Aerosol and Air Quality Research, 16: 3349–3357, 2016

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2016.10.0437

Technical Note

Capture of Sub-500 nm Particles Using Residential Electret HVAC Filter Media-Experiments and Modeling

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ABSTRACT

Electret HVAC filter are widely used to remove airborne particles in residential or commercial indoor environments. Based on the International Commission on Radiological Protection (ICRP) deposition model, sub-500 nm particles have enhanced depositions in the tracheobronchial region and the alveolar region than particles larger than 500 nm. In this study, filtration efficiencies of five residential electret HVAC filters against monodisperse silver (Ag) and potassium chloride (KCl) particles with 3–500 nm diameters at face velocities ranging 0.05–1.5 m s^{-1} were investigated. For further understanding the effect of fiber charges on particle collections, electret media were discharged and the efficiencies acquired from pure mechanical mechanisms were compared with that of electret media. The figure of merit (FOM) of the five electret filter media was also investigated to further understand the effect of charge density on filtration performance. A theoretical model without parametric fittings used in literature was adopted and further modified by considering the polarization forces for charged particles. The modified model predicted the particle penetrations very well at low face velocities for all tested media and also well at high face velocities for the media with low charges. The discrepancy occurred for the media with high charges at higher face velocities was due to the nonuniform particle concentration distribution in the media layers. The validated model is able to be applied to improve the design for electret media for nanoparticle removal.

Keywords: Electret media filtration; Electrostatic effect; Nanoparticles; Figure of merit (FOM); Most penetrating particle size (MPPS).

INTRODUCTION

Particulate matters, PM, which can be originated from many residential activities (Wallace *et al.*, 2004; Afshari *et al.*, 2005; Wallace, 2006; Lunden *et al.*, 2015) or transported from outdoor air into indoor environment through make air system and infiltration (McAuley *et al.*, 2010; Rim *et al.*, 2010; Stephens and Siegel, 2012). They were reported to not only pose adverse health effects to people in residential indoor environments (Chang *et al.*, 2015) but also classified as carcinogenic in October of 2013 by the International Agency for Research on Cancer (IARC) as Group 1. As performing a high efficiency while maintaining a low pressure drop, electret HVAC filter media are widely used to remove airborne particles (Romay *et al.*, 1998). The peak sizes of ambient fine and coarse modes (volume-based size distribution) around the world were frequently measured with ~0.2–0.7 and ~3–20 µm, respectively (Whitby *et al.*, 1972; Kanaoka *et al.*, 1987; Harrison *et al.*, 2000; Chen *et al.*, 2010; Chen *et al.*, 2016). The coarse particles can settle by themselves or easily captured by filter media while the fine particles are more difficult to be removed. Based on the International Commission on Radiological Protection (ICRP) deposition model (Hinds, 1999), with the decrease of the particle size from 500 nm, the deposition in alveolar region increases quickly and reaches its peak which is about 50% at around 20 nm while the tracheobronchial deposition reaches its peak which is about 35% at around 3 nm. So sub-500 nm particles can cause more hazards to people and it is important to challenge these electret media with sub-500 nm particles to get a more clear understanding of the performance of these media against these small particles. Besides, the existing HVAC filter test standards, ASHRAE 52.2 (ASHRAE 2012) and EN 779 (CEN 2012) only report the initial efficiency of the HVAC filters for particles larger than 200–300 nm so it is very meaningful to have insight of filtration efficiency for these media against small nanoparticles.

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As we all know, the charge on the fiber provides the potential basis for a filter having higher initial particle removal efficiency compared to filters utilizing uncharged fiber if all other filter parameters remain the same. Whereas the charges can be shielded or neutralized gradually by the incoming particles, which cause a reduced in-use efficiency of the electret based filters. So, it is necessary to remove the charge on the fiber to know the 'worst' performance of the electret filter and to compare the data obtained before and after discharging to learn about the performance elevation brought by different level of charge, which can provide useful references for improving the filter design.

In this study, five residential electret filter media were challenged with 3–500 nm silver (Ag) and potassium chloride (KCl) particles at different face velocities and different charge states for their size fractional penetrations. The theoretical particle penetrations were also investigated and compared with the experimental data to validate the model. Besides, the figure of merit (FOM) was calculated for comparing the performance among different filters and filters with different charge states.

METHODS AND MATERIALS

Filter Media

Five electrostatically-charged melt-spun type electret filter media were tested for their initial particle removal efficiency. They are used in commercial residential HVAC filters and manufactured by 3M (3M Corp., Saint Paul, MN, USA). These media were labeled with #A–#E and their specifications are shown in Table 1. Their fibers were all bipolar charged (Baumgartner *et al.*, 1986) and the charging densities were estimated according to the authors' previous work (Chen *et al.*, 2014; Chang *et al.*, 2015). The value is 75 μC m^{-2} for media #B, #D, #E and 25 μC m^{-2} for media #A and #C, respectively. They are different in thickness, effective fiber diameter, solidity and basis weight. The calculations of theoretical particle penetration were based on these values and the results can be found in a later section.

