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Filtration efficiency and loading characteristics of $PM_{2.5}$ through composite filter media consisting of commercial HVAC electret media and nanofiber layer

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ABSTRACT

Pleated electret HVAC filters are often used in residences and commercial buildings to mitigate the particles that originate both indoors and outdoors. However, there are two concerns on the performance of electret media: 1. Low efficiency for particles in diameter of 10–30 nm at initial filtration condition, which represent the MPPS (most penetrating particle size), and 2. Significant efficiency reduction during the loading process due to the shielding of fiber charge. In this study, a composite filter media composed of a main layer of HVAC electret media on the top and a thin layer of nanofiber at the bottom was prepared and tested for its $PM_{2.5}$ removal. In the initial efficiency tests, monodisperse nanoparticles ranging 8–500 nm were used to challenge the media. It was found that the nanofiber layer can enhance the efficiency for the MPPS (10–30 nm) of electret media significantly. In the loading performance, polydisperse NaCl particles which mimicked the size distribution of typical atmospheric $PM_{2.5}$ were used to challenge the media. It was found the total efficiency reduction was less than 10% for particles with sizes 50–500 nm. This reduction due to the shielding of fiber charge was much less than the electret layer (>40%) without adding nanofibers. The observation of a decent performance over the loading process was expected since the composite media made full use of both the mechanical forces and electrostatic effects. Surprisingly, the overall loading FOM (figure of merit) of the composite media was close to that of electret media, indicating that there was only a minor tradeoff of pressure drop increase when adding the nanofiber layer. In conclusion, this type of combination provided a unique structure to take advantage of electret media and a nanofiber layer for $PM_{2.5}$ removal in the application of pleated HVAC filters.

1. Introduction

As a major component of outdoor air pollution, particulate matter, PM, had been classified as carcinogenic (IARC Group 1) in October of 2013 by the International Agency for Research on Cancer, IARC. Noticeably, $PM_{2.5}$ (particles with aerodynamic diameter $\leq 2.5\ \mu m$) contributes the essential toxicity of ambient PM as Hamra et al. [14] reviewed more than 200 papers and concluded that $PM_{2.5}$ was believed to be the most relevant to adverse health effects. Besides, the relationship between $PM_{2.5}$ and lung cancer risk was robust. Some big cities in China and India, e.g. Beijing, Harbin, Shijiazhuang, Mumbai, New Delhi, etc., are frequently exposed to severe $PM_{2.5}$ pollution, which has aroused widespread public concerns [24]. Therefore, to efficiently remove $PM_{2.5}$ particles and reduce human exposure is very urgent and crucial.

Filtration is widely used in buildings to mitigate the concentration of particles which can unintentionally infiltrate or transport into indoor environment from outdoor air. In commercial buildings, pleated filters are typically installed in the supply airstreams of heating, ventilating and air conditioning (HVAC) systems that provide heated or cooled air to indoor spaces. In the US commercial buildings, this supply airstream is usually a mixture of outdoor air and recirculated indoor air while in many European commercial buildings, the supply airstream is often entirely from outdoor air [11]. Electret filter media have been widely installed in the HVAC systems, since the fiber charge can significantly enhance the particle removal efficiency but at a low pressure drop which provides significant savings in energy consumption [28]. Therefore, it is not surprising that electret media filtration has recently become

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a subject of special interest [6]. To evaluate the overall performance, a useful criterion is the figure of Merit (FOM, Pa^{-1}) which is defined as [3]:

$$FOM = -\ln(1 - E)/\Delta p, \tag{1}$$

where E is the filtration efficiency (–); Δp is the pressure drop (Pa). With high efficiency and low pressure drop, the FOM value of clean electret media is usually larger than after it has been discharged to become only mechanical media. It should be noted that FOM is not the only criterion to evaluate filtration performance. Because having a high filtration efficiency may be the priority in certain applications and a minor increase of pressure drop should be acceptable. Besides, increasing the filter thickness could easily achieve the goal, but a thick media may not be applicable in the form of pleated HVAC media [26].

There are two major concerns about the performance of electret media. The first one is the low efficiency for particles with 10–30 nm which represent the MPPS (most penetrating particle size) for clean electret media [5,9]. It has been found that extremely small particles, especially those smaller than 10 nm, have an enhanced deposition in the tracheobronchial region due to rapid Brownian motion and there is a mode around 3 nm in the tracheobronchial region deposition and a mode around 20 nm in the alveolar deposition based on ICRP deposition model [15]. To reduce human exposure to sub-30 nm particles, the efficiency of HVAC filter media at particle diameter of 10–30 nm should be enhanced. The second concern is the significant efficiency reduction during, especially in the beginning of, the loading process. That is, as more and more particles deposit on the fiber in the loading process, the efficiency decreases and reaches to a minimum value [2]. At that moment, the filter presents the worst condition during the operation as only pure mechanical filtration is remaining. Then the efficiency is reversely turning up as the cake filtration takes over.

The existing test standards such as ASHRAE 52.2-2012 [1] and EN 779-2012 [4], only challenge the HVAC filters with coarse particles (mostly ISO 12103-1 [16] A2 Fine Test Dust with volume median diameter of about 15 μm) in the loading test. The ASHRAE standard proposes an informative and optional test condition, Appendix J, to determine the minimum efficiency of an electret filter using finer salt particles during the particle loading. Therefore, it's meaningful to load the electret media with fine particles and propose possible solutions for improving the efficiency reduction in the loading process.

To enhance the performance of electret media, a thin nanofiber layer was laminated to enhance the minimal efficiency of clean filter for MPPS particles and alleviate efficiency reduction in the loading. Nanofibers are prepared with a very large surface area to volume ratio, which significantly increases the probability of the aerosol particles deposition on the fiber surface and thereby improves the filter efficiency with relatively low pressure drop [23,20,21,17]. The US Pat. No. 7,691,168 B2 [12] disclosed a filter media which included a charged filtration layer containing intertwined nanofibers and a porous support layer and the unique design of charged nanofiber layer exhibited less efficiency reduction in loading. Since surface loading of particles is taking place on the nanofiber layer [13], pressure drop across nanofiber filter can rise at a much faster rate than microfiber filter [18,19]. A microfiber filter can be placed upstream forming a dual-layer filter and help to collect part of the particles, thus suppressing the increase rate of pressure drop rise due to the downstream nanofiber layer. Another US Pat. No. 2008/0017038 A1 [27] disclosed a media combined charged melt-blown nonwoven media and a nanofiber layer that prevented the nanofiber layer from surface loading. However, it failed to exhibit significant improvement of efficiency reduction in the loading in its example data. This might be due to the fact that the challenging particles were coarse dusts (0.3–10 μm and above), which cannot represent the filter loading performance for the finer $PM_{2.5}$ particle size range. The above patent only mentioned that the nanofiber layer had an efficiency greater than 30% against 0.8 μm PSL particle, but the selection of nanofiber layer was not further explored. The mismatch of electret media and nanofiber layer may result in a very limited performance improvement.

