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Performance of Electret Filters for Use in a Heating, Ventilation and Air Conditioning System and an Automotive Cabin against Combustion and NaCl Particles

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ABSTRACT

This study was conducted to investigate the performance of a high-efficiency Heating, Ventilation and Air Conditioning (HVAC) filter and a top-of-the line Automotive Cabin Air (ACA) filter challenged with particles generated by the combustion of paper, wood, and plastic as well as with NaCl particles. The collection of submicron particles was examined under conditions representing two typical indoor air flow rates for the HVAC filter and two cabin fan control levels for the ACA filter. For the HVAC filter, almost all the collection efficiency values exceeded 80%; for the ACA filter, the collect efficiencies were much lower (< 40%) for all the tested aerosols and flow rates. Both filters demonstrated lower collection efficiency for combustion aerosols as compared to NaCl. This finding was consistent for all tested particle sizes and flow rates. The difference was always statistically significant in terms of the total efficiency (combining all sizes); however, the size-specific analysis of the differences revealed that the significance level varied with the particle size and flow rate. When tested under their operational flow conditions, the HVAC filter showed significantly better performance than the ACA filter. It was concluded that the filter performance characteristics of the HVAC and ACA filters obtained using well-established salt aerosol challenges may not accurately predict the performance of these filters against combustion aerosol particles. The difference was attributed to the interactions between the particles and filter fibers.

Keywords: HVAC filter; Automotive cabin air filter; Combustion aerosols; NaCl; Collection efficiency.

INTRODUCTION

Indoor exposure to submicrometer-sized and nano-sized particles, including those generated by combustion, has received increased attention. Combustion particles infiltrate homes from outdoors; they are also generated by various indoor activities (Stephens and Siegel, 2013). A significant association between acute asthma and increased levels of residential wood smoke particles has been reported (Boman *et al.*, 2003). Recently, the International Agency for Research on Cancer (IARC) classified indoor emissions from the household combustion of biomass fuels (primarily wood) as "probably carcinogenic to humans (group 2A)" (Bølling *et al.*, 2009). Moreover, indoor exposure to air containing combustion aerosols has been associated with adverse health effects including respiratory problems and the impairment of cardiovascular function. In particular, nano-sized particles, including those originating from combustion of different materials, have been linked to health effects such as fibrosis, chronic inflammatory lung disease, metal fume fever, and cancer (Donaldson *et al.*, 2005).

Vehicle exhaust particles and smoke produced by burning materials are constituents of particulate matter in urban residential areas. In addition, during daily commutes, drivers and passengers are exposed to high concentrations of aerosol pollutants emitted by mobile sources, primarily on-road vehicles. Approximately 50% of the population in the USA has a one-way daily commute time, between home and work, of more than 30 min (Zhu *et al.*, 2007). It has been shown that exposure to air pollutants in an automobile cabin is particularly high because of the proximity of passengers to relatively concentrated emissions from other automobiles

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and the rapid air exchange rate inside the vehicle (Park *et al.*, 2010).

Stationary filters are installed in the Heating, Ventilation, and Air Conditioning (HVAC) systems of buildings to reduce indoor exposure to aerosols, including hazards produced by combustion. Similarly, to reduce exposure to airborne particles inside vehicles, Automotive Cabin Air (ACA) filters are used. The efficiency of particle removal by HVAC and ACA filters depends on air velocity, particle size, particle shape, filter material, and environmental factors (Stephens, 2012). The filter performance is traditionally evaluated using conventional test aerosols, mostly potassium chloride (KCl) particles, according to the ANSI/ASHRAE standard (ASHRAE, 2012) or, in some protocols, charge-equilibrated sodium chloride (NaCl) particles (Halvorsen *et al.*, 1994; NIOSH, 1995; Ji *et al.*, 2003; Shi, 2012). NaCl aerosol has characteristics similar to KCl aerosol (Shi, 2012). However, the question is whether the performance data obtained with the salt particles adequately represent the characteristics of the filters against real aerosol hazards, which may have different particle size and shape, etc. Most of the current standards for testing HVAC filters (including the ASHRAE Standard 52.2, EN779) do not incorporate measurements of the removal efficiency with nano-sized particles (Stephens and Siegel, 2013). According to the International Standards Organization standard, the ACA filters are tested using particles larger than 300 nm (ISO, 2001), thus generating no information relevant to the control of nano-sized particles, including those originated by combustion.