In order to find out the effect of the electrical charge on the fiber and the filter performance difference between the charged and discharged conditions, according to EN779 (CEN, 2012), two of the filters, media #C with medium charge level and media #E with high charge level were discharged by complete immersion in isopropyl alcohol (IPA). Before being tested, the filter samples were kept in a ventilated place for 24 hours to allow them to be dried. It was confirmed that there was no structural damages by SEM analysis and also no pressure drop change between before and after IPA treatments.

Sub-500 nm Particle Filtration Test

The initial penetration of the filters were obtained by challenging the flat sheet filter media with a wide size range monodisperse particles of 3, 5, 8, 10, 15, 20, 30, 40, 50, 80, 100, 150, 200, 300, 400, 500 nm to obtain a penetration curve covering a wider size ranges. Generally, smaller particles are generated by evaporation and condensation method from metal or salt materials easier so an electric furnace (Lindberg/Blue M, Thermo Fisher Scientific Inc, Waltham, MA, USA) as shown in Fig. 1 was used in the experiments. Here, the silver particles were produced and classified into 3 to 20 nm monodisperse particles by a Nano-Differential Mobility Analyzer (Nano-DMA, Model 3085, TSI Inc., Shoreview, MN, USA) and then used to challenge the filters. In comparison, larger particles are more easily generated by atomizing salt solution. Here, the KCl particles were generated by an Collision type atomizer (Model 3079, TSI Inc., Shoreview, MN, USA) and classified into 30 to 500 nm monodisperse particles by a long DMA (Model 3081, TSI Inc., Shoreview, MN, USA). The details on the furnace temperature and solution concentration of KCl can be found elsewhere (Chang *et al.*, 2015; Chen *et al.*, 2016). All the particles were brought to Boltzmann equilibrium before entering the filter holder where the round flat sheets of filter media were mounted. The face velocities of 0.05, 0.5, 1.0 and 1.5 m s^{-1} were chosen as these velocities cover the ranges of filter real operation conditions. A differential manometer was used to measure the pressure drop of the filter at different face velocities.

The penetration, P, was calculated by taking the ratio of the downstream particle concentration of the filter for different particle sizes, $C(d_x)_{\text{down}}$, to that of upstream, $C(d_x)_{up}$, measured by the Ultrafine Condensation Particle Counter (UCPC, Model 3776, TSI Inc., Shoreview, MN, USA) as:

$$P(d_x) = \frac{C(d_x)_{down}}{C(d_x)_{up}}. \quad (1)$$

The filter efficiency, $E(d_x)$ was then calculated as:

$$E(d_x) = 1 - P(d_x). \quad (2)$$

No less than six repeats of penetration tests using new media for each test for all four face velocities were conducted to get reliable and representative results. Besides, an extra of 18 samples for each media #C and #E were required for

Table 1. Specifications of electret filter media.

Media	Thickness (mm)	Effective fiber Diameter (μm)	Basis weight (g m^{-2})	Solidity (1-porosity)	Charge density (μC m^{-2})	Pressure drop at 14 cm s^{-1} (mm H_2O)
#A	0.94	26.3	61.7	0.072	25	0.45
#B	0.97	24.0	67.5	0.077	75	0.61
#C	0.70	16.5	66.5	0.105	25	1.56
#D	0.73	17.2	61.2	0.092	75	1.21
#E	0.83	15.6	76.7	0.102	75	1.95

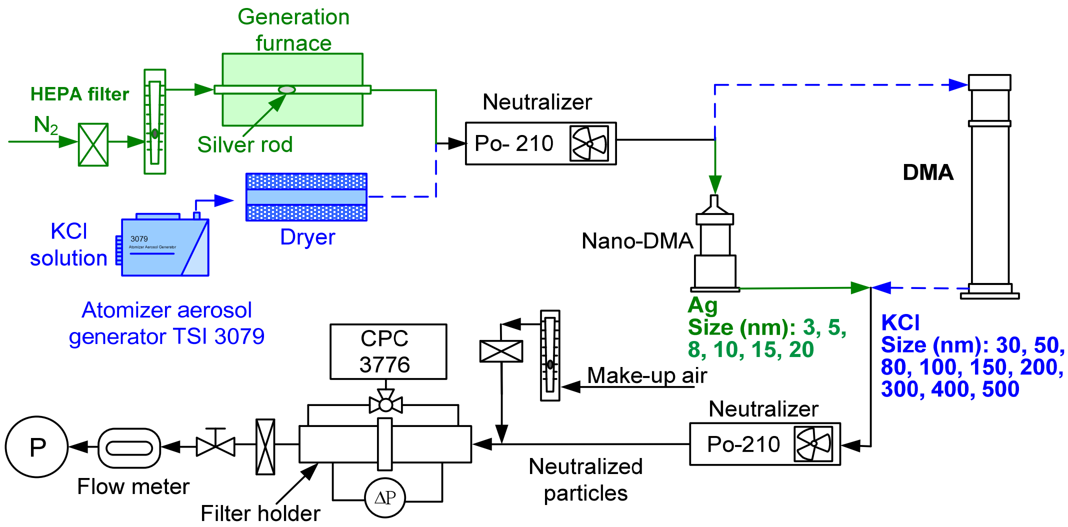

Fig. 1. Experimental setup of particle generation and filtration test.

the filtration tests under discharged condition at three different face velocities (0.05, 0.5 and 1.5 m s^{-1}). Therefore, there were more than 24 pieces of filter samples tested for each media #A, #B, #D and more than 42 pieces for each media #C and #E.

