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Structural improvement to quadruple service life of a high-efficiency electret filter

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Abstract

The electret filter is composed of permanently charged electret fibers highly capable of collecting charged and uncharged nanosize particles. Compared to the ordinary non-electret fiber, the aerosol collection efficiency η of the electret fiber can initially be significantly higher. In our previous study, η of the electret fiber under dust loading is found to be approximated as the sum of the electrical and mechanical collection efficiencies. It is also shown that the former efficiency can be approximated as a logarithmic function of the dust load. Since the expensive electret filter cannot practically be cleaned and re-used, it is crucial to lengthen its service life without compromising its collection efficiency. In the present study, the time-dependent dust-loaded collection efficiencies of four electret filters with the same average packing density of 0.04 but different linear spatial distributions of the packing density along the filter thickness (0.04 throughout, front 0.03–back 0.05, front 0.02–back 0.06, front 0.01–back 0.07) are simulated and compared. The maximum penetrations and clogging points of the four filters are different. At the maximum 4% penetration through filter D (front 0.01–back 0.07) is two times higher than filter A (0.04 throughout), but the dust load at clogging point of filter D is about 4 times higher than filter A. The results show a significant difference in the distributions of the mass deposited particles along the filter thickness as time passes. As a result, it is possible to quadruple the filter service life by packing the filter loosely on the inlet side and progressively more densely towards the outlet side, while maintaining a sufficiently high aerosol collection efficiency at all times.

Keywords: Dust loading effect; Electret filter

1. Introduction

Fibrous air filters are used in various industries for dust collection and environmental protection. The electret filter is used to clean gas streams of dilute particle concentrations at low pressure drop and high efficiency. It is composed of permanently charged electret fibers highly capable of collecting charged and uncharged fine particles. Compared to the ordinary non-electret fiber, the aerosol collection efficiency of the electret fiber can initially be significantly higher, even if the aerosol particles are uncharged. Therefore, electret fibers are often employed to enhance the collection efficiency of HEPA and ULPA filters. As the constituent fibers are covered with collected particles, the filter characteristics change with the dust load. The electret fiber has four different mechanisms of particle deposition, namely, inertial capture, interception, diffusion and electrostatic mechanism. The collection efficiency of the clean electret fiber in the initial stage is remarkably high because of its strong electrostatic effects. As dust loading proceeds, the collection efficiency of the electret filter might briefly fall as a function of dust load because the electrostatic effect exhibited by the fiber surface is screened by the deposited particles. It is known that most on-coming particles are collected on already captured particles to form complicated agglomerates on an electret fiber. As a consequence, the mechanical effect on the overall efficiency gradually picks up and ultimately becomes the dominant collection mechanism.

The collection efficiency of clean air filter are well known and widely studied [1–7]. The collection efficiency

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Nomenclature

C_i	influent particle concentration (kg/m^3)
C_e	effluent particle concentration (kg/m^3)
d_f	diameter of a fiber (m)
E_m	collection efficiency of filter (–)
M	dust load in a unit filter volume (kg/m^3)
Pn	penetration (–)
t	time (s)
v	face velocity (m/s)
η	single-fiber collection efficiency (–)
η_{0E}	electrical single-fiber collection efficiency of the clean fiber (–)
η_{0M}	mechanical single-fiber collection efficiency of the clean fiber (–)
η_E	electrical single-fiber collection efficiency under dust load condition (–)
η_M	mechanical single-fiber collection efficiency under dust load condition (–)
λ_E	electrical enhancement factor (m^3/kg)
λ_M	mechanical enhancement factor (m^3/kg)
α	packing density of filter (–)

of the electret filters could initially degrade with the agglomerative deposition of particles [8–12].