The present study was conducted to examine the performance of a widely used high-efficiency HVAC filter (and a top-of-the-line electrostatic ACA filter) against aerosol particles generated by the combustion of paper, wood, and plastic (mostly represented by a nano-sized fraction) as compared to the performance of these filters against NaCl aerosol particles. The filter performance was quantified in terms of the particle collection efficiency and pressure drop.

MATERIALS AND METHODS

Test Filters

A commercially available MERV14 HVAC filter ($16 \times 25 \times 5$ in^3 $\approx 41 \times 63 \times 13$ cm^3, Pleated panel type, Nordic Pure, Inc., Celina, TX, USA) and an ACA filter ($8.5 \times 8.5 \times 1.4$ in^3 $\approx 21.6 \times 21.6 \times 3.6$ cm^3, Pleated panel type, Denso, Long Beach, CA, USA) were tested in this study. According to Standard 52.2, the MERV 14 filter should remove more than 90% of airborne particles within a range of 1.0 to 10.0 µm and more than 75% of airborne particles between 0.3 and 1.0 µm (ASHRAE, 2012). The filter manufacturer refers to the performance testing using challenge aerosols such as tobacco smoke, pollen, dust mite debris, mold spores, dust and dander. No similar information is available with respect to the efficiency of the selected ACA filter; the preliminary performance-based evaluation suggested that this filter is one of the most efficient among automobile cabin aerosol filters. Both filters chosen for this study are made of electrostatically charged media (electret filters).

Rectangular samples, area $A_{Sample} = 4.0 \times 5.0$ inches for HVAC filter (1/20 of the total area) and 2.0×2.6 inches for ACA filter (approximately 1/14 of the total area), were cut from the commercial filters to be utilized for testing. We chose the dimensions of the samples sizes so that the available air supply units and filter holders could be deployed and a uniform flow distribution through the filter surfaces could be assured (to minimize the boundary effects). In the experiments, the flow rates through the samples, Q_{Sample}, were established to achieve the same face velocity, V, as in the full-size filters under the operational conditions set by their manufacturers (Q_{Filter}), see Table 1. The testing was conducted at air flow conditions representing two ventilation flow rates for the tested HVAC filter (Q = 75 CFM ≈ 127 m^3 h^{-1} and 150 CFM ≈ 254 m^3 h^{-1}) and two ventilation flow rates for the tested ACA filter (Q = 57 CFM ≈ 97 m^3 h^{-1} and 115 CFM ≈ 195 m^3 h^{-1}). According to ANSI/ASHRAE Standard 62.2, a ventilation air flow of 150 CFM is recommended for a living space with three bedrooms and a floor area of 3,500– 4,000 ft^2 ≈ 325– 372 m^2 (ASHRAE, 2013). The flow rates chosen for testing the ACA filter, 57 and 115 CFM, were referred to by Park *et al.* (2010) as those produced in the automobile cabin under moderate ventilation (fan set at level "2") and high ventilation (level "4"), respectively. It is acknowledged that the HVAC and ACA filters were tested under their operational flow rates, which resulted in different face velocities ($V_{HVAC} < V_{ACA}$).

Pressure Drop Measurement

The pressure drop through the tested filters was measured with a Magnehelic® gauge (Series 2000, Dwyer Instruments Inc., Michigan City, IN, USA) operating in a range from 0 to 10 mm H_2O. Measurements were conducted at two specific flow rates Q_{Sample} listed in Table 1 for each filter. The pressure drop values were recorded before and after the filter performance testing.

Test Aerosols

The combustion aerosols were generated inside a room-size test chamber (142 × 95 × 102 inches^3 ≈ 3.6 × 2.4 × 2.6

Table 1. Test flow rates established for filter samples with an area-based adjustment.

Filter	Flow rate, Q_{Filter} (CFM)	Face velocity, V (cm s^{-1})	Flow rate, Q_{Sample} $^{a)}$	
			CFM	L min^{-1}
HVAC	75	13.7	3.75	106
	150	27.4	7.5	212
ACA	57	57.8	4.11	116
	115	117	8.28	234

$^{a)}$ $Q_{Sample} = Q_{Filter} \times (A_{Sample}/A_{Filter})$ to assure the same face velocity through the sample and the whole filter.