RESULTS AND DISCUSSION

Experimental Sub-500 nm Particle Penetration through Electret Media

As mentioned, the HVAC filter media are usually evaluated only with particles larger than 200 or 300 nm according to ASHRAE 52.2 and EN 779, it is important to obtain their efficiencies against smaller nanoparticles since the majority of ambient particles, e.g., $PM_{2.5}$, in number reside in these size ranges. Figs. 2(a), 2(b), 2(c) and 2(d) compare the particle penetrations between the five electret media at four different face velocities of 0.05, 0.5, 1.0 and 1.5 m s^{-1}, respectively. It is to be noted that the error bars shown in Fig. 2 and all other figures in this paper represent the 95% confidence interval among six times of reparative experiments. Basically, it is seen the penetration increase with increasing face velocities for all five media. Besides, the second mode occurred in larger size range becomes more and more obvious with increasing face velocity. The first modes are in the range of 10 to 30 nm and the second ones are in the range of 150 to 200 nm. However, different charge densities led to different performance. For example, with increasing face velocity, the global MPPSs decreased and stayed in the small size range for the filters with high charge level while the MPPSs shifted to the large size ranges for the filters with medium charge. This indicates at high face velocity and in the large particle size, the deposition is the electrostatic force dominant for high charged filter while it is mechanical effects dominant for the medium charged filters.

Possessing different thickness, effective fiber diameter, basis weight and solidity among these media, it led to different particle penetrations. Nevertheless, these media can be roughly grouped into two according to the penetration curves. That is, media #A and #C performed similarly and were regarded as lower grade, while media #B, #D and #E showed similar penetration curves and were regarded as higher grade. Interestingly, the two lower grade media had lower charge intensity while the other three had higher intensity. A further evidence showing the importance of charge can be proven by comparing media #B with #E. Due to the difference of charge level, although the two had similar mechanical parameters, there were significant differences of their penetration curves. Therefore, it could be concluded that the charge density dominated the performance of these media and is the key parameter. It is observed penetration of large particles in different filters vary greatly, for example, at face velocity of 1.0 m s^{-1}, 500 nm particles penetrated 85% through media #A while the value was only 25% in media #E. There was a total of 60% of difference. The elevated penetration for larger particles with higher face velocity was because the shortened residence time minimized the electrostatic deposition. In comparison, for particles smaller than 20 nm (sub-20 nm), the difference was almost below 20% among all different filters in all face velocities. The small differences of penetrations for sub-20 nm particles were basically due to that the mechanical diffusion mechanism dominated the depositions of small particles as small particles had higher mobility and meanwhile they were hardly polarized by media charge. That is, diffusion was the major deposition mechanism for sub-20 nm particles and the close mechanical parameters among these media (as mentioned earlier) resulted in the smaller penetration differences. However, the statement made here may not be applicable for particles with different materials as the polarization probability is greatly depended on the material of the particles. Table 2 summarizes the MPPSs and the corresponding penetrations of MPPSs for all five filter media at all four face velocities.

Evaluations of Filters Based on Figure of Merit

As seen from Fig. 2, at a fixed face velocity, media #A had the highest penetration followed by media #C, #B, #D