The collection efficiency of the electret filter depend on many parameters such as the aerosol particle sizes, the fiber charge density, charge on particles, filtration velocity, filter packing density and the filter thickness. Kanaoka et al. [13] proposed a three-dimensional stochastic model of an ordinary fiber for the case of deposition of aerosol particles by convective Brownian diffusion. They found that the ratio of the collection efficiency of a single dust-loaded fiber to that of a clean fiber was expressible as a linear function of the mass of particles in a unit filter volume. Baumgartner and Loffler [9] studied the initial and dust loading condition of the electret filter. They were interested in the particle sizes ranging from 10 nm to 10 μm for various types of electret filters. They also simulated the particle deposition around a cylindrical electret fiber to predict the collection efficiency of clean fibers. Brown et al. [10] found that the collection efficiency of the electret filters exponentially decreases with the operation time because the electrical effect decreases. Walsh and Stenhouse [11] carried out experiments to study the effect of particle size, charges and composition on the electret filter under dust-loading condition. They showed that the uniformly small particles can reach the maximum penetration and the clogging point faster than the uniformly large particles. Kanaoka et al. [14] studied a practical three-dimensional simulation method for predicting the agglomerative deposition process of sub-micron aerosol particles on an electret fiber. This study led to prediction of how the morphology of particle accumulates on a constituent fiber changed and affected the collection efficiency of the filter under the dust-loaded condition. Ji et al. [12] conducted experiments to study the effect of dust loading on the collection performance of the electret cabin air filters. They proposed that the amount of charge, the particle sizes and the particle material affected the collection performance. They also showed the collection efficiency degraded as more particles deposited, and showed a minimum efficiency at steady state. Tanthapanichakoon et al. [15] developed a three dimensional stochastic model to simulate the deposition process on an electret fiber by considering the effect of Brownian diffusion in the model. The model was shown to predict the agglomerative deposition process reasonably well and, in the case of weak electrical effects, they also approximated the collection efficiency enhancement factor as linear function of dust load.

In our previous study, the collection efficiency of the electret fiber under dust loading is found to be approximated as the sum of the electrical and mechanical collection efficiencies. It is also shown that the electrical collection efficiency can be approximated as a logarithmic function of the dust load [16]. In the present study, the time-dependent dust-loaded collection efficiencies of electret filters with the same average packing density but different spatial distributions of packing density along the filter thickness are simulated and compared. The results show a significant difference in the distributions of the mass deposited particles along the filter thickness as time passes. It is possible to significantly lengthen the filter service life by packing the filter loosely on the inlet side and progressively more densely towards the outlet side, while maintaining a sufficiently high aerosol collection efficiency at all times.

1.1. Simulation of the collection efficiency of the electret filter

In our previous study, the correlation for the collection efficiency of the electret fiber (η) is found by summing a logarithmic function for the electrical collection efficiency (η_E) and the previously obtained linear function of mechanical collection efficiency (η_M).

$$\eta = \eta_E + \eta_M$$
$$= \eta_{0E}[1 + (\beta \ln m + \gamma)m] + \eta_{0M}[1 + \lambda_M m] \quad (1)$$

or

$$\eta = \eta_{0E}[1 + \lambda_E m] + \eta_{0M}[1 + \lambda_M m],$$
$$\text{where } \lambda_E = \beta \ln m + \gamma \quad (2)$$

Under dust-loaded condition, the local aerosol concentration C and dust load m in the filter can be obtained by numerically integrating Eqs. (3) and (4) together with Eq. (2) and the applicable initial and boundary conditions.

$$\frac{\partial C}{\partial x} = -\frac{4}{\pi}\frac{\alpha}{1-\alpha}\frac{\eta}{d_f}C \quad (3)$$

$$\frac{\partial C}{\partial x} = -\frac{1}{v}\frac{\partial m}{\partial t} \quad (4)$$

Initial condition $t=0$: $m=0$ for $0<x<L$

Boundary condition $x=0$: $C=C_i$ for $t>0$

The filter collection efficiency is calculated from $C_e=C$ at $x=L$ as follows.

$$E_m = 1 - \frac{C_e}{C_i} \quad (5)$$

To estimate the collection efficiency of the electret filter under dust-loaded condition, the following assumptions are made:

(1) The local collection performance (between x and $x+\Delta x$) can be regarded as constant for a sufficiently short time interval (t and $t+\Delta t$).