m^3, L × W × H) by burning wood (24-cm pellet, 1.9 ± 0.5 g), paper (23 × 24 cm brown multifold paper towel, 2.1 ± 0.2 g), and plastic (20.5-cm flexible straw, 0.57 ± 0.01 g) – one material at a time. Each tested material was held with a caliper, ignited using a long-reach lighter, and completely burnt inside the test chamber. After an active burning, a combustion aerosol was allowed to reach a relatively stable particle size distribution and a homogenous concentration – a 5 min period preceding the test. In addition, for comparison testing, the filter performance evaluation was conducted with a well-established NaCl aerosol challenge. The NaCl particles were aerosolized using a particle generator (Model 8026, TSI Inc., Shoreview, MN, USA) and charge-equilibrated by passing through a ^{85}Kr electrical charge equilibrator (Model 3054, TSI Inc., Shoreview, MN, USA) in the test chamber.

Experimental Design

The experimental setup is presented in Fig. 1. The test filters were mounted on a specially designed holder. The burning was initiated at a distance of approximately 2 m from the holder.

A P-Trak ultrafine particle counter (UPC) (8525, TSI Inc., Shoreview, MN, USA; operational range from 20 nm to > 1,000 nm) was used to measure the total concentrations upstream (C_{up}) and downstream (C_{down}) of the test filter. Additionally, an aerosol spectrometer consisting of a Model 1320 nanoparticle aerosol monitor, and a Model 1.108 optical particle counter (OPC) (Grimm Technologies Inc., Ainring, Germany) was used for size-selective measurement in parallel with the P-Trak. Considering the size distributions of the tested aerosols (mostly nano-sized and some submicrometer particles), we recorded the data generated by nanoparticle aerosol monitor between 20 and 300 nm and OPC data from 300 to 900 nm (the spectrometer capable of measuring in a wider particle size range). The nanoparticle module measures a mobility particle diameter while the OPC module measures the optical diameter. For the Grimm instrument, a total concentration value was determined by integrating at least ten scans recorded by the aerosol spectrometer over 1 min each. For P-Trak, the total concentration value was calculated as an average of at least ten readings (the recording time was set to be also 1 min).

Resulting from the data collected with each of the two instruments, the filter collection efficiency (η) was calculated as follows:

$$\eta = 1 - \frac{C_{down}}{C_{up}} \times 100\ (\%) \qquad (1)$$

The overall collection efficiency (derived from measuring the total particle concentrations) and the size-specific collection efficiencies (derived from the particle size selective measurement) were determined using the above equation. Each experiment was performed in five or six replicates, and the mean and standard deviation of the filter collection efficiency were calculated accordingly.

Data Analysis

The statistical analysis was performed using Microsoft Excel 2010 (Microsoft Corp., Redmond, WA, USA) and SPSS version 12.0 (SPSS Inc., Chicago, IL, USA). The t-test was used to analyze the differences in the total and size-specific particle collection efficiencies between NaCl and each of the combustion aerosols for each filter and a corresponding flow rate. The t-test was also used to examine the differences in total particle collection efficiency measured with the Grimm aerosol spectrometer and the P-Trak UPC. A one-way analysis of variance (ANOVA) was conducted to determine the significance of the differences in filter collection efficiency between the three combustion aerosols.