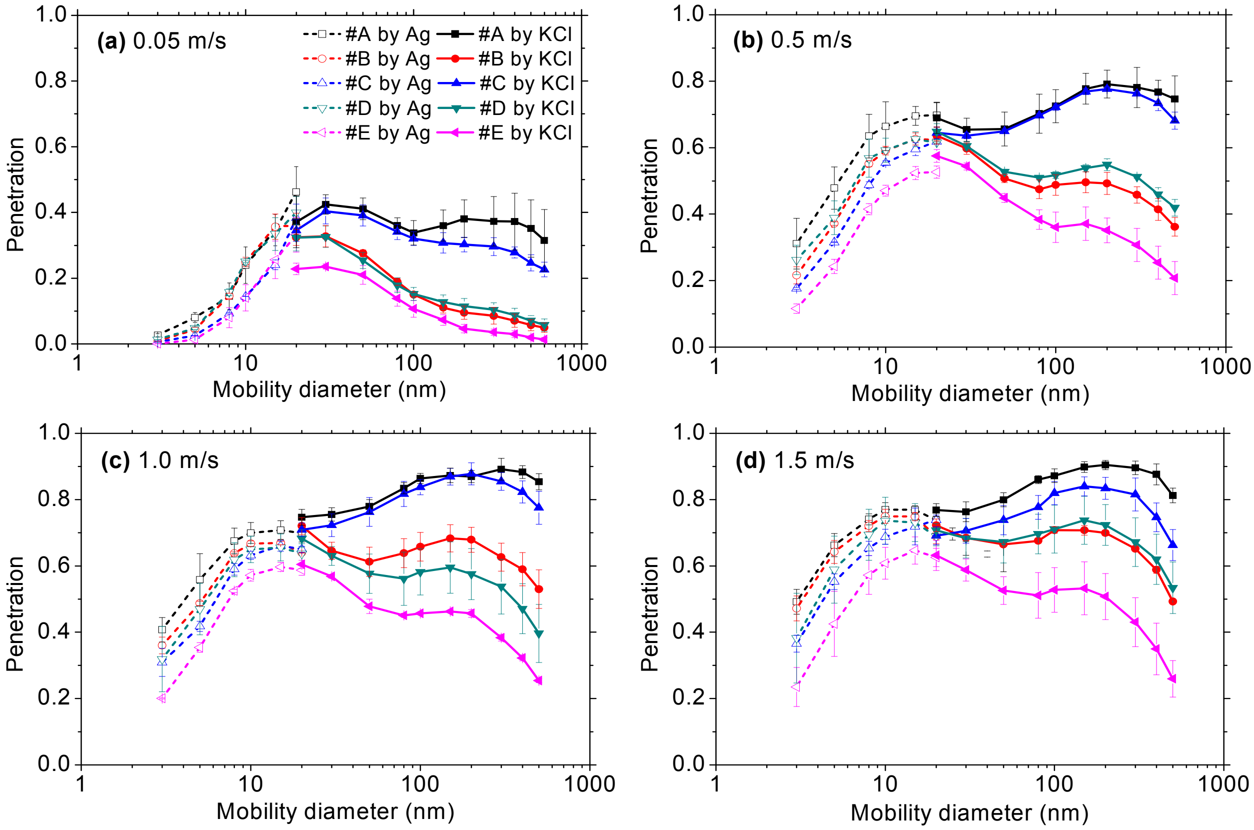

Fig. 2. Particle penetration through five electret filter media at face velocities of 0.05 (a), 0.5 (b), 1.0 (c) and 1.5 m s^{-1} (d).

Table 2. Performance comparison at different velocities.

Media	MPPS (nm)								Penetration at MPPS							
	0.05 m s^{-1}		0.5 m s^{-1}		1 m s^{-1}		1.5 m s^{-1}		0.05 m s^{-1}		0.5 m s^{-1}		1 m s^{-1}		1.5 m s^{-1}	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
#A	20	200	20	200	10	200	10	200	0.61	0.42	0.70	0.79	0.71	0.89	0.77	0.90
#B	30	--	15	150	15	150	10	150	0.40	--	0.63	0.50	0.67	0.68	0.75	0.71
#C	30	--	20	200	15	200	15	150	0.48	--	0.62	0.78	0.66	0.88	0.74	0.84
#D	30	--	15	200	15	200	10	150	0.44	--	0.63	0.55	0.66	0.60	0.74	0.74
#E	25	--	20	150	15	150	15	150	0.35	--	0.53	0.37	0.60	0.46	0.65	0.53

--: Not existed.

and then #E. However, this does not mean that media #A is the "worst" and media #E is the "best" because filtration efficiency is not the only criterion for grading filters, instead, pressure drop may be more important, which closely related the pressure drop of the filtration to the operation costs. Therefore, in order to evaluate the filtration performance of these five filters comprehensively, the figure of merit (FOM, also known as the quality factor) is investigated here, which is defined as (Brown, 1993):

$$Q = \frac{-\ln(P(d_x))}{\Delta p}, \tag{3}$$

where Δp is the pressure drop of the filter at a certain face velocity which was obtained in the test.

Good filters give high filtration efficiency while the pressure drop is remained to be low. So, according to Eq. (3), a larger value of FOM indicates a better quality of the filter. Fig. 3 shows the comparison of the FOM for the filters at face velocities of 0.05 and 0.5 m s^{-1}, respectively. The results for 1.0 and 1.5 m s^{-1} are similar with that of 0.05 and 0.5 m s^{-1}, which are not shown here. It can be seen that the ranking orders of the FOM are much different from that ranked based on penetrations when the pressure drop is taken into consideration. Comparing the FOM, media #A was originally ranked as the "worst" according to the penetration, it became the best or the second best media among the five.

A more detailed analysis for the particles smaller than 20 nm, media #A and #B have the higher FOM among five filters for the both face velocities. This is in good agreement with that reported in the literature where the FOM of small nanoparticles increased with increasing fiber diameter for mechanical filter media (Wang *et al.*, 2008). This is