In this study, initial filtration efficiency and FOM of commercial HVAC electret media and composite media for 8–500 nm particles were tested under face velocities of 0.05 and 0.25 $m\ s^{-1}$. For the filter loading characteristics, polydisperse particles which mimicked the size distribution of typical atmospheric $PM_{2.5}$ were generated for loading tests [24,9]. The results of efficiency, FOM and pressure drop of electret media and composite media were compared and analyzed. The final goal is to propose a filter media design which can obtain both a high initial efficiency and minimized efficiency reduction in loading process against $PM_{2.5}$ and nanoparticles.

2. Experimental

2.1. Filter media specification

The flat sheet electret filter media used in commercial residential HVAC filter obtained from a manufacturer, as rated with MERV (minimum efficiency reporting value) 14, was investigated for its initial and loading performance against polydisperse NaCl particles which mimicked the size distribution of typical atmospheric $PM_{2.5}$. The specifications of these media are shown in Table 1. This type of filter media is electrostatically-charged melt-spun type and has a significant microscopic bipolar charge on the fibers. In this study, the charging density were estimated to be about 100 $\mu C\ m^{-2}$ based on the measurement by Li et al. [22] and theoretical calculation by Chen et al. [10]. A melt-blown nanofiber layer was laminated to the electret filter media. The nanofiber layer was composed of 0.2–0.3 μm diameter fine fibers which were shown to be free of charge via the IPA vapor exposure method per ISO/TC 142. In this composite media, electret media worked as the inlet and nanofiber layer worked as the outlet.

2.2. Initial penetration measurement

In this study, initial penetration of filter media was tested using silver particles of 8–20 nm and NaCl particles of 30–500 nm. The experimental setup for this measurement is shown in Fig. 1. For particles in the range of 8–20 nm, an electric furnace (Lindberg/Blue M, Thermo Fisher Scientific Inc, Waltham, MA, USA) was used to generate silver nanoparticles from a pure silver rod (purity: 5N, ESPI Metals, Ashland, OR, USA). The nitrogen gas (Ultra high purity 99.999%) was used as the carrier gas with a flow rate of 1.5 $L\ min^{-1}$. The size distribution and concentration of the silver nanoparticles was controlled by varying the furnace temperatures. Two different temperatures at 1100 and 1150 °C were used in the experiments and the obtained size distributions are shown in Fig. S1 of Supplementary Material. Monodisperse silver nanoparticles with mobility diameter of 8, 10, 15, 20 nm were classified from these two different distributions by a nano-differential mobility analyzer (nano-DMA, Model 3085, TSI Inc., Shoreview, MN, USA) and used to challenge the filter media. To be mentioned the 8–15 nm particles were from 1100 °C temperature and 20 nm was from 1150 °C.

For particles in the range of 30–500 nm, a collision-type atomizer (Model 3079, TSI Inc., Shoreview, MN, USA) was used to generate NaCl particles from NaCl solutions. The NaCl (assay 99.2%) was well dispersed in the high purity water (HPLC-grade). Compressed air with pressure of 30 psi was applied to atomize the NaCl

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Table 1
Specifications of electret and nanofiber filter media.

Filter media	Thickness (mm)	Fiber diameter (μm)	Pressure drop at 5 cm s^{-1} (Pa)	Charging intensity (μC m^{-2})
Electret media	1 ± 0.2	10 ± 3	10 ± 1	100
Nanofiber	0.1 ± 0.02	0.3 ± 0.1	23 ± 1	zero

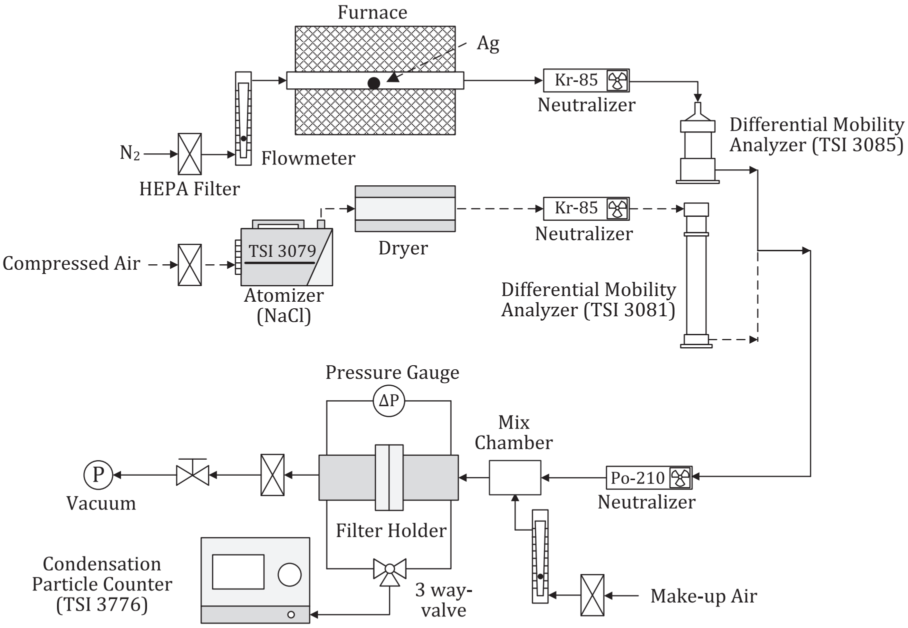

Fig. 1. Experimental setup of particle generation and filter initial efficiency tests.

solutions. Then the aerosolized droplets were dried by the diffusion dryer and turned from liquid to solid particles. The size distribution and concentration of the NaCl particles was controlled by varying the NaCl solution concentration. Similarly, two different mass concentrations of 0.01% and 1% were used in the experiments and the obtained size distributions are shown in Fig. SI. Monodisperse NaCl nanoparticles with mobility diameter of 30, 50, 80, 100, 150, 200, 300, 400, 500 nm were classified from the two different distributions by a long differential mobility analyzer (long DMA, Model 3081, TSI Inc., Shoreview, MN, USA) and used to challenge the filter media. The 30–80 nm particles were from the 0.01% solution and 100–500 nm particles were from 1% solution.