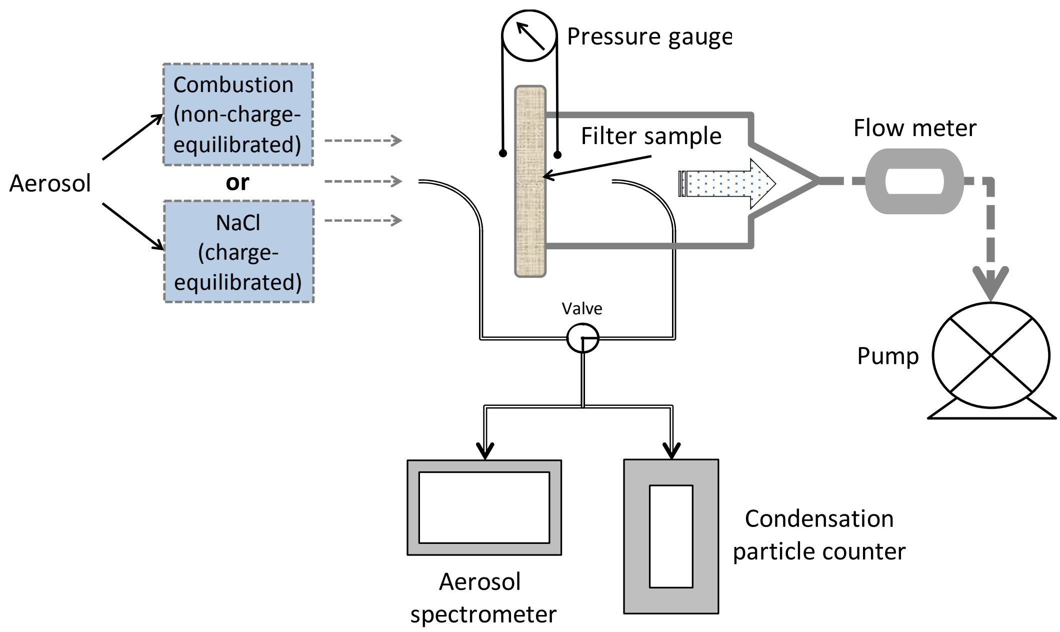

Fig. 1. Experimental set-up.

RESULTS AND DISCUSSION

Pressure Drop Measurement

The pressure drop values obtained for the tested filters are presented in Table 2. For the HVAC filter, the pressure drop was as low as 0.2 and 0.4 mm H_2O at face velocities of 13.7 and 27.4 cm s^{-1} (correspond to Q_{Filter} of 75 and 150 CFM), respectively. Higher values were obtained when testing the ACA filter (Table 2). The pressure drop should increase linearly as the face velocity increases (Liu *et al.*, 2011); the experimental data support this expectation for the HVAC filter, but not precisely for the ACA filter, which is likely associated with the limit of detection of the Magnehelic® gauge (0.05 mm H_2O) as well as the boundary effects.

The values presented in Table 2 are much lower than those presented in the ASHRAE Standard 52.76, which lists 375 Pa (approximately 38.2 mm H_2O) at 3,375 m^3 $hour^{-1}$ (approximately 1,986 CFM). The finding is not surprising considering that our HVAC testing protocol adopted the ANSI/ASHRAE Standard 62.2, which utilizes much lower air flow rates (see above) and consequently produces lower pressure drop values. The study of Stephens and Siegel (2013) performed with MERV-13 and MERV-16 filters at 930–940 CFM reported the pressure drops of 4.1 and 2.5 mm H_2O, respectively (the quoted paper did not provide an explanation why a lower pressure drop corresponded to a higher efficiency filter, which seems counter-intuitive). For ACA filters, Park *et al.* (2010) reported pressure drop values of 1.2 and 2.4 mm H_2O at face velocities of 60 and 120 cm s^{-1}, respectively, which, again, were greater than those measured in our experiments. Although Park *et al.* did not specify the ACA filter model they tested, we noted that the latter had a supporting layer, which could cause a higher pressure drop (the model used in our test did not have an additional layer). Additionally, the differences may be associated with filter characteristics such as thickness and packing density that influence the pressure drop.

Particle Size Distributions of Combustion Aerosols

Fig. 2 presents the particle size distributions measured for the three combustion aerosols (paper, wood, and plastic) as well as for the NaCl aerosol. The temperature (Mean ± STD) and relative humidity (Mean ± STD) were (20.5 ± 1.2)°C and (20.5 ± 4.8)%, respectively. The peak particle sizes for all four fell between 40 and 50 nm. At least 95% of the particles were in the size range of 20 to 150 nm. This is also consistent with previous studies (Baxter *et al.*, 2010; He *et al.*, 2013). To ensure sufficient particle number concentrations (especially downstream of the tested filters), the particle size-specific collection efficiency values were determined within a narrower range, 20–150 nm, in 8 channels.

Total Collection Efficiency

The total collection efficiencies obtained from the UPC measurements are presented in Fig. 3. For the HVAC filter, all the values determined at the low flow rate (Q_{Filter} = 75 CFM), except plastic, were above 90%; at Q_{Filter} = 150 CFM, the values, again with an exception of plastic, exceeded 80% (Fig. 3(a)). The same filter collected NaCl particles more efficient than combustion particles: 98% at 75 CFM and 94% at 150 CFM. The difference was statistically significant ($p < 0.05$) for both flow rates. The findings are generally consistent with the collection efficiencies anticipated based on the MERV 14 filter rating [although no direct comparison can be made given that our tests involved lower particle sizes compared to the filter testing standard (ASHRAE, 2012)]. The collection efficiencies obtained with the ACA filter were much lower: approx. 20% for all combustion aerosols at both tested flow rates. Sodium chloride particles were collected at significantly greater efficiency (> 30%) although this level was still rather low from the practical standpoint (Fig. 3(b)). Overall, the results indicate that the tests with the NaCl challenge consistently overestimated the filter performance against combustion aerosol particles.