(2) When the local dust load a single fiber is the same, the local electrical enhancement factor is the same regardless of the fiber location in the filter and filtration time.

The simulation conditions are listed in Table 1. The simulation is carried out until the filter becomes clogged. The % penetration P is defined as $P=100(1-E_m)$. Table 2 shows the equation of the filter packing density of four filters. The four filters have same average packing density, $\alpha=0.04$, but different spatial distributions of packing density along the filter thickness. Fig. 1 shows the filter packing density distribution of the filters along thickness. Fibers are packed uniformly in filter A. For filters B–D, the packing density changes along the filter thickness, with a minimum packing density at the inlet side and a maximum packing density at the outlet side of filter.

Table 1
Simulation conditions used

Simulation conditions used
Time step $\Delta t=0.03$ s
Differential filter thickness $\Delta x=0.00002$ m
Packing density of filter $\alpha=0.04$ (–)
Face velocity of filtration=0.1 m/s
Influent dust concentration $C_i=0.01$ mg/m^3
Electret fiber diameter $d_f=20$ μm
Particle diameter $d_p=1$ μm
Electret fiber charge $=1.2\times10^{-4}$ C/m^2

Table 2
Packing density of the electret filter

Filter	Packing density
A	0.04
B	$6.67L+0.03$
C	$13.333L+0.02$
D	$20L+0.01$

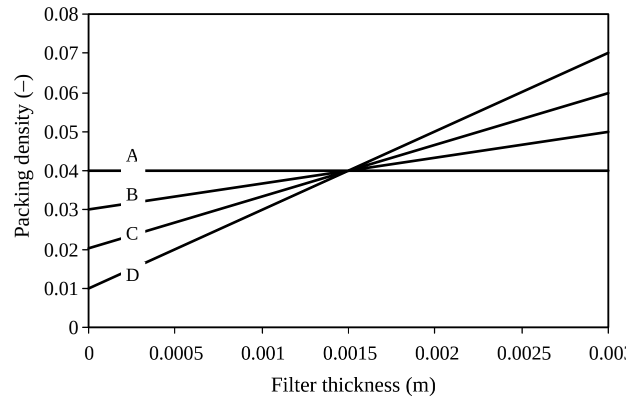

Fig. 1. Electret fiber packing density distribution along thickness.

2. Results and discussion

As fine particles deposit on the fibers, their collection efficiencies increase while the filter gradually becomes clogged. Filter collection efficiency depends not only on filtration condition and particle properties, but also on the filter properties, such as fiber diameter, packing density, packing structure.

To clearly demonstrate the intended effect, the value of C_i is deliberately set quite high while the electret fiber diameter, much larger than the conventional HEPA filter. As a result, the collection efficiency would drop as low as 96% on the number basis with respect to the 1 μm particles.

Fig. 2 compares the penetration through four different filter structures with the same average packing density. The penetrations of the four filters initially increase with dust load with filter A's raising the most rapidly. After a period of time, the penetration through all filters starts to gradually decrease and becomes zero upon clogging. In this calculation, all conditions except for the packing density distribution of fibers are equal. As expected, the maximum

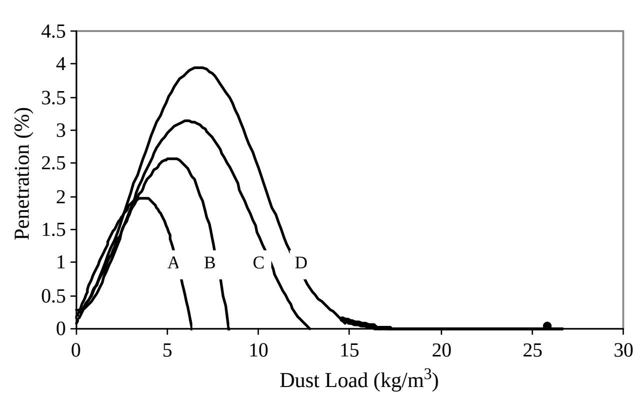

Fig. 2. Penetration of different electret fiber under loading condition.