As shown in Fig. 1, before introducing the monosized particles into the filter holder to challenge the filter, the particles were neutralized by a neutralizer to bring particles to be Boltzmann equilibrium to minimize the effect of electrostatic depositions. The filtration efficiency for each tested particle size was determined by the ratio of the downstream particle concentration of the filter media to that of upstream measured by the ultrafine condensation particle counter (UCPC, Model 3776, TSI Inc., Shoreview, MN, USA) with high flow (1.5 L m^{-1}) as:

$$E(d_x) = 1 - \frac{C_{down}(d_x)}{C_{up}(d_x)} \tag{2}$$

where $E(d_x)$ is filtration efficiency for each tested particle size (–); $C_{down}(d_x)$ is the downstream particle concentration (# cm^{-3}); $C_{up}(d_x)$ is the upstream concentration (# cm^{-3}).

2.3. Loading test

The loading performance of electret filter media was evaluated by challenging with polydisperse NaCl particles which mimicked the size distribution of typical atmospheric $PM_{2.5}$. The experimental setup developed for loading test is shown in Fig. 2. The electric furnace (the same as initial penetration measurement) was used to generate polydisperse particles from NaCl powder and the filtered compressed air was used as the carrier gas. The size distribution was controlled by varying the furnace temperature and flow rate of carrier gas.

In this study, the furnace temperature was set at 790 °C and the carrier gas flow rate was 1.5 L min^{-1}. The size distribution of the mimicked $PM_{2.5}$, shown in Fig. 3(a), was measured by the Scanning Mobility Particle Sizer (SMPS, Model 3936, TSI Inc., Shoreview, MN, USA) for particles with 0.02–0.8 μm and by the Optical Particle Sizer (OPS, Model 3330, TSI Inc., Shoreview, MN, USA) for particles larger than 0.8 μm. To be noted, the error bars represent the 95% confidence interval in Fig. 3(a) as well as for all other figures in this paper. The distribution had a number median diameter and mass median diameter of 85 nm and 300 nm, respectively. It is to be mentioned that the mimicked $PM_{2.5}$ has a mass concentration cut at around 2.5 μm, which meets the set of requirement. To observe the morphology of the particles, the particles were collected on the 1 μm track-etched polycarbonate membrane filter and analyzed by SEM. As shown in Fig. 3(b) and (c), the particles generated by this method were well-dispersed and not agglomerated. For achieving a more realistic loading scenario in the filter application, a sufficient low mass concentration with ~7.0 mg m^{-3} of mimicked $PM_{2.5}$ was prepared for the tests.

The face velocity for the loading test was 0.25 m s^{-1}, which was close to the operation face velocity through media in real application according to the filter media provider. A Magnehelic gauge was used to measure the pressure drop of the filter media at different loading stages. The efficiency against different particle size was measured by the Scanning Mobility Particle Sizer (SMPS) during loading. Before and after the loading tests, the mass of the

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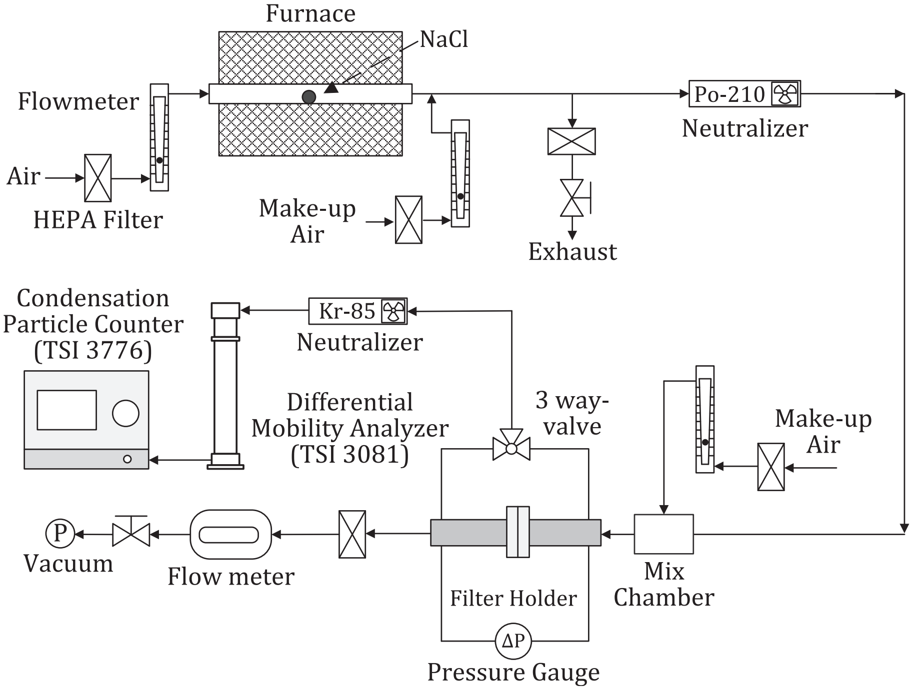

Fig. 2. Experimental setup of $PM_{2.5}$ NaCl particle generation and loading tests.