As shown in Table 3, a type of combustion aerosol was a significant factor affecting the collection efficiency of the HVAC filter (ANOVA, $p < 0.01$). The filter collection efficiency was the lowest for plastic particles followed by paper and wood, regardless of the flow rate. For the ACA filter, no significant differences in collection efficiency were observed between different combustion aerosols at either flow rate (ANOVA, $p > 0.05$).

The total particle collection efficiency values determined based on the measurements conducted by the non-size-selective P-Trak UPC agreed with the data obtained the Grimm spectrometer (by integrating over the size range of 20 to 900 nm). No significant difference in the measured collection efficiency between the two devices was observed ($p > 0.05$). This agreement suggests that both measurement techniques can be successfully used interchangeably to quantify the total concentration of combustion particles, at least under the test conditions applied in this study.

Particle Size Specific Collection Efficiency

The size-specific collection efficiencies of the HVAC and ACA filters are presented in Figs. 4 and 5. At Q_{Filter} = 75 CFM, the HVAC filter was more than 90% efficient for all measured particle sizes and all aerosols except plastic; for plastic, the lowest collection efficiency (about 80%) was identified for particles close to 50 nm in diameter. At

Table 2. Pressure drop measured for the tested filters (average of three replicates)

Filter	Flow rate Q_{Filter} (CFM)	Face velocity (cm s^{-1})	Pressure (mm H_2O)
HVAC	75	13.7	0.23 ± 0.06
	150	27.4	0.43 ± 0.06
ACA	57	57.8	0.37 ± 0.06
	115	116	0.63 ± 0.06

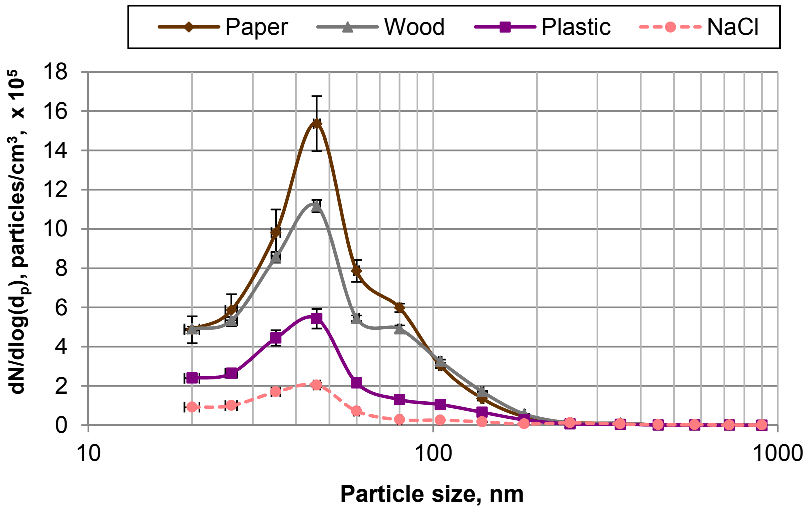

Fig. 2. Particle size distributions of three combustion aerosols and NaCl aerosol.