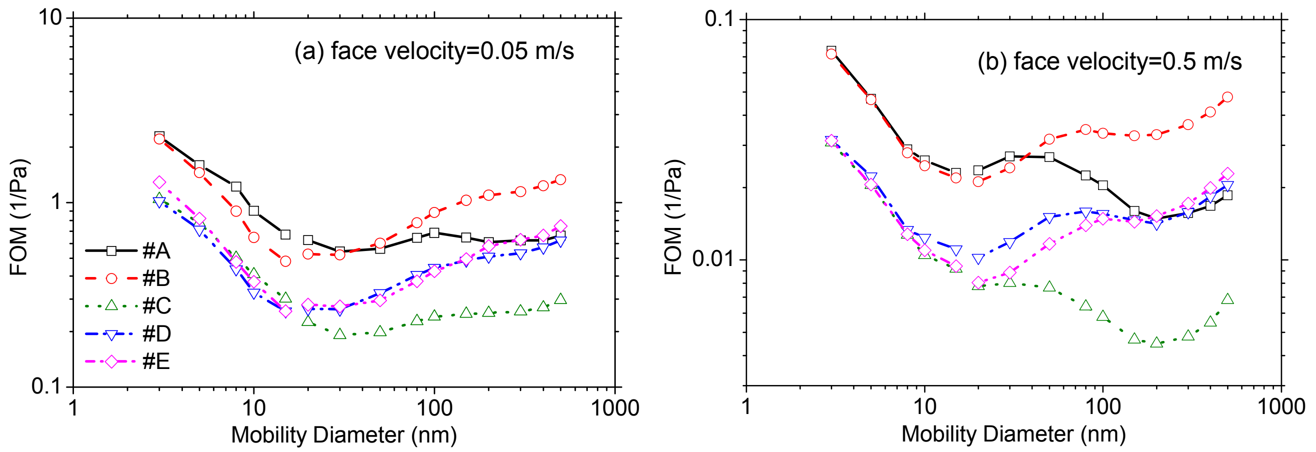

Fig. 3. FOM of five electret filter media at face velocities of 0.05 (a) and 0.5 (b).

applicable to the current electret media because they acted as mechanical media for particles smaller than ~20 nm because their depositions were not significantly enhanced by the electrostatic effects as mentioned earlier. Hence, from the perspective of designing "good" filters for small nanoparticle removal, increasing the fiber diameter while remaining the solidity the same is the key method. However, to achieve an optimal design, the performance of the filter against whole size ranges of particles should be considered and there is always a trade-off between efficiency and pressure drop.

In comparison, for larger particles, Wang *et al.* (2008) observed that the trend of FOM ranking was changed (curves crossed) from that of smaller particles, where the larger diameter fibers had smaller FOMs. However, it is seen the ranking orders mostly keep the same for the whole particle size ranges for the current electret media, except media #A. The FOM of media #A became lower than that of media #B starting from about 30 nm. That is, the media #A with lower charged and lower solidity acted similarly with that of mechanical media, which was in good agreement with that found by Wang *et al.* (2008). Here to be mentioned, the minimum of FOM in Wang *et al.* (2008) was about 100 nm whereas that of the current filters was about 20–30 nm (first local minimum), which was due to the inherent difference between electret and mechanical media, i.e., the difference of the MPPS. Besides, the FOM of media #D and #E kept a medium value and that of media #C is always the smallest one in the size range larger than 20 nm.

It is to be concluded that the trends observed can be again closely related to the charging intensity of the filters. Here media #C with medium charge density and media #E with high charge density were taken as examples to explain why the charge density is the crucial factor responsible for the FOM results. As shown in Fig. 4(b), it is seen the differences of particle penetrations between the electret filter and the same filters after discharging were very significant by the higher charged media #E for particles larger than 10–20 nm at both 0.05 and 0.5 m s^{-1} face velocities. In comparison, the penetrations were not significantly reduced by the electrostatic deposition for the lower charged media #C at 0.5 m s^{-1} face velocity, as shown in Fig. 4(a). This explains the dramatic FOM reduction for media #A, the low charged media, at 0.5 m s^{-1} as shown in Fig. 3(b). For the particles smaller than 10–20 nm, the penetration of electret filter and the discharged filter are very close, which indicates that the charge on the fiber cannot effectively polarized the silver nanoparticles smaller than 10–20 nm. On the contrary, the charges on the electret filters, especially high charge, helped the filters to capture larger KCl particles of 20 to 500 nm largely. For example, the penetration of 500 nm particles through highly charged media #E at face velocities of 0.05, 0.5, 1.5 m s^{-1} were decreased from 0.86, 0.94, 0.90 to 0.02, 0.21, 0.25, respectively, while that through medium charged media #C were reduced from 0.89, 0.94, 0.91 to 0.25, 0.68, 0.78, respectively. Although the filtration efficiency of discharged media #C and #E are similar (not depicted) due to the close media mechanical parameters, the collection efficiency of 20–500 nm particles through electret filters differ greatly because of their different charge densities. Therefore, raising the charge density is one of important ways to increase the capture capability of electret filter for 20–500 nm particles assuming the particle material is remained unchanged, which are the major size ranges of $PM_{2.5}$ in number and should be removed effectively.