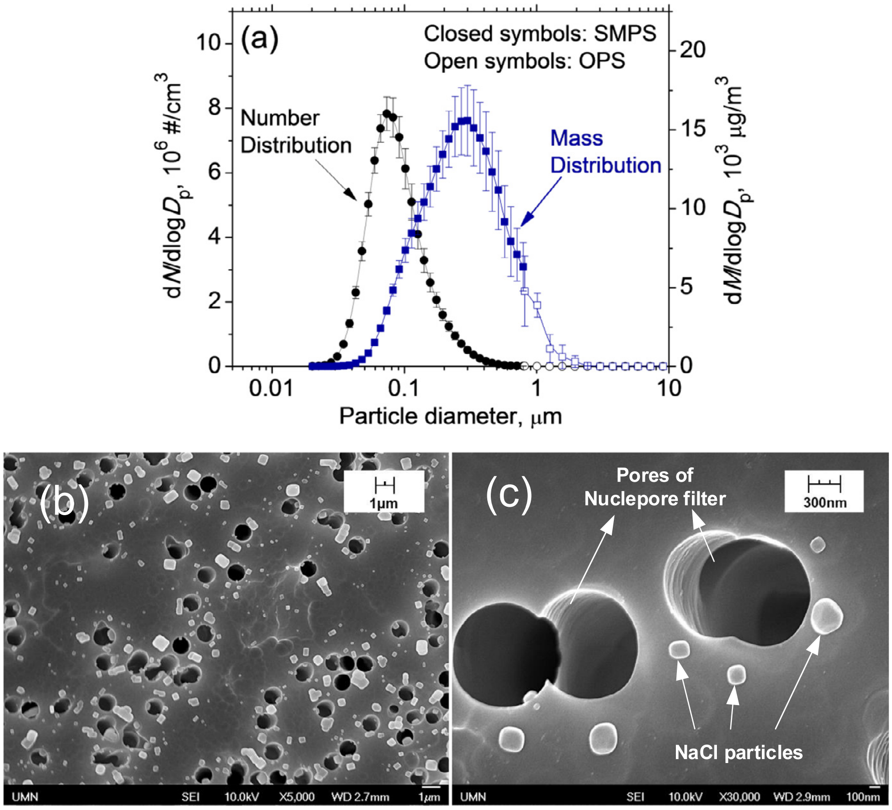

Fig. 3. Size distribution (closed symbols: SMPS; open symbols: OPS) of NaCl particles for loading test and SEM images of NaCl particles collected by 1 μm track-etched polycarbonate membrane filter.

filter media was weighed by an electrical balance (Type B 120S, Sartorius AG, Göttingen, Germany) with readability down to 0.1 mg. Thus the overall particle mass deposited, M, on the filter media was calculated by subtracting the weight of clean media from that of loaded media. Assuming the starting time of loading was t_0 ($t = 0$) and the ending time was t_n, the time interval for each SMPS and pressure measurement was t_i ($i = 0, 1, \ldots, n$). The total mass concentration given by SMPS for upstream and

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downstream were $m_{up,i}$ and $m_{down,i}$ at t_i. Then the deposited particle mass m_i (g m^{-2}) on filter media at t_i (min) can be calculated by Eq. (3) as:

$$m_{\mathrm{i}} = \frac{\sum_{j=0}^{i}(m_{\mathrm{up,j}} - m_{\mathrm{down,j}}) \times (t_{\mathrm{j}} - t_{\mathrm{j-1}})}{\sum_{j=0}^{n}(m_{\mathrm{up,j}} - m_{\mathrm{down,j}}) \times (t_{\mathrm{j}} - t_{\mathrm{j-1}})} \times M \tag{3}$$

The final mass deposited for the loading test was controlled to be about 6 g m^{-2} when the pressure drop reached 2–3 times that of the initial condition. The total time required to complete a cycle of loading test was about 2.0 h and 1.5 h for the electret media and composite media, respectively. There was a total of 5 repeated experiments conducted using five different media from different pieces for both electret and nanofiber media to obtain a representative and reliable data set.

3. Results and discussion

3.1. Filtration performance of clean media

Fig. 4(a) and (b) showed the initial filtration efficiency curves of the electret media, nanofiber layer and composite media at face velocities of 0.05 and 0.25 m s^{-1}, respectively. It can be seen the filtration efficiency decreases with increasing face velocity for the tested particle sizes. For the electret media, the most penetrating particle size (MPPS) was seen to be ~30 nm and there was a deep U shape efficiency curve, meaning the efficiency increased significantly both with increasing and decreasing sizes from the MPPS. This is typical and was because that the sub-30 nm particles were difficult to be polarized by charges on fibers while the depositions of particles larger than ~30 nm were enhanced by Columbic effect [5]. So the remaining primary removal mechanism for sub-30 nm nanoparticles was only the diffusion effect. As mentioned, the electret media was rated with MERV 14 which was regarded as medium to high grade HVAC filter media. However, the standard test method ASRAE 52.2 only considers the efficiency of particles larger than 300 nm. So the high MERV value does not necessarily reflect high removal efficiency for nanoparticles, which was clearly evidenced.

In comparison, the nanofiber layer has a MPPS of about 100–150 nm and similarly a deep U shape is seen as that of electret media. The nanofiber layer did not have electrostatic charge so the mechanical mechanisms employed by the filter media for 100–150 nm particles were weak, which led to the lowest filtration efficiency. Nevertheless, the nanofiber layer had a significantly higher efficiency around the MPPS of electret media. Therefore, by combining these two types of filter media, the MPPS of the composite media moved from ~30 nm of electret media to 50 nm and expectedly the efficiency curve of overall size ranges was improved significantly. The new minimal efficiency was only slightly lower than that of other particle sizes as a less deep U curve is seen. In conclusion, the electret media enhanced the filtration efficiency at the MPPS of nanofiber layer and the nanofiber layer increased the efficiency at the MPPS of electret media. This combination made full use of both the mechanical and electrostatic forces and resulted in a much higher and more flat efficiency curve. However, it is to be mentioned, the comparison between the different media shown in Fig. 4 was made based on the same face velocity, but the more realistic comparison for their filtration performance should be made under the same pressure drop. This kind of comparison will be discussed in the following section.

Fig. 5(a) and (b) shows the comparison of the FOM (efficiency based on the same pressure drop) among the electret media, nanofiber layer and composite media for 8–500 nm particles at face velocities of 0.05 and 0.25 m s^{-1}, respectively. The FOM of 0.05 m s^{-1} was higher than that of 0.25 m s^{-1}. When particles are larger than 30 nm, clearly the electret media showed higher FOM than the composite media and then followed by the nanofiber layer. However, for sub-30 nm nanoparticles, the FOMs were close to each other between different types of media, especially at 0.05 m s^{-1} face velocity. This reflects that the addition of a nanofiber layer does help to achieve the improvement of nanoparticle efficiency but without paying too much of a tradeoff with the resulting pressure drop increase. A more detailed comparison revealed that although the combined media showed advantage against nanofiber layer in terms of FOM, the electret media still had the highest FOM. But, as mentioned in the introduction section, the filtration performance of electret media would deteriorate quickly in the loading process. Therefore, the initial FOM was not adequate enough to assess the performance in the whole course of filtration whereas it is more important to evaluate their performance over the loading process which will be shown in the following section.

3.2. Filtration efficiency of loaded media

Fig. 6 shows the comparison of efficiency evolution between electret and composite media during loading with polydisperse NaCl particles which mimicked the size distribution of typical atmospheric $PM_{2.5}$, in which the results for particles of 50, 80, 100, 200, 300 and 500 nm were depicted. These particle sizes were selected because most of atmospheric $PM_{2.5}$ particles were in the range of 50–500 nm based on number distribution of particle size.