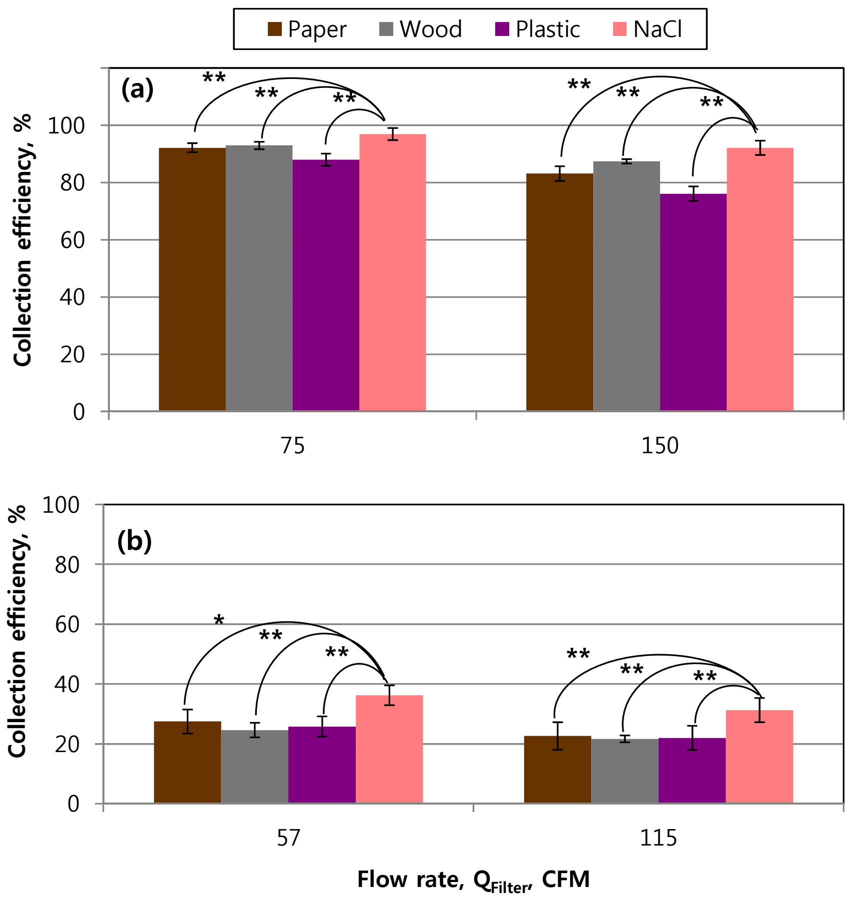

Fig. 3. Total particle collection efficiency of the HVAC (a) and ACA (b) filters determined with a UPC. Symbols * and ** denote statistically significant difference (* $p < 0.05$, ** $p < 0.01$). Each data point presents an average of 5-6 repeats, error bars present standard deviation.

Q_{Filter} = 150 CFM, only NaCl particles were removed with a > 90% efficiency (except one size, about 80 nm, for which the efficiency was 87%) while the particles produced by combustion of paper and wood were collected mostly at 80–90% efficiency; for plastic combustion particles, the collection efficiency at the higher flow rate was as low as approx. 62% at 46 nm. In conclusion, across the particle size range tested, the NaCl particles were collected more efficiently than the combustion particles under both flow rates (Fig. 4). For paper and plastic combustion aerosols,

Table 3. A type of combustion aerosol (paper, wood, and plastic) as a factor affecting the filter collection efficiency (ANOVA results).

Filter	Flow rate Q_{Filter} (CFM)	SS[a]	DF[b]	Mean Square	F value	p-value
HVAC	75	198.30	2	99.15	19.10	< 0.01
	150	46.05	2	23.03	8.30	< 0.01
ACA	57	21.07	2	10.53	0.96	0.41
	115	2.55	2	1.27	0.10	0.91

[a] SS: sum of squares;
[b] DF: degrees of freedom.