Comparison of Particle Penetration between Data and Theory

For achieving a better design of filter media, an accurate prediction of filter efficiency using theoretical models is desirable. A theoretical model without parametric fittings used in literature was adopted. The theoretical particle penetration, P_{theo}, through the filter is usually calculated using the single fiber theory (Wang *et al.*, 2007, 2011; Bahk *et al.*, 2013):

$$P_{theo} = \exp\left(-\frac{4\alpha E_T t}{\pi d_f (1-\alpha)}\right), \quad (4)$$

where α is the solidity of the filter, t is the thickness of the filter, d_f is the fiber diameter of the filter media and E_T is

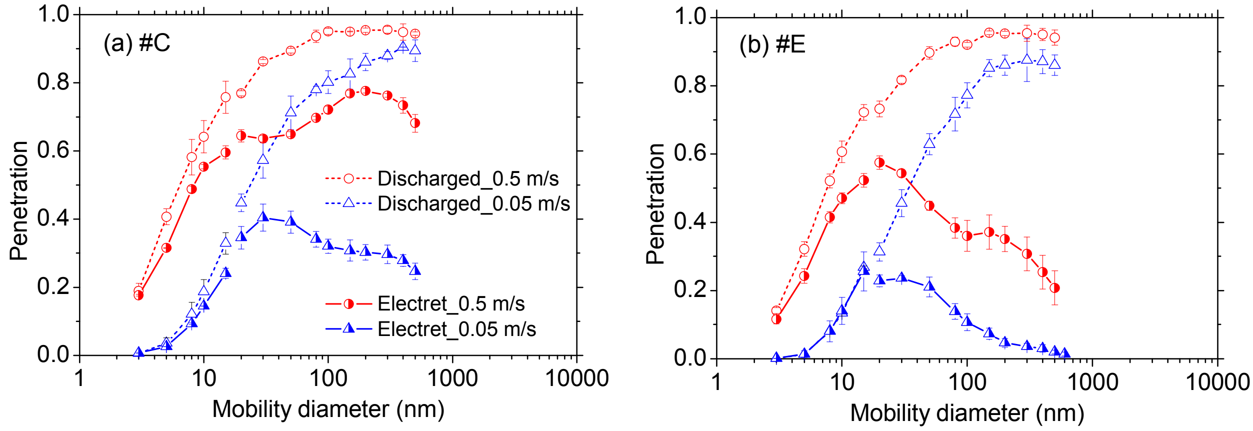

Fig. 4. Comparison of penetrations of particle through electret and discharged media #C (a) and #E (b).

the total single fiber efficiency. For electret filter, the mechanical and electrostatic depositions of particles should be superposed in the model. Therefore, E_T is the sum of efficiencies resulting from diffusion (E_D), interception (E_R), interception of diffusing particles (E_{DR}), impaction (E_I) and electrostatic attraction (E_q). The E_T was calculated as (Lathrache *et al.*, 1986; Chen *et al.*, 2014; Chang *et al.*, 2015):

$$E_T(n) = 1 - (1 - E_D)(1 - E_R)(1 - E_{DR})(1 - E_I)(1 - E_q). \quad (5)$$

In Eq. (5), E_q can be further calculated according to the depositions by the Coulombic force, $E_{qC}(n)$, and the depositions by dielectric polarization force, E_{qD}, as:

$$E_q = 1 - (1 - E_{qC}(n))(1 - E_{qD}), \quad (6)$$

where $E_{qC}(n)$ is the function of number of charges, n, the particles carried. So Eq. (4) and Eq. (5) are rewritten as:

$$P_{theo} = \sum_{n=-10}^{n=10} f(n) \times \exp\left(-\frac{4\alpha E_T(n)t}{\pi d_f(1-\alpha)}\right), \text{ } n \text{ including 0, and} \quad (7)$$

$$E_T(n) = 1 - (1 - E_D)(1 - E_R)(1 - E_{DR})(1 - E_I)(1 - E_{qC}(n))(1 - E_{qD}) \quad (8)$$

The $E_{qC}(n)$ and E_{qD} can be calculated as (Chang *et al.*, 2015):

$$E_{qC}(n) = \left(\frac{1-\alpha}{\text{Ku}}\right)^{1/8} \frac{\pi N_{CD}}{1 + 2\pi N_{CD}^{1/4}}, \quad (9)$$

$$N_{CD} = \frac{C_c \sigma q(n)}{3\pi\mu\varepsilon_0(1+\varepsilon_f)d_x U_0}, \quad (10)$$

$$E_{qD}\left(\frac{1-\alpha}{\text{Ku}}\right)^{2/5} \frac{\pi N_{DD}}{1 + 2\pi N_{DD}^{2/3}}, \quad (11)$$

$$N_{DD} = \frac{2C_c\sigma^2 d_x^{\ 2}}{3\mu\varepsilon_0(1+\varepsilon_f)d_f U_0}\left(\frac{\varepsilon_p - 1}{\varepsilon_p + 2}\right), \quad (12)$$