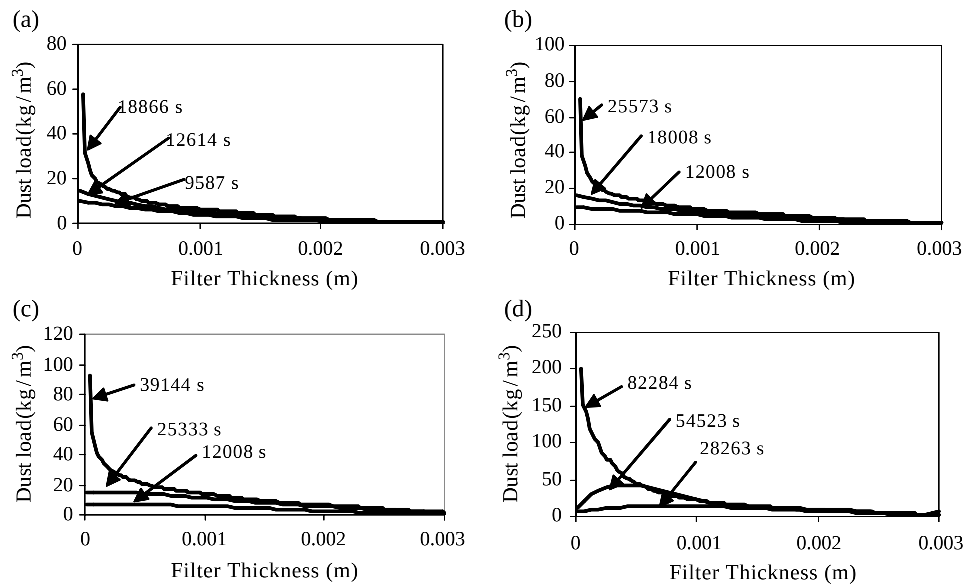

Fig. 3. Distribution of dust inside the four electret filters. (a) Filter A; (b) filter B; (c) filter C; (d) filter D.

penetrations and clogging points of four filters are different. At 4% the maximum penetration of filter D is two times higher than filter A, but the dust load at clogging point of filter D is about 4 times higher than filter A. Similarly, filter C shows a maximum penetration which is around 1.5 times of filter A, and the dust load at clogging point around 2 times of the case of filter A. For filter B, the maximum penetration is about 1.25 times of filter A, and the dust load at clogging point is 1.3 times of filter A. Obviously, we can lengthen the filter service life while maintaining sufficiently high aerosol collection efficiency at all times, for example by designing the filter structure as that of B, C or D.

Fig. 3 shows the distribution of mass deposited inside four filters. In Fig. 3(a), the maximum dust load always appears at $L=0$, the inlet side of the filter, and decreases steeply inside it. The front side of filter A will reach to clogging point of 60 kg/m^3 at 18,866 s or 314 min.

Similarly, in Fig. 3(b), the clogging time of filter B is around 25,573 s or 426 min. It shows about 1.4 times longer service life than filter A. In Fig. 3(c), the maximum dust loaded initially appears at $L=0$. After about 15,000 s, the maximum dust load of filter C slightly shifts back words. At 25,333 s, the maximum dust load appears at a filter depth of 0.0005, and then the maximum dust load starts to shift to the inlet side of filter. At the clogging point, the maximum dust load appears at the front end of the filter after 39,144 s, a service life about 2 times longer than filter A. Fig. 3(d) shows that the clogging time of filter D is around 82,284 s, about 4.3 times that of filter A.

3. Conclusion

The expensive electret filter cannot practically be cleaned and re-used. Therefore, it is vital to improve the filter service life. Our simulation results show that it is possible to significantly lengthen the filter service life by packing the filter loosely on the front side and progressively more densely towards the back side, while maintaining a sufficiently high aerosol collection efficiency at all times. To obtain the optimal filter packing density, it is necessary to know only the correlation between the collection efficiency of the fiber and the dust load. Once the fiber packing density in a filter has been selected, we can reasonably predict the collection efficiency (or penetration) as a function of overall dust load or filtration time as well as the clogging condition.

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