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Factors Affecting Particle Depositions on Electret Filters Used in Residential HVAC Systems and Indoor Air Cleaners

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ABSTRACT

Filters made from electret media with quasi-permanent electrical charges have been widely applied to control particulate matter (PM) pollution. However, studies using parametric analysis to examine the effects of the operating face velocity, charge density, fiber diameter, porosity, and thickness on the energy efficiency of the filtration are lacking. A reliable parametric analysis requires an accurate filtration model. Without adding any empirical parameters, a modified model developed earlier by the authors was the first to accurately predict the efficiency of electret filters at different face velocities and with different filter charge densities for neutralized particles. To further verify the applicability of this model, we conducted filtration experiments in which singly charged, neutral, and neutralized monodisperse particles with 3–500 nm through two different electret filters, one with a charge density of 0.075 and the other with a charge density of 0.025 mC m^{-2}, as well as through discharged electret filters. The results of the modified model agreed well with the experimental data. The validated model was then used to conduct the parametric analysis to clarify the effects of the aforementioned parameters on filter performance. It was found that the increase in efficiency due to the fibers' charge states varied largely with the face velocity and the charge density of the electret. Furthermore, when the pressure drop was held constant, using thicker filters with less solidity reduced particle penetration. The results in this work can be applied to the design and operation of future electret filters.

Keywords: Electret filter; Electrostatic effects; Charge density; Particulate matter; Face velocity.

INTRODUCTION

Particulate matter (PM) is one of the air pollutants most implicated in adverse health effects (Oberdorster *et al.*, 2004; Wallace and Ott, 2011; Pui *et al.*, 2014). In developing countries, ambient PM has become one of the most important mortality risk factors worldwide (Cohen *et al.*, 2017). Recent studies by Organisation for Economic Co-operation and Development (OECD) and other scientific organizations on the premature death by air pollution showed it caused ~1 million premature deaths in China in 2010. This made up about 15% of the total deaths in China in the same year (Horton, 2012). The premature deaths can increase to 3 million for both China and India in 2060 if the air pollution is not improved (OECD, 2016).

Electret filters, which are more efficient and have a lower pressure drop than traditional filters, are being widely used in respirators as the personal protection equipment and in heating, ventilating, and air-conditioning (HVAC) systems of residential, commercial, office, school and hospital buildings to provide a clean indoor air (Baumgartner *et al.*, 1986; Romay *et al.*, 1998; Wang *et al.*, 2016a; Dunkhorst *et al.*, 2018). However, there is a lack of research on parametric analysis to examine the effects of operation face velocity (or related to pleat counts), charge density, fiber diameter, porosity, thickness, etc., on their performances, which would relate to energy consumption closely.

A reliable parametric analysis requires an accurate filtration model. Several studies have used experimental data, theoretical models, or comparisons between the two to investigate the particle collection mechanisms of electret filters (Lathrache *et al.*, 1986; Kanaoka *et al.*, 1987; Pich *et al.*, 1987; Chen *et al.*, 2014; Chang *et al.*, 2015). However, a robust model which was applicable to conditions with large ranges of particle sizes and high face velocities was not found (Chang *et al.*, 2016).

Recently, we experimentally and theoretically investigated the particle collection mechanisms of five electret filter

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media used in residential HVAC systems (Chang *et al.*, 2015; Chang *et al.*, 2016). In the theory, the existing filtration model by Lathrache *et al.* (1986) was further modified by considering the polarization effects for charged particles. The modified model was found to accurately predict particle depositions for electret filters carrying different charge densities at a wide ranges of face velocities (0.05–1.5 m s^{-1}; Chang *et al.*, 2016). In those experiments, we only investigated neutralized particles (in Boltzmann equilibrium). Therefore, it is important to validate the modified model with particles of different charge states, e.g., singly charged and zero charge (neutral).

In this study, efficiencies of two electret filter media used in residential HVAC systems were examined by challenging them with monodisperse silver (Ag) and potassium chloride (KCl) particles, ranging from 3 nm to 500 nm in diameter (majority of typical $PM_{2.5}$ in number concentration) at different face velocities. In the experiments, penetrations of particles with the charge state of neutralized, singly charged and neutral (without charge), through the electret filters and discharged filters were tested. Then the modified model was compared with the experimental data. After good agreements between the model and data were obtained, the validated model was used to conduct the parametric analysis to comprehend the effects of face velocity and filter properties on filtration performances. The aim is to attain an energy-efficient filtration.