where Ku is the Kuwabara hydrodynamic parameter (Chang *et al.*, 2015), C_c is the Cunningham slip correction factor, μ is the air viscosity (Ns m^{-2}), σ is the charge density of the fiber (C m^{-2}), q(n) is carried charges by the particle (C), ε_f is the fabric dielectric constant (1.5 for the polypropylene of current electret media) and ε_0 is the permittivity of the vacuum (8.85 × 10^{-12} C^2 N^{-1} m^{-2}). From Eqs. (7) and (8), it becomes clear that when the particles are zero charged (neutral, $n = 0$), the depositions by the Coulombic force will be zero, the last second term of Eq. (8) is equal to 1, so only the electrostatic depositions by polarization are remained. This only takes the polarization deposition for zero charged particles into account which is the same as that by Chang *et al.* (2015). In comparison, if the particles carry charges, from Eqs. (7)–(8), the both Coulombic and polarized depositions are included. This is the major difference with that of Chang *et al.* (2015). To be noted, although it is not seen any additional term was used for including the polarization of charged particles, however, the term has been inherently contained. The polarization only for zero charged particles was usually considered (Lathrache *et al.*, 1986; Chen *et al.*, 2014; Chang *et al.*, 2015) but this study further took the effects for charged particles into consideration. Although some researchers have already reported the effects but normally parametric fittings were applied in their models (Kanaoka *et al.*, 1987; Otani *et al.*, 1993).

Figs. 5(a) and 5(b) show the comparisons of particle penetrations between the data and the theoretical predictions by the original (solid curves, without considering the polarization for charged particles) and modified models (dashed curves) for media #C (25 µC m^{-2}) and #E (75 µC m^{-2}), respectively, for 0.05, 0.5 and 1.5 m s^{-1} face velocities. For both media #C and #E, at face velocity of 0.05 m s^{-1}, the modified model was in very good agreement with experiments for all particles sizes. In comparison, the original model only agreed with experiments for particles smaller than 100–200 nm and it largely overestimated the penetrations for particles beyond the sizes. For higher face

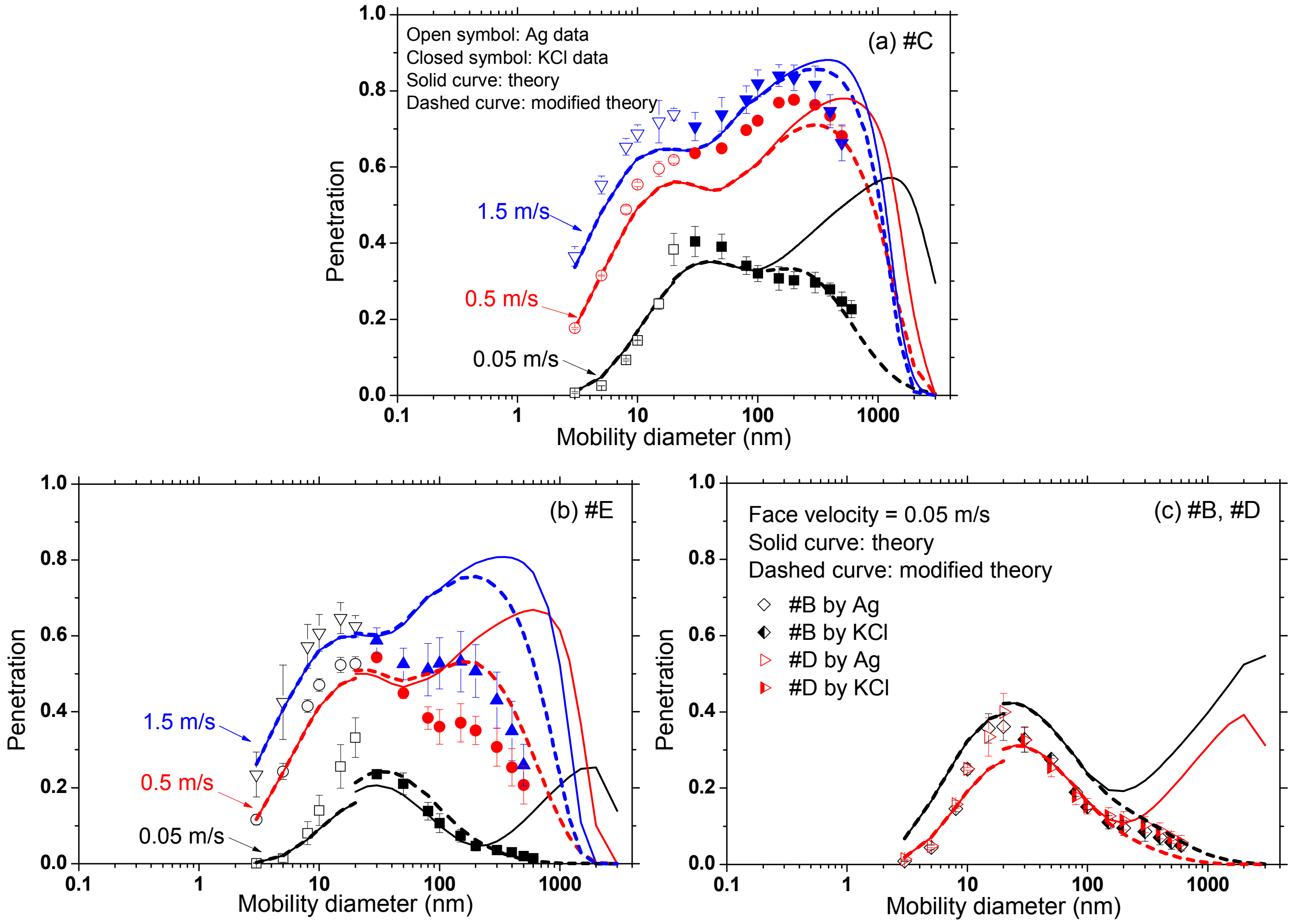

Fig. 5. Comparison of experimental and theoretical penetrations of particle through media #C (a) and #E (b) at 0.05, 0.5 and 1.5 m s^{-1} and media #B and #D (c) at 0.05 m s^{-1} face velocity.