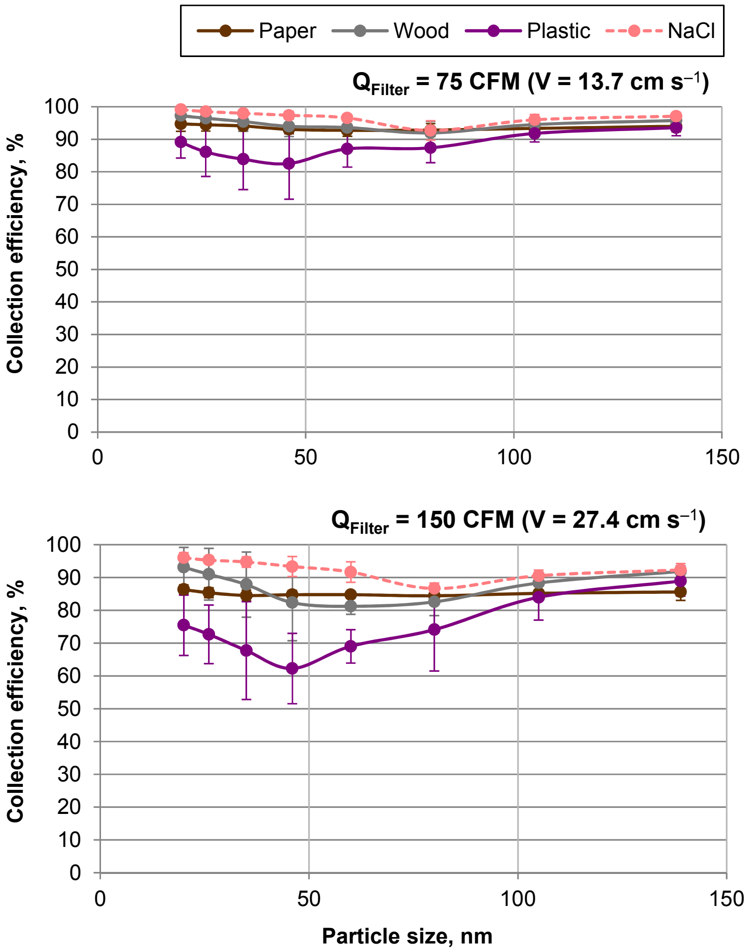

Fig. 4. Size-specific collection efficiency of the HVAC filter against combustion and NaCl aerosol particles. Each data point presents an average of 5–6 repeats, error bars present standard deviation.

this difference was significant ($p < 0.05$) across the particle size range of 20 to 105 nm at both flow rates (the only exception was 80 nm at 75 CFM). For wood, although all the collection efficiency values fell below the corresponding values obtained for NaCl, the difference failed to reveal statistical significance for most of the particle sizes.

For the ACA filter operating at Q_{Filter} = 57 CFM, all size-specific collection efficiencies were below 40% for all combustion aerosols as well as NaCl (with one exception for NaCl: 42% at 80 nm). For the tested combustion materials, the collection efficiency was around 30% in the particle size range from 20 to 150 nm, which is notably lower than that of NaCl particles. However, this difference was significant for some particle sizes, but was not significant ($p > 0.05$) for most. At Q_{Filter} = 115 CFM, the size-specific collection efficiencies fell below 30% with two exceptions such as NaCl at 80 and 105 nm (35% and 31%, respectively). As seen from Fig. 5, the collection efficiency values obtained for all three combustion aerosols fell consistently below the NaCl values. However, this difference was found statistically significant ($p < 0.05$) only for plastic combustion aerosol, but fell short of significance for paper and wood.

Our findings for ACA filters do not contradict the previously reported performance characteristics of cabin air filters against KCl particles, which listed a 43.9% collection for 100 nm particles at a face velocity of 10.8 cm s^{-1}, as