It is seen the filtration efficiency of EM decreased dramatically with an overall reduction of 20–40% efficiency, and quickly right after 0.5 g m^{-2} of loading, for all particle sizes. In comparison, the EM + NL media have only a slight reduction of efficiency by 3–10% after 0.5 g m^{-2} of loading. The occurrence of early stage

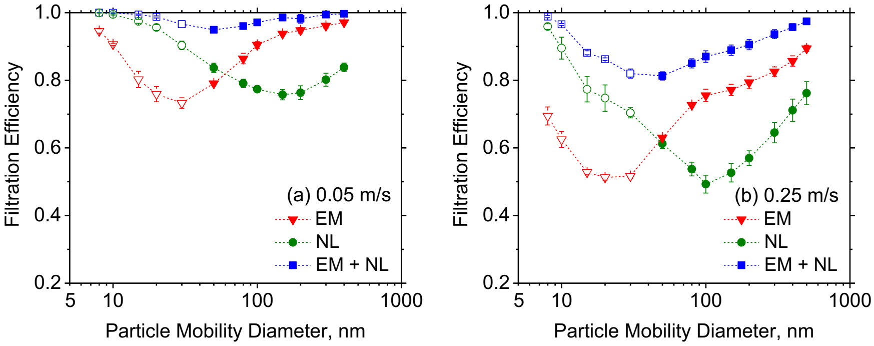

Fig. 4. Initial efficiency curves for electret media (EM), nanofiber layer (NL) and the composite media (EM + NL) under face velocity of (a) 0.05 m s^{-1}, (b) 0.25 m s^{-1}. (Open symbols: Ag particles; closed symbols: NaCl particles.)

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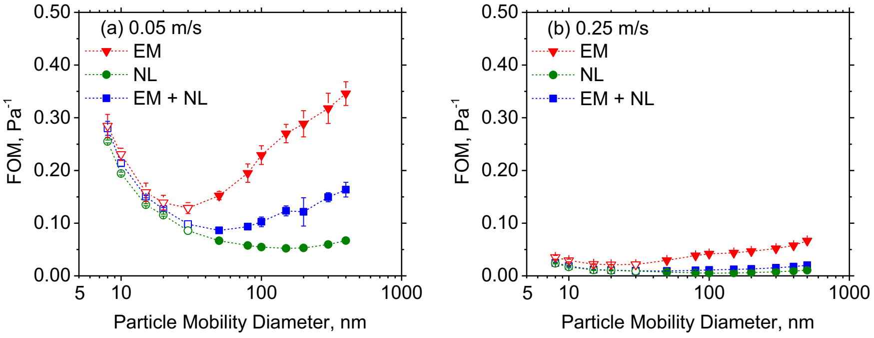

Fig. 5. Figure of Merit for electret media (EM), nanofiber layer (NL) and composite media (EM + NL) under face velocity of (a) 0.05 m s^{-1}, (b) 0.25 m s^{-1}. (Open symbols: Ag particles; closed symbols: NaCl particles.)

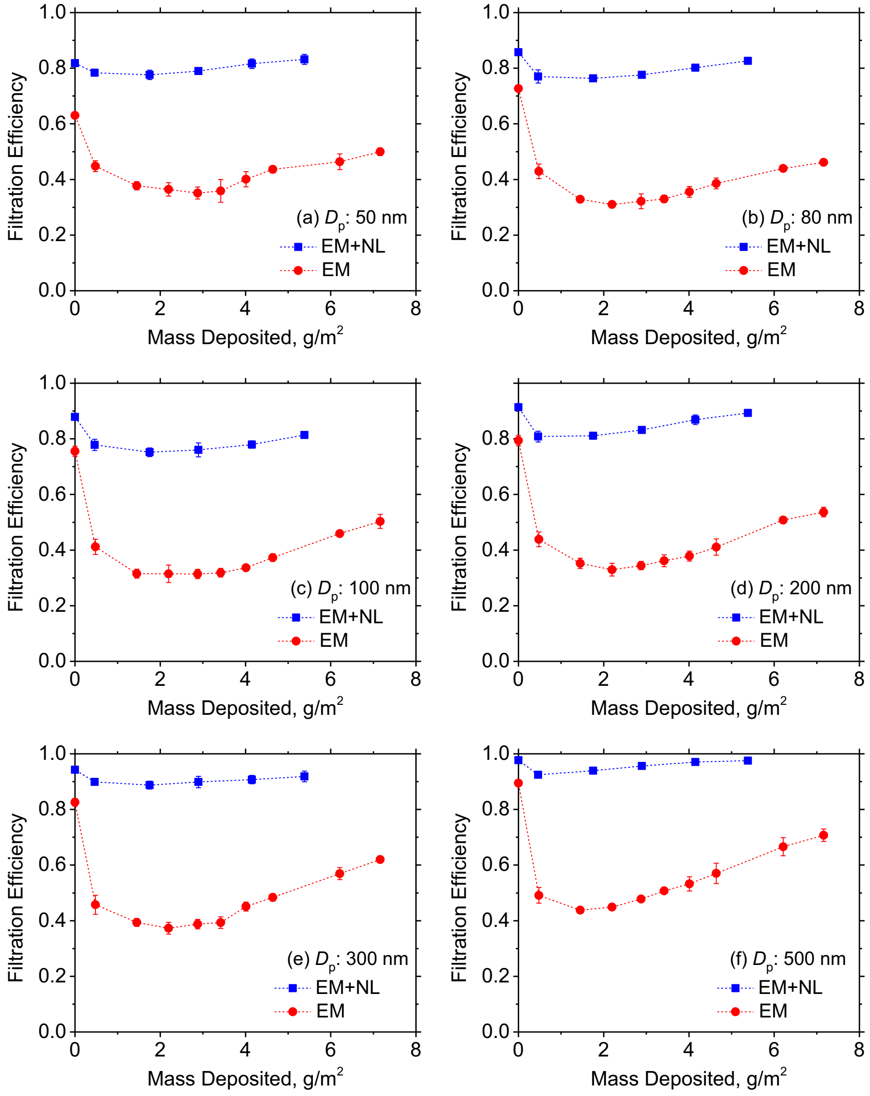

Fig. 6. Filtration efficiency evolution of electret media (EM) and composite media (EM + NL) for particles of (a) 50 nm, (b) 80 nm, (c) 100 nm, (d) 200 nm, (e) 300 nm and (f) 500 nm during loading with $PM_{2.5}$ polydisperse NaCl particles.

efficiency reduction was because that when particles began to deposit on the charged fibers of electret media, the fiber charges were quickly shielded [25]. For the minimal efficiency along the loading process, the EM reached the minimum at around 2 g m^{-2} with a total efficiency reduction of 30–45% from the initial efficiency while that of the EM + NL occurred earlier at about 0.5–1 g m^{-2} and only with 4–10% of reduction. Table S1 of Supplementary Material summarizes the initial and minimum efficiency values during loading tests for both electret and composite media. According to the data obtained, it is to be emphasized that the MERV 14 electret media had a severe efficiency reduction and led to a significantly low efficiency with $PM_{2.5}$ loading. It is

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meaningful to add the thin layer of nanofiber to enhance the removal of small particles.