METHODS

Experimental

The two electret filters tested were commercial residential HVAC filter media made by 3M (3M Corp., Saint Paul, MN, USA). Details of the filter specifications are summarized in Table 1. They are all bipolar charged and the charging densities were estimated based on the measurement by Li *et al.* (2012) and confirmed by the modified model of this study. The one with a lower charge of 0.025 mC m^{-2} was rated with a Minimum Efficiency Reporting Value of 12 (MERV 12, Filter #1) and the other was with MERV 11 (Filter #2). The major difference of Filters #1 and #2 was their charge density. For other mechanical properties, the two are close to each other. The similarity of their mechanical properties allows one to have a focus and detail analysis on the charge effects on the filtration performance under different operating face velocities.

The experimental setup for obtaining the initial efficiency of the two electret filters with and without discharging against monodisperse Ag and KCl particles of 3–500 nm with neutralization, singly charge and neutral is shown in Fig. 1. To discharge the electret filters, the standard method of ISO 16890 was used, in which the filters were exposed to IPA vapor for 24 hrs (Tang *et al.*, 2018). To be mentioned, the data for the singly charged and neutral particles will be used to further validate the robustness of the modified model developed earlier. The Ag and KCl particles were generated in a polydisperse states by an electric furnace (Lindberg/Blue M, Thermo Fisher Scientific, Waltham, MA, USA) and a collision-type atomizer (Model 3079, TSI Inc., Shoreview, MN, USA), respectively. To obtain monodisperse Ag particles (3–20 nm), a Nano-Differential Mobility Analyzer (Nano-DMA; Model 3085, TSI Inc., Shoreview, MN, USA), was used, while that of KCl particles (30–500 nm) were classified by a Long DMA (Model

Table 1. Properties of the electret filter media.

Media	Thickness (mm)	Effective fiber diameter (µm)	Basis weight (g m^{-2})	Solidity (1-porosity)	Charge density (mC m^{-2})	Pressure drop at 14 cm s^{-1} (mm H_2O)
#1	0.70	16.5	66.5	0.105	0.025	1.56
#2	0.83	15.6	76.7	0.102	0.075	1.95

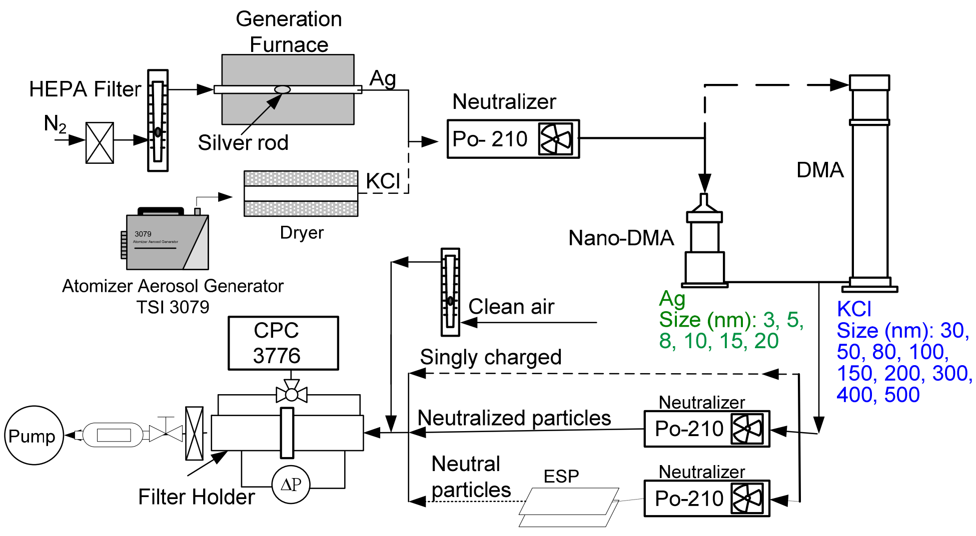

Fig. 1. Experimental setup for particle generation and filtration efficiency measurement.

3081, TSI Inc.). The size distributions of generated particles were shown in Figs. S1–S2 of Supporting Information (SI). As DMA classifies particles based on the differences in electrostatic mobility among charged particles, particles after classification are mostly singly charged. We manipulated the charge state of all particles as follows: To create neutralized particles, we brought the DMA-classified particles into Boltzmann equilibrium by passing them through a neutralizer; to create singly charged particles, we used the particles classified by the Nano-DMA and Long DMA directly; and to create neutral particles, we removed all charged particles from the neutralized particles by passing them through an electrostatic precipitator (ESP). The flat sheet filter was mounted in the filter holder as shown in Fig. 1. The experiment was carried out at face velocities of 0.05, 0.5, and 1.0 m s^{-1}. We measured the aerosol concentrations upstream and downstream of the filter with an Ultrafine Condensation Particle Counter (UCPC; Model 3776, TSI Inc.) to determine the particle penetration which was the ratio of downstream to upstream particle concentration. The efficiency of filter was then determined as unity minus penetration. For neutral particles larger than 300 nm, the particle concentration was low. In order to get reliable result, the sampling was not stopped until more than 10^4 upstream counts was obtained, then the same sampling time was adopted for downstream sampling.