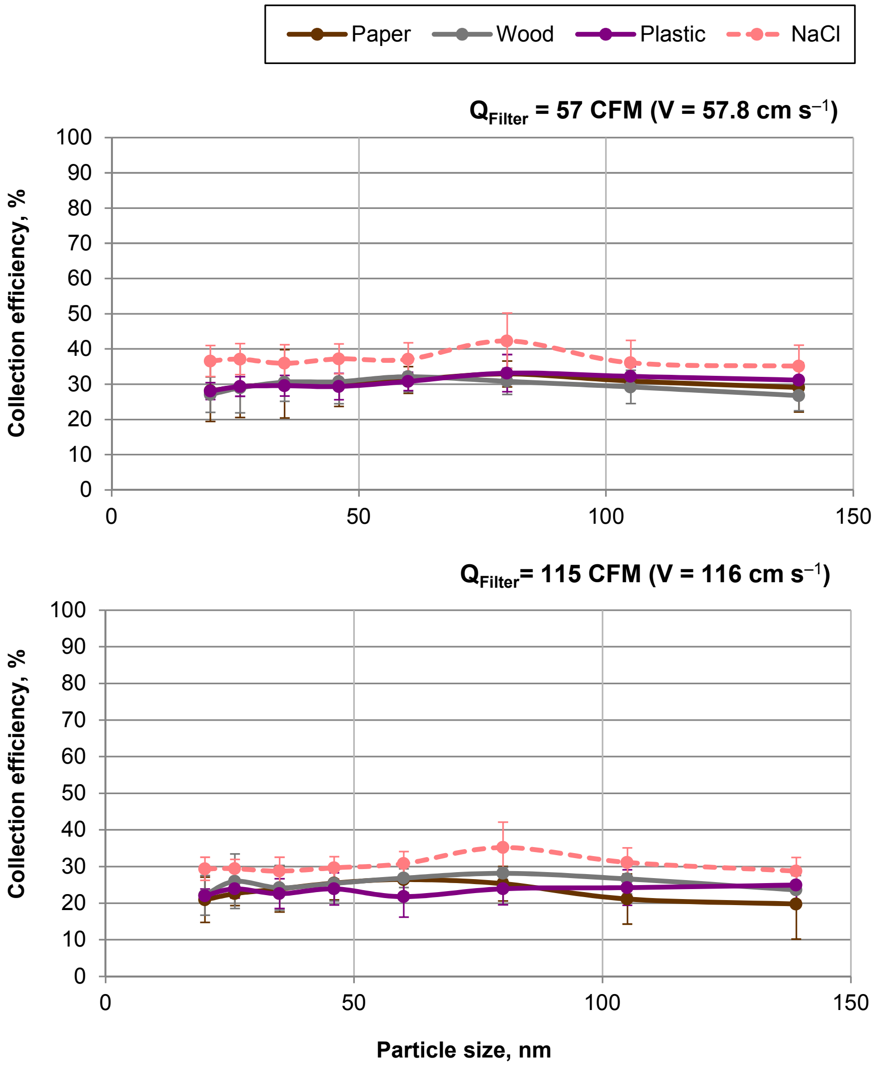

Fig. 5. Size-selective collection efficiency of the ACA filter against combustion and NaCl aerosol partilces. Each data point presents an average of 5–6 repeats, error bars present standard deviation.

well as a 69.3% and 65.2% collection for $PM_{2.5}$ at face velocities of 60 and 120 cm s^{-1}, respectively (Qi *et al.*, 2008, Park *et al.*, 2010).

In summary, for all tested particle sizes, the combustion aerosol particles penetrated both tested filters, HVAC and ACA, more readily than NaCl particles. While the difference appeared to be consistent across the size range (Figs. 4 and 5), it was not always statistically significant. At the same time, the cumulative effect determined in terms of the total collection efficiency (involving all the sizes) was significant for all tested conditions ($p < 0.05$), which is in a full agreement with the analysis of data presented in Fig. 3.

Data Interpretation

The main finding of this study is that the combustion particles were less efficiently collected by both HVAC and ACA filters than NaCl particles. Possible reasons are discussed below. Combustion of different materials releases particles and vapors containing hydrophobic molecules (or hydrophobic portions of molecules). e.g., burning plastic is known to emit hydrophobic organic compounds (Teuten *et al.*, 2007). Similar to oil particles or vapors, the combustion particles may degrade filters with electrically charged fibers if deposited on these fibers (Biermann *et al.*, 1982; Tennal *et al.*, 1991). This is likely to be the case for any "electret" filter material, including the tested HVAC (and possibly ACA) filter media. The effect decreases the filter collection efficiency due to partial charge neutralization (Biermann *et al.*, 1982), dielectric shielding of fibers, and ionic conduction (Tennal *et al.*, 1991). Other possible mechanisms that may explain the differences in penetration of combustion and NaCl particles through the tested filters include the formation of loose agglomerates on the fibers, neutralization or reduction of charge occurring on fiber due to deposition of oppositely charged particles, as well as chemical reaction (Barrett and Rousseau, 1998). The above mechanisms have been considered in our recent studies (Grinshpun *et al.*, 2013, 2014; Gao *et al.*, 2015), which reported similar differences in collecting combustion and NaCl particles by an N95 NIOSH-certified respirator filter.

CONCLUSIONS

The pressure drop of the HVAC filter and the ACA filter used in this study did not exceed 0.6 mm H_2O, which is lower than the levels reported in previous investigations, where the authors apparently tested filter materials characterized by greater resistance and/or used different testing protocols (e.g., higher flow rates).

In contrast to the HVAC filter that collected > 90% of NaCl particles and > 60% of combustion particles regardless of their size under all tested conditions, the ACA filter exhibited notably lower efficiency (mostly below 40%). Based on the total aerosol concentration measurement, the HVAC and ACA filters demonstrated significantly lower collection efficiency for combustion particles compared to NaCl particles at all the tested air flow rates ($p < 0.05$). For both filters, the particle size-specific collection efficiency of all combustion aerosols was lower than that of NaCl with the significance level varying with the particle size and flow rate.

Differences in collection of aerosol particles of different type are attributed to the interactions between particles and the fibers of electret filters. This process is influenced by the particles' morphology as well as the charges and surface properties of the particles and fibers.

In conclusion, the performance characteristics of the stationary filters, such as the tested HVAC and ACA, obtained using a well-established protocol involving salt particles as the challenge aerosol may not accurately predict (and rather overestimates) the air purification level provided by these filters against combustion aerosol particles.

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