After reaching the minimal efficiency, the increase of efficiency was initiated due to the cake formation when only a pure mechanical filtration is taking place. From that point onwards, mechanical filtration dominates the loading process, and the efficiency started to continue increasing. But even after about 7 g m^{-2} of mass deposition, the efficiency of different particle size was still lower than the initial efficiency. In the composite media, as the efficiency of electret media layer continues to decrease, its efficiency reduction may be compensated by the nanofiber layer. Before the buildup of massive dendrites on electret fibers, the nanofiber layer and the growing particle chains on nanofibers can keep the overall efficiency from reducing significantly. It is concluded that with a proper design, the composite media showed a great improvement in term of minimizing the efficiency reduction during loading, as well as maintaining a high efficiency for $PM_{2.5}$.

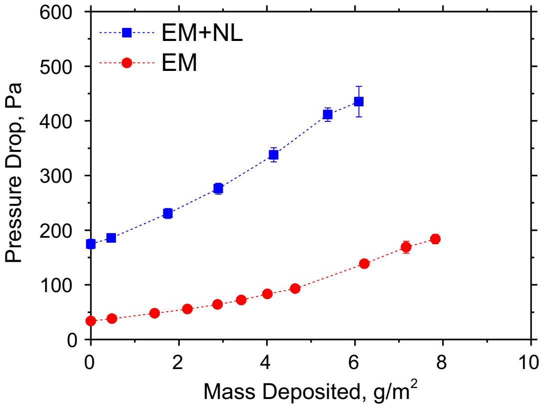

Fig. 7. Comparison of pressure drop between electret media (EM) and composite media (EM + NL) during loading with $PM_{2.5}$ polydisperse NaCl particles under face velocity of 0.25 m s^{-1}.

3.3. Pressure drop and FOM of loaded media

Since the composite media performed at a high efficiency along the loading process, it is important to evaluate its capacity for holding the $PM_{2.5}$. Therefore, the pressure drop growth versus the deposited mass of $PM_{2.5}$ between the electret and composite media were compared in Fig. 7. Despite the fact that overall efficiency of the composite media was much higher than that of electret media, surprisingly, its pressure drop increase rate was

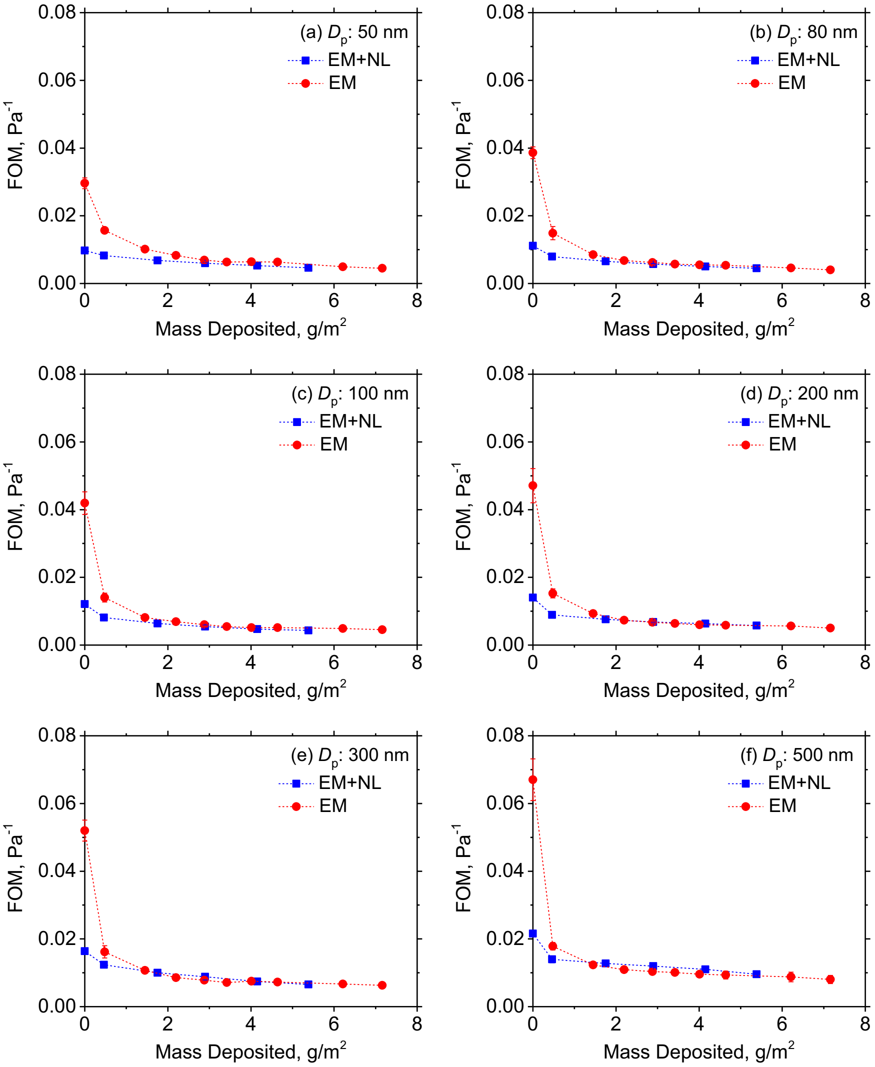

Fig. 8. FOM evolution of electret media (EM) and composite media (EM + NL) for particles at diameter of (a) 50 nm, (b) 80 nm, (c) 100 nm, (d) 200 nm, (e) 300 nm and (f) 500 nm during loading with $PM_{2.5}$ polydisperse NaCl particles.