Modified Model

In our previous papers (Chang *et al.*, 2016), a modified model was developed and found to have good agreement for different electret filters for neutralized particles. The model was based on single fiber theory and superposition of mechanical and electrostatic deposition mechanisms. The theoretical particle penetration, P_{theo}, through the filter is calculated as:

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

where α was the solidity of the filter, t was the thickness of the filter, d_f was the filter media fiber diameter, and E_T was the total single fiber efficiency. E_T was calculated as (Chen *et al.*, 2014; Lathrache *et al.*, 1986):

$$E_T(n) = 1 - (1 - E_D)(1 - E_R)(1 - E_{DR})(1 - E_I)(1 - E_{qC}(n))(1 - E_{qD}) \tag{2}$$

where E_D was the diffusion efficiency, E_R was the interception efficiency, E_{DR} was the efficiency of the interception of diffusing particles, E_I was the impaction efficiency, $E_{qC}(n)$ was the efficiency by the Coulombic force, and E_{qD} was the efficiency by dielectric polarization force. $E_{qC}(n)$ is the function of number of charges, n, the particles carried (including 0). So Eq. (1) was rewritten as:

$$P_{theo} = \sum_{n=-10}^{n=10} f\left(n\right) \times \exp\left(-\frac{4\alpha E_T\left(n\right)t}{\pi d_f\left(1-\alpha\right)}\right), \tag{3}$$

where $f(n)$ was the fraction of particles with n of unit charge. The detail calculation of E_D, E_R, E_{DR}, E_I, $E_{qC}(n)$ and E_{qD} can be found elsewhere (Chang *et al.*, 2016). The major difference of the modified model with that of other works (Lathrache *et al.*, 1986; Chen *et al.*, 2014; Chang *et al.*, 2015; Kanaoka *et al.*, 1987; Otani *et al.*, 1993) is that the polarization for charged particles is taken into consideration in E_{qD} of Eq. (2).

RESULTS AND DISCUSSION

Effects of Charge States on Particle Penetration

Neutralized Particles through Discharged Filter

The penetration of neutralized particle through discharged filter media were much higher than that of neutralized particle through electret filter media, especially for the particles larger than 20 nm as shown in Figs. 2(a)–2(c). For example, at face velocities of 0.05, 0.5 and 1.0 m s^{-1}, the most penetrating particle size (MPPS) appeared at 400, 200, and 150 nm for Discharged Filter #1 and the corresponding penetrations were 0.91, 0.96 and 0.97, respectively, while the MPPSs and the corresponding penetrations for Discharged Filter #2 were 300, 150, and 150 nm, and 0.88, 0.96 and 0.97, respectively. Meanwhile, for neutralized particles, electret filter media were much more efficient than discharged media. For example, at face velocities of 0.05, 0.5 and 1.0 m s^{-1}, the MPPS of particles through Electret Filter #1 occurred at 30, 200 and 200 nm and corresponding were reduced to 0.40, 0.78 and 0.88, respectively, while the MPPS of particles through Electret Filter #2 were 30, 20, and 20 nm and corresponding penetration were reduced to 0.24, 0.58 and 0.61, respectively. Thus, charged fibers capture particles larger than 20 nm more effectively, because large particles typically carry more charges than small ones.

Neutral and Singly Charged Particles through Electret Filter

Neutral particles penetrated electret filter media at a higher rate than neutralized particles as shown in Figs. 2(a)–2(c). Their MPPS decreased as face velocity and charge density increased. For example, at face velocities of 0.05 m s^{-1} and 0.5 m s^{-1}, the most penetrating particle size for Filter #1 were 80 nm and 50 nm, respectively, while that for Filter #2 were 50 nm and 30 nm, respectively. Irrespective of face velocity, the penetration of singly charged particles smaller than 100 nm through electret filter media were lower than those of neutralized and neutral particles, due to the combined effects of Brownian diffusion, Coulombic force, as well as the enhanced imaging force. Same as neutral particles, the MPPS of singly charged particles decreased as face velocity and charge density increased. However, the MPPS of singly charged particles was > 100 nm, while that of neutral particles was < 100 nm. It becomes clear that particle charge significantly affected electret filter media efficiency. Increasing the charges carried by particles would effectively improve the efficiency of the electret filter media (bipolar-charged) but with the exception when particles and filters (unipolar-charged) are like-charged.