velocities with 0.5 and 1.5 m s^{-1}, the modified model was still in fairly good agreement with data for media #C but large discrepancies were clearly seen for media #E. Nevertheless, the modified model predicted the particle penetrations better than the original model. We further depicted the comparisons between modified model and data for media #B and #D at 0.05 m s^{-1} face velocity in Fig. 5(c) to see whether the low face velocity was an important parameter for obtaining the good agreement. The results for media #A were not shown since the results were similar. It becomes clear that velocity should be an important factor. In Brown (1993), it has been discussed that the single fiber efficiency model may not be applicable if the diffusivity of the particles is not sufficiently great to distribute the incoming particles uniformly in concentration within an inter-layer spacing of the media. The following equation was given to set the criterion (Brown 1993):

$$\frac{4De}{U_0 d_f^2 E_T^2} \geq 1, \tag{13}$$

where D and e are diffusivity of the particles and half-layer spacing in fiber array and face velocity, respectively. Calculations showed that Eq. (13) were smaller than 1 (~0.9) for particles around 100 nm at 0.5 m s^{-1} and around 50 nm at 1.5 m s^{-1} for media #E. So this analysis explained the importance of the face velocity as speculated earlier. It is to be noted that Brown (1993) developed Eq. (13) for mechanical filter media and this study further extended its applicability to electret media. By using Eqs. (4)–(13), one should be able to predict the particle penetrations accurately for their own fibrous electret media since there are no parametric fittings involved.

CONCLUSIONS

In this study, five HVAC electret filters were challenged with sub-500 nm silver and KCl monodisperse particles at face velocities of 0.05, 0.5, 1.0 and 1.5 m s^{-1}. Experimental results showed that the Most Penetrating Particulate Size (MPPS) moves to the smaller particle size range with increasing face velocity. At face velocities of 0.5 to 1.5 m s^{-1}, clear bimodal penetration curves were observed, peaking at 10–30 and 150–200 nm, respectively. For highly charged filter, the first mode is higher than the second one while it showed a reverse trend for medium charged filter. Elevated penetrations for 3 nm nanoparticles were observed at elevated face velocities of 1.0 and 1.5 m s^{-1} which indicated these filter may not be used at such high face velocities if high capture efficiency was expected for small nanoparticles. FOM calculations showed that the low grade media #A with low charge had the highest FOM for sub-30 nm nanoparticles. In comparison, the higher charge media had significant elevation of FOM for larger size ranges. By comparing the penetration curves between charged and discharged media, a large enhancement of particle captures was observed, especially for the media with high charge at low face velocity. A model based on single fiber theory and theoretical electrostatic deposition was applied and modified by considering the polarization for charged particles to predict the particle penetration and compared with experimental data. Good agreements were obtained for all filters at low face velocity for all particle sizes. Discrepancy was found for large particles at higher face velocities due to the nonuniform particle concentration distribution of challenging particles in fiber layers. One should avoid using the validated modified model to predict particle penetrations by electret media at high face velocities and Eq. (13) can be used as criterion for the applicability for the model.

ACKNOWLEDGMENTS

This work was supported by the NSF Grant (Award ID: 1236107) on "GOALIE: Unipolar Diffusion Charging of Spherical and Agglomerated Nanoparticles and its Application toward Surface-Area Measurement." This work was also supported by the National Natural Science Foundation of China (Award ID: 51404064), the Fundamental Research Funds for the Central Universities (Award ID: N130401002), the National Science and Technology Major Project of the Ministry of Science and Technology of China (Award ID: 2016YFC0801704, 2016YFC0203701, 2016YFC0801605), the National Key Technology Research and Development Program of the Ministry of Science and Technology of China (Award ID: 2015BAK40B00), the Key Technology Research on Major Accident Prevention of the State Administration of Work Safety of China (Award ID: beijing-0003-2015AQ) and the Reform and Development Project of Beijing Municipal Institute of Labor Protection on "Performance Optimization of Respirator for Fine Particle". The authors thank the support of members of the Center for Filtration Research: 3M Company, A.O. Smith, BASF Corporation, Boeing Company, China Yancheng Environmental Protection Science and Technology City, Cummins Filtration Inc., Donaldson Company, Inc., Entegris Inc., Guangxi Wat Yuan Filtration System Co., Ltd., MSP Corporation, Samsung Electronics Co., Ltd., Shigematsu Works Co., Ltd., TSI Inc., W.L. Gore & Associates, Inc., Xinxiang Shengda Filtration Technique Co., Ltd. and the affiliate member National Institute for Occupational Safety and Health (NIOSH).

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Received for review, October 8, 2016
Revised, October 22, 2016
Accepted, October 24, 2016