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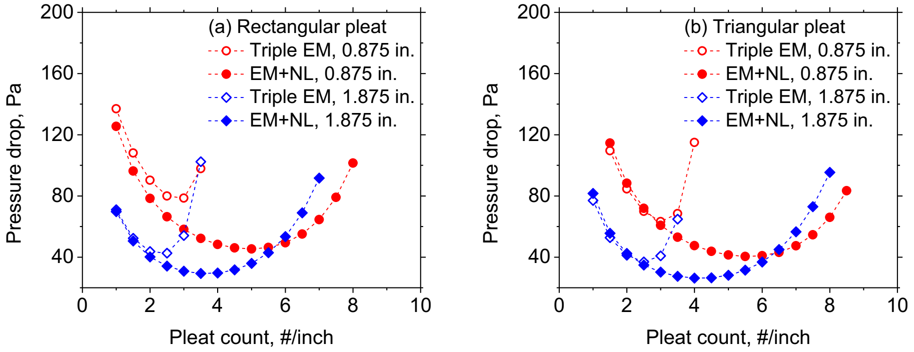

Fig. 9. Pressure drops of clean filters made by triple-layer electret media (Triple EM) and composite media (EM + NL) under different pleat heights (0.875 in. and 1.875 in.) and different pleat shapes: (a) rectangular, (b) triangular.

close to that of electret media (similar slope). By gravimetric analysis, the final mass deposition for the composite media was 5.94 ± 0.25 g m^{-2}, in which particles deposited in the electret media and nanofiber layer were 3.26 ± 0.11 and 2.68 ± 0.25 g m^{-2}, respectively. The electret media layer held ~55% of PM2.5 particles and kept the pressure drop of nanofiber layer from increasing too quickly, because electret media were composed of more open structure with coarse fibers, which can provide less susceptible to clogging than the nanofiber layer. If the composite media continued to be tested after loading 6.08 g m^{-2} of mimicked $PM_{2.5}$, it is expected that the electret media layer would have an increasing efficiency (acting as a loaded mechanical filter as shown in Fig. 6) and would hold a higher percentage of particles, which would help the nanofiber layer to have less clogging. It is concluded that this type of combination provided a unique structure to take advantage of electret media and a nanofiber layer in a long term filtration application for the removal of $PM_{2.5}$.

It is very important to further examine and compare the FOM between electret and composite media during loading with mimicked $PM_{2.5}$ to ensure that the new composite media is able to perform nicely in the application of $PM_{2.5}$ removal in HVAC filters. Fig. 8 shows the FOM evolution of electret media and composite media for particles at diameter of (a) 50 nm, (b) 80 nm, (c) 100 nm, (d) 200 nm, (e) 300 nm and (f) 500 nm during loading with polydisperse $PM_{2.5}$ particles. To be noted, since the comparison was made for the FOM, one can treat the results are applicable for the comparison between the composite media and the electret media with 3–4 layers when they have the same pressure drop. From the figure, basically, it is seen the FOM decreases with decreasing particle size for the both media because their MPPSs were smaller than 50 nm.

For the electret media, the FOM decreased dramatically and quickly in the beginning of the loading stage as the enhancement of electrostatic deposition from fiber charges deteriorated. This is similar with that observed for the efficiency reduction shown in Fig. 6. After about 1.0 g m^{-2} of mass deposition, the FOM became very stable. The reduced and more stable FOM was more representative than the initial high FOM when the long term real filtration performance was considered. In comparison, the FOM of composite media decreased only slightly at first and then became stable. Excluding the initial loading stage, the FOM of composite media were pretty close to, or in a few instances slightly higher than the electret media, meaning that the resulting pressure drop increase of the composite media could be neglected. In real filtration applications such as HVAC filters and air cleaners, filter media are often pleated to increase the total surface area and reduce the face velocity compared to that of a flat sheet of media. With much lower face velocity, assuming many pleats are made, the pleated filter would also have enhanced filtration efficiency and reduced pressure drop. To further explain the performance advantages of composite media compared to triple-layer electret media, the pressure drops of clean HVAC filters made by triple-layer electret media and composite media were calculated based on models of Chen et al. [7] and Chen et al. [8]. In the calculation, the size of HVAC filter was 610 × 610 mm and airflow rate was 0.93 m^3/s according to examples in ASHRAE 52.2-2012 [1]. The selected pleat heights were 0.875 inches and 1.875 inches based on commercial HVAC filters. Both the rectangular pleat [7] and triangular pleat [8] were considered in the modelling. The results were shown in Fig. 9 and the detailed values were shown in Table S2 of SI. As can be seen, the composite media can achieve a 30–40% lower pressure drop at optimal pleat count condition than that of triple-layer electret media under both rectangular (a) and triangular (b) pleat designs. It becomes clear that, in term of pleat configuration, the large thickness of 2.4 mm by using three layers of electret media can lead to higher filter pressure drop as revealed in Fig. 9 and Table S2. Therefore, the more reasonable way of loading characteristics evaluation is to compare performance the one-layer electret media and composite media whose thickness is similar.

To be concluded, although the composite media performed just similarly well as the electret media according to the FOM, the real filter application should be taken into account, i.e. the application for pleated filter. Besides, it is expected that the performance of the currently proposed composite media can be further improved after an optimization design for the nanofiber layer has been further made.

4. Conclusions

This study proposed a composite filter media composed of commercial HVAC electret media and a nanofiber layer in order to enhance the efficiency of the clean filter for small particles with diameters of 10–30 nm and to alleviate the efficiency reduction in the loading process. The initial filtration efficiency and FOM of electret media and composite filter media for particles of 8–500 nm were tested under the face velocities of 0.05 and 0.25 m s^{-1}. The MPPS of electret media was found to be around 30 nm, while the MPPS of the nanofiber layer was 100–150 nm. By combining these two types of filter media, the electret media can enhance the efficiency at the MPPS of nanofiber layer, and the nanofiber layer can increase the efficiency at the MPPS of electret media. This combination made a full use of both the mechanical and electrostatic forces and resulted in a much more flat and high efficiency curve. The electret media showed higher FOM than composite media only for particles larger than 30 nm.