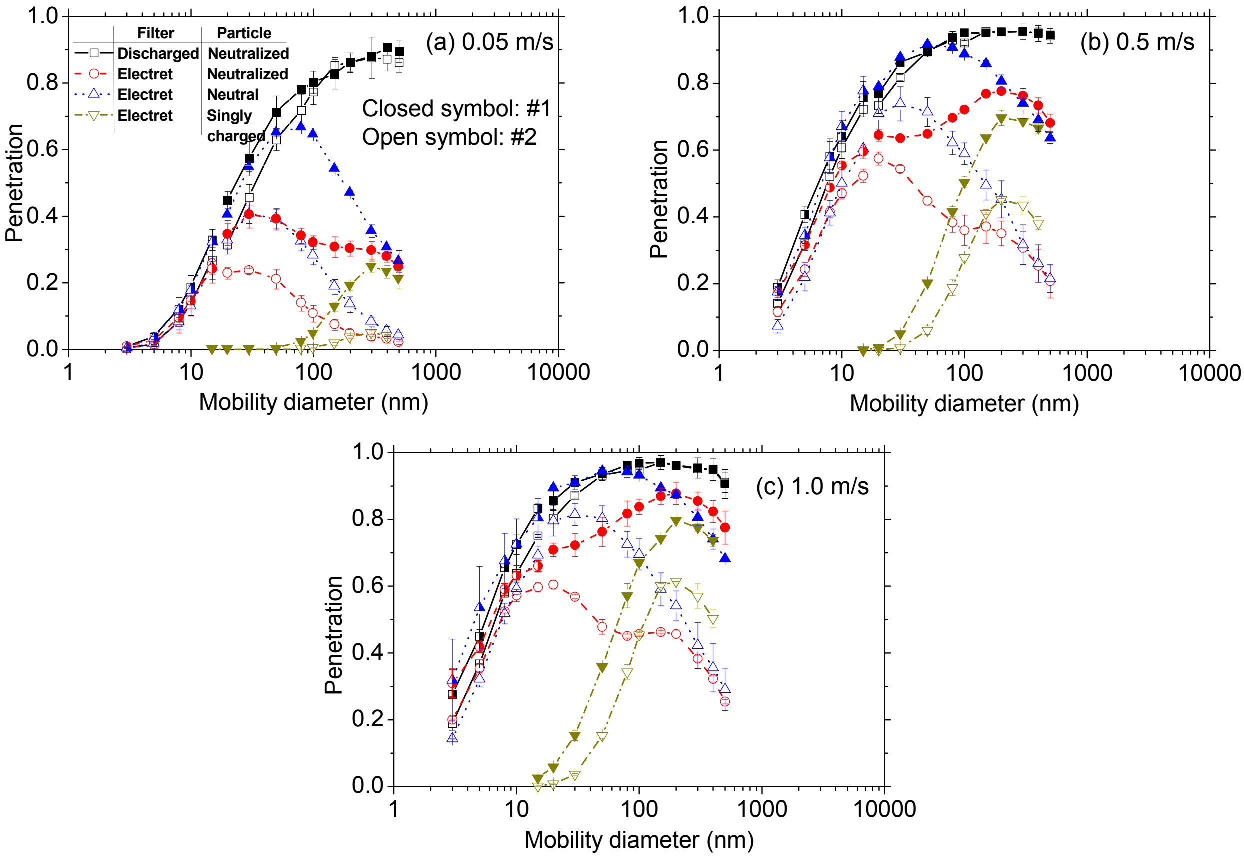

Fig. 2. The penetration of particles with different charge states through electret and discharged filter media at face velocities of (a) 0.05 m s^{-1}, (b) 0.5 m s^{-1}, and (c) 1.0 m s^{-1}.

Face Velocity Effects

We also observed that face velocity affected the enhancement in efficiency contributed from fiber charge. The enhancement was the penetration reduction (or efficiency increase), compared the electret to discharged filter (pure mechanical filter). Fig. 3 shows the efficiency enhancement at different face velocities of 0.05, 0.5 and 1.0 m s^{-1} for neutralized particle. It is seen the trend of efficiency enhancement curves for the two electret filter were similar, in which these curves intersected at a particle size of ~30–50 nm. Thus, the influence of face velocity on the efficiency enhancement varied with particle size. Nevertheless, the enhancement was more significant for Filter #2 as it had higher charge density. For Filter #2 at tested three face velocities and Filter #1 at low face velocity as 0.05 m s^{-1}, the enhancements reduced with reducing particle size in general as electrostatic effects are more efficient for larger particles. Besides, the enhancement was more significant for lower than higher face velocities. For example, at 0.05 m s^{-1}, the enhancement for 300 nm (efficiency usually used to determine filter grade) particles in Filter #2 was 0.84, and that of Filter #1 was 0.58. However, as the face velocity raised to 1.0 m s^{-1}, the enhancement for 300 nm particles were reduced to 0.57 and only 0.10 for Filter #2 and #1, respectively. This indicates that charging the media with a moderate or low level, e.g., 0.025 mC m^{-2} here for Filter #1, did not improve the efficiency much for larger particles. It is also seen high velocity is unfavorable for small particles. Therefore, operating the moderate and low charge electret filter at high velocity should be avoided. Nonetheless, the enhancements for smaller particles (< ~30 nm) were larger at higher face velocities than the lower. This was due to the reduced diffusive deposition at higher velocities and the electrostatic deposition became relatively important. In conclusion, the effect of face velocity on efficiency enhancement was significant for electret filter. The effect is actually quite complex and it cannot be completely elucidated by the current limited experimental data. Therefore, a more detailed discussion will be made in later section by parametric analysis using the validated model.

