. EPA's recently published recommendations to "completely cover the entire outside air intakes" of residential ECs with 10-cm (4-inch) MERV 13 filters, which were published after our work began (US EPA, 2024). **Figure 10** shows a flow diagram of our selection logic from lab testing.

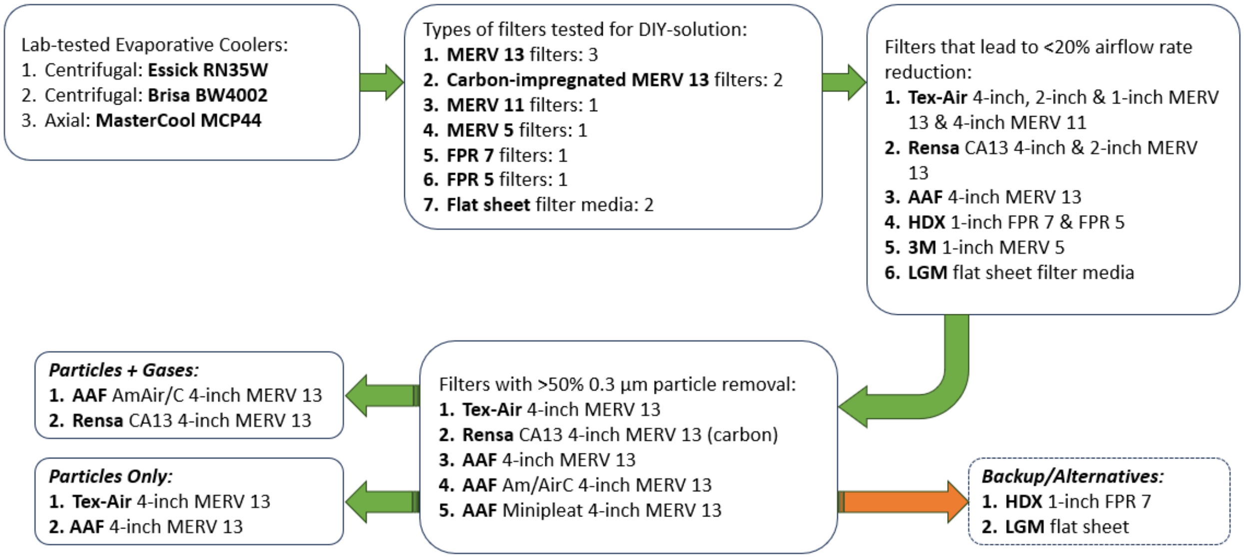

Figure 10. Filter selection diagram for EC intake attachment solution.

Table 2 summarizes approximate upfront costs and high-level performance metrics of various direct attachment filtration solutions for the three tested residential ECs. Total installation cost estimates are made using the dimensions and quantities of filters needed for each test EC described in **Table 2** and include only the approximate costs of new filters; the cost of two bungee straps adds about $5 per pair. Total cost estimates and flow rate performance are both shown separately for each type of EC tested in the lab given their differences in filter sizes and quantities and airflow performance. A range of upfront costs for new filters is approximated based on a survey of a combination of commercially available options from online retailers and from personal communications with filter manufacturers and suppliers of products that have similar characteristics to those specific filters that we tested. Therefore, the cost ranges shown in **Table 2** account for variability in both upfront filter costs and the quantities and dimensions of filters that may be needed to fit ECs of a similar size.

Table 2. Summary of types, costs, and performance metrics of recommended DIY direct attachment filter solutions tested on the three EC units in the laboratory.

	Tested Products	**Measured Removal Efficiency**			**Flow Rate Reduction (%)**	**Approx. Unit Filter Cost (USD)**	**Approx. Total Install Cost (USD)**
		0.3-0.5 µm particles	2.5-5 µm particles	Benzene/ Toluene			
Particles + VOCs							
10-cm (4-inch) carbon-impregnated MERV 13	AAF AmAir/C	>50%	>80%	Not tested	Brisa: 10-15% Essick: 10-15% MasterCool: 40-45%	24x30-inch: $90-115 16x25-inch: $45-65	Brisa: $270-390 Essick: $180-330 MasterCool: $210-230
	Rensa CA-13	>50%	>80%	20-40%			
Particles Only							
10-cm (4-inch) MERV 13	Tex-Air MERV 13	>50%	>70%	n/a	Brisa: 5-10% Essick: 5-10% MasterCool: 35-40%	24x30-inch: $25-35 16x25-inch: $15-30	Brisa: $75-180 Essick: $60-120 MasterCool: $70-90
	AAF MERV 13	>50%	>70%	n/a			

These comparisons show that a direct attachment deep-bed MERV 13 solution without impregnated carbon can achieve desired particle removal with relatively small impacts on airflow rates (on centrifugal fan ECs only) at a cost of approximately $100 or less, depending on the unit costs of filters. While an impregnated carbon MERV 13 solution achieves the same performance goals in addition to providing some VOC removal, the high upfront filter cost increases the total installation cost to nearly $200 for smaller centrifugal ECs or axial ECs to nearly $400 for larger centrifugal ECs.

There are several limitations to this work. For one, the commercial availability of the deep-bed carbon-impregnated MERV 13 filters remain somewhat limited and therefore may be difficult for consumers to acquire unless increased demand leads to increased production and supply. Second, our testing was limited to the range of filters and attachments tested herein; there may be other products at different price or performance. Our experimental testing was also limited to the particles and VOC constituents shown herein; future work should also evaluate performance in removing SVOCs (such as PAHs), trace metals, and other constituents commonly found in wildfire smoke. Our cost estimates are provided as ranges, since costs can vary highly by supplier, filter characteristics, dimensions, quantities purchased, and other factors, but they do suggest that it is likely that subsidies would be required to achieve both particle and gas filtration. However, it would be useful to gain a better understanding of people's willingness-to-pay for these solutions.

Further, in the pilot field survey, we noticed that limited space and sometimes even obstructions surrounding ECs could make our proposed direct attachment DIY solution difficult to install in some settings. Although the proposed solutions can theoretically be implemented on roof-installed ECs, such installations may be infeasible in many settings and thus our solution may be limited only to through-the-wall or through-the-window EC units. Additionally, we focused on a solution for relatively short-term deployment during wildfire events but have not investigated ideal filter maintenance or replacement cycles. Longer-term applications may be needed in some locations with longer wildfire seasons or among certain vulnerable populations. As such, future work should evaluate both the short- and long-term performance of such solutions, including operations and maintenance, in real-world settings. Finally, future work should also strive to evaluate the impact of the DIY solution on respiratory outcomes in real-world intervention trials. To that end, the DIY solution has been deployed in a second phase of the FRESCA study to better understand in-situ performance and impacts on indoor concentrations of particulate matter (including PAHs and trace metals) in participant homes in the San Joaquin Valley, California; results will be presented elsewhere.

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Disclaimer and Data Availability

Certain equipment, instruments, and materials are identified in this manuscript. Such identification is not intended to imply recommendation or endorsement of any product by the authors or funding agency. Primary data from this project are posted to a public repository, Open Science Framework (OSF): https://osf.io/arz3d/. Additional data not posted to the repository are available upon reasonable request.

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