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The loading performance of the two filter media was evaluated by polydisperse NaCl particles which mimicked the size distribution of typical atmospheric $PM_{2.5}$. The electret media showed an efficiency reduction of 30–45% compared with initial efficiency. In comparison, the efficiency of the composite media declined much less than that of the electret media. The efficiency reduction of electret media layer can by compensated by the nanofiber layer with proper design. The comparison of efficiency and FOM evolution between the two media showed that except the higher initial FOM, the electret media and the composite media performed nearly equivalently, however because the composite media is inherently thinner, it may have potential benefits when applied towards pleated HVAC filters requiring high pleat counts. The composite media is not only compatible with electret media in terms of pressure drop but also performing better $PM_{2.5}$ removal over the loading process during the loading process. This type of composite media provided a unique structure that takes advantage of electret media and a nanofiber layer.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.seppur.2017.03.040.

References

[1] ASHRAE, ANSI/ASHRAE Standard 52.2: Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA, 2012.

[2] L.W. Barrett, A.D. Rousseau, Aerosol loading performance of electret filter media, Am. Ind. Hyg. Assoc. J. 59 (1998) 532–539.

[3] R.C. Brown, Air Filtration: An Integrated Approach to the Theory and Application of Fibrous Filters, Pergamon, Oxford, UK, 1993, p. 9.

[4] CEN, EN 779: Particulate Air Filters for General Ventilation—Determination of the Filtration Performance, European Committee for Standardization, Brussels, Belgium, 2012.

[5] D.Q. Chang, S.C. Chen, A.R. Fox, A.S. Viner, D.Y.H. Pui, Penetration of sub-50 nm nanoparticles through electret HVAC filters used in residence, Aerosol Sci. Technol. 49 (2015) 966–976.

[6] S. Chazelet, D. Bemer, F. Grippari, Effect of the test aerosol charge on the penetration through electret filter, Sep. Purif. Technol. 79 (2011) 352–356.

[7] D.R. Chen, D.Y.H. Pui, B.Y.H. Liu, Optimization of pleated filter designs using a finite-element numerical model, Aerosol Sci. Technol. 23 (1995) 579–590.

[8] D.R. Chen, D.Y. Pui, Y.M. Tang, Filter pleating design for cabin air filtration, SAE Tech. Pap. 960944 (1996) 93–100.

[9] S.C. Chen, D.Q. Chang, C. Pei, C.J. Tsai, D.Y.H. Pui, Removal efficiency of bimodal $PM_{2.5}$ and PM_{10} by electret respirators and mechanical engine intake filters, Aerosol Air Qual. Res. 16 (2016) 1722–1729.

[10] S.C. Chen, J. Wang, Y.K. Bahk, H. Fissan, D.Y.H. Pui, Carbon nanotube penetration through fiberglass and electret respirator filter and nuclepore filter media: experiments and models, Aerosol Sci. Technol. 48 (2014) 997–1008.

[11] W.J. Fisk, D. Faulkner, J. Palonen, O. Seppanen, Performance and costs of particle air filtration technologies, Indoor Air 12 (2002) 223–234.

[12] A.R. Fox, M.E. Jones, U.S. Patent No. 7,691,168 B2, U.S. Patent and Trademark Office, Washington, DC, 2010.

[13] K. Graham, M. Ouyang, T. Raether, T. Grafe, B. McDonald, P. Knauf, Polymeric Nanofibers in Air Filtration Applications, Presented at the Fifteenth Annual Technical Conference & Expo of the American Filtration & Separations Society, Galveston, Texas, United States, 2002.

[14] G.B. Hamra, N. Guha, A. Cohen, F. Laden, O. Raaschou-Nielsen, J.M. Samet, P. Vineis, F. Forastiere, P. Saldiva, T. Yorifuji, D. Loomis, Outdoor particulate matter exposure and lung cancer: a systematic review and meta-analysis, Environ. Health Perspect. 122 (2014) 906–911.

[15] W.C. Hinds, Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles, second ed., John Wiley, New York, 1999, pp. 233–241 and 304–315.

[16] ISO 12103-1: Road vehicles – Test dust for filter evaluation – Part 1: Arizona Test Dust, International Organization for Standardization, Geneva, Switzerland, 1997.

[17] Y.Y. Kuo, F.C. Bruno, J. Wang, Filtration performance against nanoparticles by electrospun Nylon-6 media containing ultrathin nanofibers, Aerosol Sci. Technol. 48 (2014) 1332–1344.

[18] W.W.F. Leung, C.H. Hung, Investigation on pressure drop evolution of fibrous filter operating in aerodynamic slip regime under continuous loading of submicron aerosols, Sep. Purif. Technol. 63 (2008) 691–700.

[19] W.W.F. Leung, C.H. Hung, P.T. Yuen, Experimental investigation on continuous filtration of sub-micron aerosol by filter composed of dual-layers including a nanofiber layer, Aerosol Sci. Technol. 43 (2009) 1174–1183.

[20] W.W.F. Leung, C.H. Hung, P.T. Yuen, Effect of face velocity, nanofiber packing density and thickness on filtration performance of filters with nanofibers coated on a substrate, Sep. Purif. Technol. 71 (2010) 30–37.

[21] W.W.F. Leung, C.H. Hung, Skin effect in nanofiber filtration of submicron aerosols, Sep. Purif. Technol. 92 (2012) 174–180.

[22] L. Li, Z. Zuo, D.A. Japuntich, D.Y.H. Pui, Evaluation of filter media for particle number, surface area and mass penetrations, Ann. Occup. Hyg. 56 (2012) 581–594.

[23] A. Podgórski, A. Bałazy, L. Gradoń, Application of nanofibers to improve the filtration efficiency of the most penetrating aerosol particles in fibrous filters, Chem. Eng. Sci. 61 (2006) 6804–6815.

[24] D.Y.H. Pui, S.C. Chen, Z. Zuo, $PM_{2.5}$ in China: measurements, sources, visibility and health effects, and mitigation, Particuology 13 (2014) 1–26.

[25] D.C. Walsh, J.I. Stenhouse, The effect of particle size, charge, and composition on the loading characteristics of an electrically active fibrous filter material, J. Aerosol Sci. 28 (1997) 307–321.

[26] J. Wang, S.C. Kim, D.Y.H. Pui, Figure of merit of composite filters with micrometer and nanometer fibers, Aerosol Sci. Technol. 42 (2008) 722–728.

[27] T.T. Wu, U.S. Patent Application No. 2008/0017038 A1, U.S. Patent and Trademark Office, Washington, DC, 2008.

[28] B.Y. Yeom, E. Shim, B. Pourdeyhimi, Boehmite nanoparticles incorporated electrospun nylon-6 nanofiber web for new electret filter media, Macromol. Res. 18 (2010) 884–890.