Here, we examined the applicability and accuracy of the modified model by comparing its predictions with data for singly charged, neutral and neutralized particles through the two electret filter at face velocities of 0.05 and 0.5 m s^{-1}. To avoid a busy figure, results for 1 m s^{-1} were not included. As shown in Fig. 4, the modified model was in good agreement with the experimental data. In addition to the validation using the authors' data, the modified model was also verified by the data reported in the literature. Very good agreements were also obtained and shown in Fig. S3 of SI, indicating the model is robust and could be used for parametric analysis. It is confirmed that a good agreement was also obtained between data and model for the case of 1 m s^{-1}.

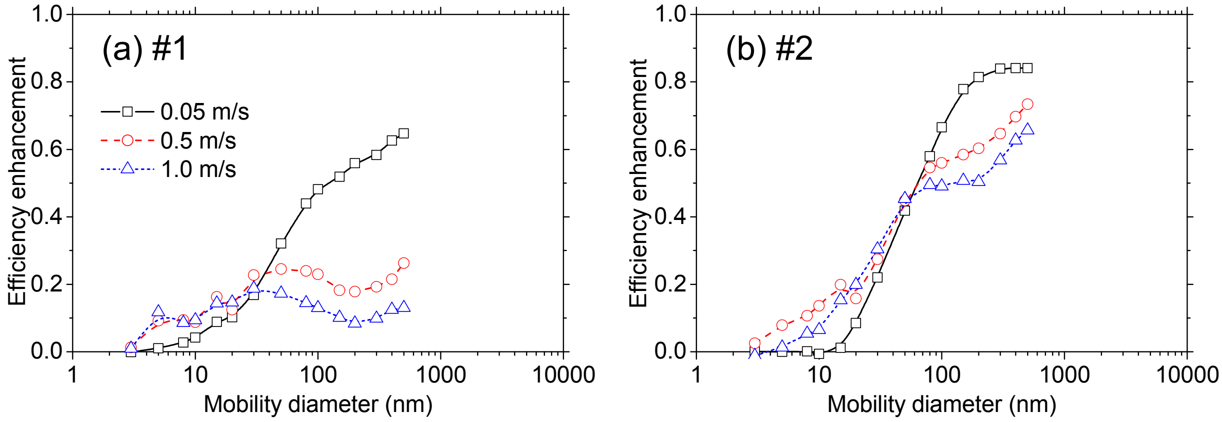

Fig. 3. Efficiency enhancement (differences in neutralized particle penetration) between Electret and Discharged Filter Media (a) #1 and (b) #2, due to the charge on fiber.

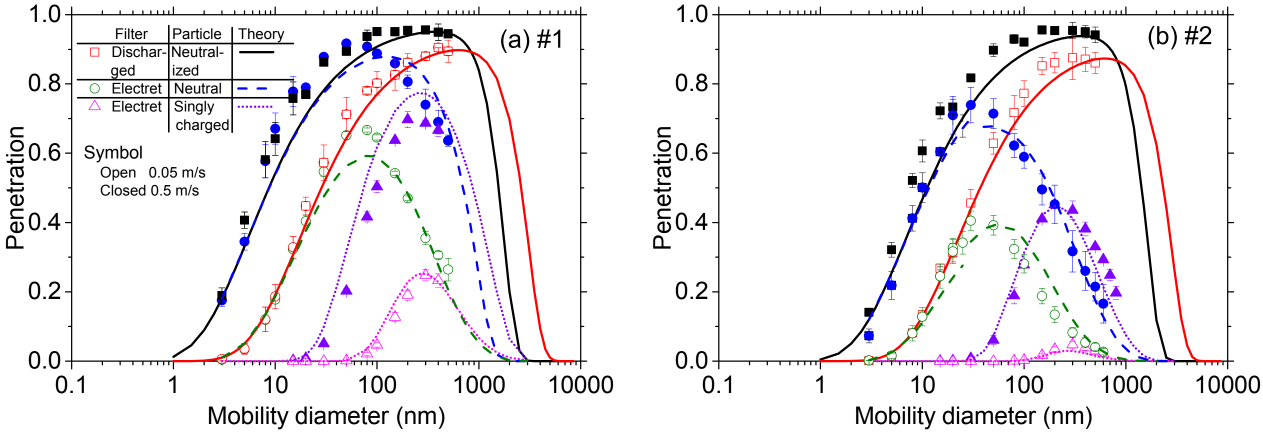

Fig. 4. Comparison of experimental and theoretical particle penetrations through Electret Filter #1 (a) and #2 (b) at face velocities of 0.05 m s^{-1} (open symbols) and 0.5 m s^{-1} (closed symbols). Squares represent the penetration of neutralized particles through discharged (mechanical) filter, circles represent the penetration of neutral particles through electret filter, and triangles represent the penetration of singly charged particles through electret filter.

Factors Affecting Filter Performance

Charge Density Effects

Here, we used the verified model to investigate the factors that may affect filter performance, which provides useful information for filter designs and optimization of filter operations is expected. We selected Filter #2 with 0.5 m s^{-1} face velocity as an example to show the effects of charge density on efficiency enhancement for neutralized particles. To be anticipated, the results will be similar when using Filter #1 in the calculation as its filter parameters are close to that of Filter #2. As can be seen from Fig. 5, the efficiency of electret filter media increases with increasing charge density. To be mentioned, for easy distinguishing the modeling results, different symbols were included in this figure and Figs. 6–8. The charge density determined the effective range of particle sizes due to the charge. When the charge density was small, i.e., < 0.01 mC m^{-2}, the efficiency of small particle (~30 nm) was improved more noticeably than that of large particles. There are two reasons: First one is that, as discussed earlier, under quite high face velocity, i.e., 0.5 m s^{-1} here, the reduced diffusive deposition enhances the relative importance of the charge effects. The second is that the low charge density created only a minor Coulombic forces and polarization forces for large particles, which have greater inertia. As charge density

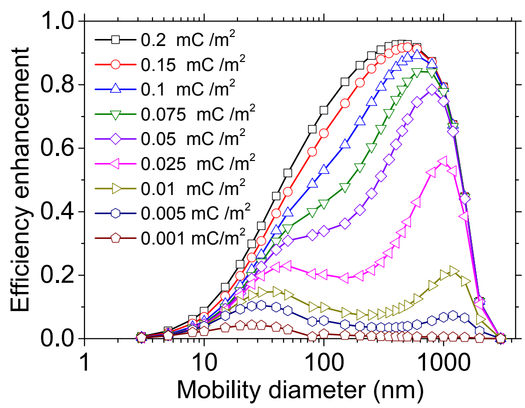

Fig. 5. Efficiency enhancement varied with fiber charge density at face velocity of 0.5 m s^{-1}.

increased, the effects of the Coulombic and polarization forces between the charged fibers and particles largely increased, improving the efficiency of particles from 3 nm to 3000 nm. The increase in large-particle filtration efficiency was much greater than the increase in small-particle filtration efficiency because large particles have more charges than small particles. As the charges on the fibers increased, fibers became more attracted to charged particles. From the figure we also saw that the increased fiber charges primarily improved the efficiency of particles between 10 nm and 3000 nm in size, in which the efficiency of submicron particles was improved more sharply than that of other size particles. A similar result was seen for the cases of 0.05 and 1 m s^{-1} face velocities (not shown here and can be found in Figs. S4–S5 of supporting information). At a charge density of 0.075 mC m^{-2} (Filter #2), the enhancement for 1000, 800 and 600 nm particles was 0.78, 0.84 and 0.84, respectively. This range of particle sizes was approximately equivalent to the mode of ambient $PM_{2.5}$ measured in different locations (Whitby *et al.*, 1972). Therefore, fiber charge greatly enhanced the efficiency of $PM_{2.5}$, thus, electret filter is very capable for the control of $PM_{2.5}$.

Face Velocity Effects

Face velocity is an important parameter for filter media and is also the first consideration in filter design (Hinds and Kadrichu, 1997). Because of its importance, the effects of face velocity on efficiency have been extensively reviewed and studied (Brown, 1993; Romay *et al.*, 1998; Hinds, 1999; Chang *et al.*, 2015; Chang *et al.*, 2016; Wang *et al.*, 2016b). However, there is a lack of focus on electret filter due to the lack of an accurate model. Here, using the modified model we calculated the influences of face velocity on charge enhanced efficiency using the parameters of Filters #1 and #2 with only varying face velocities from 0.005 to 1.5 m s^{-1}. The results are shown in Fig. 6. The modes indicate the most favorable operation velocity to optimize the charge effects. It is seen the velocities for the Electret Filter #1 (0.025 mC m^{-2}) and #2 (0.75 mC m^{-2}) were in the ranges of ~0.01–0.1 and ~0.05–0.2 m s^{-1}, respectively. To obtain these operation face velocities, it can be easily achieved by varying the pleat counts according to the operation flow rates. More detailed discussion of velocity effects will be shown in the following.

Fig. 6 also indicated that the influence of face velocity on the efficiency enhancement by charge were size dependent. For supermicron particles (> 3 µm), the enhancement was more significant at low face velocities (< 0.05 m s^{-1}) due to the weakening of impaction deposition. Same as that has been found in experimental data, the effectiveness of fiber charge increased with increasing velocity for particles smaller than 30–40 nm. For medium-sized particles, with increasing face velocity the enhancement first increased but then decreased, thus, there existed a face velocity at which the fiber charge was most effective.

To closely look into the most favorable operation face velocity for different particle sizes, Fig. 7 summarizes the variation of size dependent efficiency enhancement with face velocities. It is seen the curves shift to larger face velocities for the higher charged filter (Filter #2). The velocity where the mode occurs is the favorable velocity. For example, in the Filter #2, the 600 nm particles peaked at 0.2 m s^{-1} with the enhancement of 0.897, while that of 1000 nm particles in Filter #1 peaked at 0.04 m s^{-1} with the enhancement of 0.862. In general, the higher charge density increases the optimal operation face velocity for submicron particles. From this figure one can individually find the favorable face velocities for different particle sizes. The summarized results of enhancement under favorable velocity, termed maximum efficiency enhancement, and the corresponding favorable velocities for each particle sizes were shown in Fig. S6 of Supporting Information.

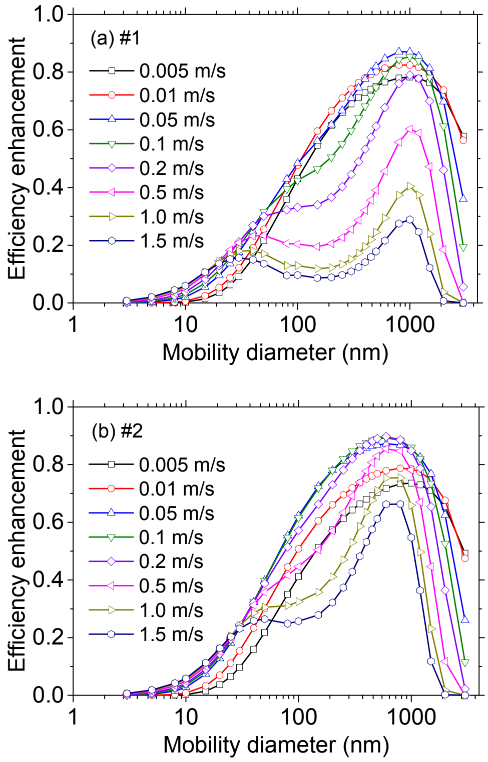

Fig. 6. Efficiency enhancement varied with face velocity in (a) Filter #1 and (b) Filter #2.

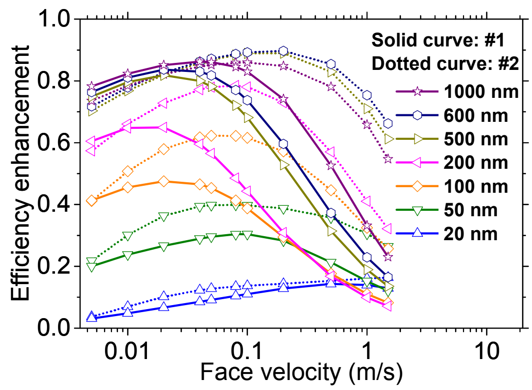

Fig. 7. Comparison of the variation of efficiency enhancement with increased face velocity for different particle sizes.

Fiber Diameter Effects

According to the single fiber theory, when the other parameters remain unchanged, reductions in fiber diameter would improve the filter efficiency (Brown, 1993), however, the pressure drop is then increased accordingly. Filter efficiency can also be improved by other means, such as to increase fiber thickness and solidity. In order to more clearly understand the effects of fiber diameter for electret filters without altering pressure drop, we investigated how the filter performance changed with the fiber diameter.

The pressure drop, Δp, of a fibrous filter at a given face velocity of U_0 is inversely proportional to the square of fiber diameter, d_f, and could be calculated according to Eq. (9.36) of Hinds (1999) as:

$$\Delta p = \frac{\mu t U_0 \left[64\alpha^{1.5} \left(1 + 56\alpha^3 \right) \right]}{d_f^2} \tag{4}$$

where μ, t, and α are viscosity, filter thickness and solidity, respectively. Eq. (4) is valid here because the fiber diameter investigated were larger than 5 µm. For smaller fibers, i.e., < 1 µm, Eq. (3.65) of Brown (1993) which took the slip correction effects into account should be applied. According to Eq. (4), when fiber diameter decreases, the pressure drop at certain face velocities can be kept constant by reducing fiber thickness or solidity. We here investigated how the penetration changed with fiber diameter in the electret filters where pressure drop was kept at a constant by reducing filter thickness or solidity. The results under the face velocity of 0.1 m s^{-1}, the velocity was found to be favorable for both electret filters, are shown in Figs. 8(a) and 8(b) for reducing thickness and solidity, respectively.

In the case of reducing filter thickness (Fig. 8(a)), as fiber diameter decreased, the particle penetration of the electret filter media increased significantly. For example, as the fiber diameter was decreased from 16.45 µm to 5 µm, the maximum penetration of the electret filter media increased by 0.14 (from 0.304 to 0.442, or relative difference of 45%), while that of mechanical filter only increased by 0.02 (from 0.898 to 0.917; figure not shown). The change of penetration due to the change of fiber diameter in electret filter was more pronounced than that of mechanical filter. In comparison, in the case of reducing filter solidity, the penetration of all particle sizes decreased with increasing fiber diameter, but the changes were all small.

It becomes clear that, under the constant pressure drop, fiber diameter, filter thickness, and filter solidity all can affect the strength of the electrostatic effects but with different degrees. Under a constant pressure drop, reduction in filter thickness or solidity modulated the influence of fiber diameter on particle penetration differently. In addition to changing the filter thickness, the changes also alter the residence time of particles in the filter. Thus, changes in filter thickness might have additional effects on particle captures. Changes of filter solidity alter the number of fibers in the filter without affecting particle residence time. Thus, when considering particle penetration through filters with constant pressure drop and equivalent fiber diameter, thicker filters with lower solidity have a combined positive effect for reducing particle penetration. This result should be noted in future filter designs.

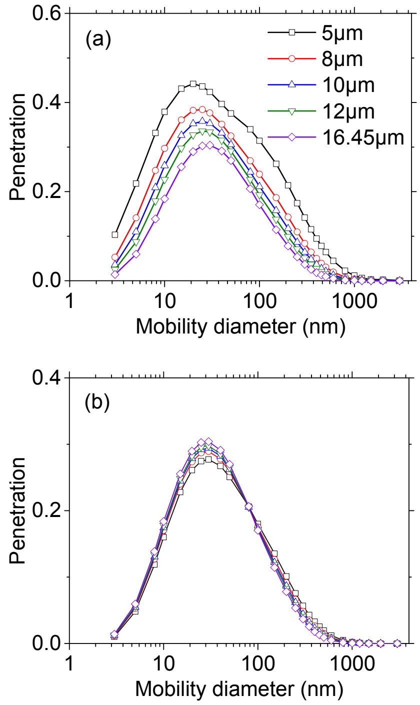

Fig. 8. Particle penetration as fiber diameter changes in electret filters kept at a constant pressure drop by (a) reducing fiber thickness and (b) reducing fiber solidity at face velocity of 0.1 m s^{-1}.

From another point of view, as the fiber diameter increases, increasing the filter thickness increases the efficiency of the electret filter media without increasing pressure drop. It has also been shown that the FOM of the electret filter media is slightly affected by filter thickness (Huang *et al.*, 2013). Therefore, the use of fine fibers does not effectively increase the efficiency of the filter material without increasing the pressure drop (energy consumption), and in some cases may be counterproductive. If the installation space is not too limited, it is an economical choice to increase the efficiency of the filter media by appropriately increasing the thickness and fiber diameter.

CONCLUSIONS

In this study, the efficiency of two electret filters used in residential HVACs and IACs were measured at different face velocities using monodisperse Ag and KCl particles ranging from 3 nm to 500 nm in diameter. Particles in three different charge states—neutralized (to Boltzmann's equilibrium), singly charged, and neutral were tested. A modified model based on single fiber theory was validated by the experimental data and data reported in the literature, indicating that this model can predict the performance of charged filters based on various filter parameters via parametric analysis.

The parametric analysis showed that the efficiency of the electret filter media increased with the charge density, with the largest enhancement observed for particles in the submicron range (~0.1–1 µm). The face velocity was also found to be a crucial parameter in determining the performance of the electret filter, although the specific amount of efficiency enhancement (the difference in performance between the electret filter and the discharged electret filter) depended on the size of the particles. For submicron particles (< 1000 nm), the optimal face velocity in terms of filter efficiency was ~0.05–0.2 m s^{-1} for electret filters with charge densities of 0.025 and 0.075 mC m^{-2}. Analyzing the effects of the fiber diameter, porosity, and thickness indicated that when the pressure drop remained constant, thick filters with less solidity were more efficient than thin filters with more solidity. The results presented in this paper should be applied in filter design and operations.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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