Filtration characteristics of a fibrous filter pretreated with anionic surfactants for monodisperse solid aerosols

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Abstract

This study elucidates the effects of using an anionic surfactant-pretreated filter as an electret filter on the aerosol penetration. Anionic surfactants (sodium oleate, SO; sodium dodecyl sulfate, SDS) were used to pretreat polypropylene fibrous filters to make them negatively charged. Various factors, including the particle size (0.05–0.5 μm), the aerosol charge state (Boltzmann-equilibrium charge, neutral and singly charge), the face velocity (0.1, 0.3, 0.5 and 1.0 m/s), the species of aerosol (sodium chloride, NaCl and aluminum oxide, Al_2O_3), the relative humidity (RH 30% and 70%) and the concentration of surfactant (0.01, 0.05 and 0.08 M) were considered to evaluate their effects on the aerosol collection characteristics.

Experimental results from our study demonstrate that the aerosol penetrations through anionic surfactant-pretreated filters (ASPFs) were lower than through the untreated filter. The 0.3 μm -aerosol penetrations through an untreated, 0.01, 0.05 and 0.08 M SO-pretreated filters with Boltzmann-equilibrium charged aerosol were about 78%, 53%, 45% and 40%. The penetration of 0.3- μm aerosol of 0.01, 0.05 and 0.08 M SDS-pretreated filters with Boltzmann-equilibrium charged aerosol were, 62%, 58% and 51%. Pretreating the filter with anionic surfactant did not change the structure of the filter and the mechanical capture force. The electric field measured by an electrofieldmeter of the ASPFs was larger than that of untreated filter obviously. These findings imply that pretreatment with anionic surfactant made the filters charged. The surface charge of the ASPFs increased with the anionic-surfactant concentration. The increase of the collection efficiency of the ASPFs is in the range of 5–30%, and that depends on the aerosol size and surfactant concentration. Comparing between the aerosol penetration through the ASPFs with singly charged aerosol and that through the untreated filter with neutral aerosol indicates that the penetration through the ASPFs with singly charged aerosol decreases by a factor of 1.3–12.5. In contrast with the penetration through the ASPFs to that through the untreated filter with neutral aerosol, the penetration reduction factor of the ASPFs is in the range of 1.1–1.9. As the results shown, the Coulombic capture force is dominant for the smaller aerosol ($< 0.1 \mu\text{m}$) and the

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dielectrophoretic capture mechanism works at larger aerosol size ($> 0.2 \mu\text{m}$). Additionally, the penetrations through the ASPFs increased with the face velocity. ASPFs performed better when the tested aerosol had a larger dielectric constant (k) such as the penetration through 0.05 M SO-pretreated filter with $0.3 \mu\text{m}$ Al_2O_3 aerosol ($k = 9.6$) was 47% and that with NaCl aerosol ($k = 5.9$) was about 53%. RH has no effect on the aerosol penetration through the ASPFs.

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Keywords: Aerosol penetration; Anionic surfactant-pretreated filter; Aerosol charge state; Dielectric constant; Relative humidity

1. Introduction

On an average, people spend as much as 87.2% of their time in indoor environment (Lance, 1996). Hence indoor air quality has become an increasing important problem. Indoor suspended particulates play an important role in indoor air quality because it causes many respiratory diseases. Therefore, more and more air-cleaning technologies have been used to remove the indoor particulates.

Air filtration is an effective technology for removing aerosols from a gas stream. Recently, electret filters have been extensively used in air filtration, since they have high filtration efficiency without increasing the pressure drop. The fibers in the filter are permanently charged, so electrostatic forces act between the charged fibers and the aerosol. The aerosol capture mechanisms of these filters depend on a combination of the electrostatic mechanisms (dielectrophoretic and Coulombic), as well as the conventional mechanisms, including impaction, interception, diffusion, and gravitationally settling. Normally, the efficiency of collection of an electret filter exceeds that of a conventional mechanical filter, especially for submicron aerosols.

The performance characteristics of electret filters have been widely studied (Baumgartner and Löffler, 1986; Lathrache and Fissan, 1987; Fjeld and Owens, 1988; Chen and Huang, 1998; AFFCO, 1998). Several researchers have examined the capture mechanisms of electret filters (Baumgartner and Löffler, 1986; Lathrache et al., 1986; Trottier and Brown, 1990; Romay et al., 1998) and some studies (Brown, 1981; Pich et al., 1987; Lathrache and Fissan, 1987; Kanaoka et al., 1987) have developed semi-empirical and theoretical expressions for dielectrophoretic and Coulombic single-fiber efficiencies to illustrate the performance of the electret filters. The Coulombic effect was dominant for the aerosol smaller than $0.1 \mu\text{m}$ and the dielectrophoretic effect was dominant when aerosol larger than $0.3 \mu\text{m}$ (Romay et al., 1998).

Various studies addressed the variation in the aerosol loading characteristics of electret filters with the operating time (Walsh and Stenhouse, 1997, 1998; Barrett and Rousseau, 1998; Ji et al., 2003). Walsh and Stenhouse (1997) examined that small particles accelerate filter clogging to rapidly reduce the filtration efficiency. Barrett and Rousseau (1998) showed that the solid aerosol would clog the pore of the electret filter and the deposited aerosol would reduce surface charge. The liquid aerosol would not clog the pore of the electret filter but coated over the surface of the charged fibers. That would directly decrease the surface charge and cause the collection efficiency degraded more quickly.

Numerous investigations have investigated the diversity of collection characteristics of the electret filter when filtering with various species of aerosol (Lehtimäki and Heononen, 1994; Ginestet and Pugnet, 1997). Ginestet and Pugnet (1997) found that the initial aerosol penetration of the electret filter for the solid aerosol is higher than that for liquid aerosol. Other works have demonstrated that increasing the relative humidity (RH) may reduce the collection efficiency of electret filters (Ackley, 1982; Moyer and

Nomenclature

a	fitted coefficient
b	fitted coefficient
c	fitted coefficient
C_c	Cunningham slip correction factor
d	fitted coefficient
d_f	mean fiber diameter
d_p	particle diameter
e	fitted coefficient
f	fitted coefficient
g	fitted coefficient
m	filter thickness
E	effective electric field (V/m)
E_c	single-fiber efficiency due to Coulombic force
E_m	single-fiber efficiency due to mechanical mechanism
E_o	single-fiber efficiency due to dielectrophoretic force
E_Σ	total single-fiber efficiency
k	dielectric constant
P	aerosol penetration
Q	filter fiber charge (coulomb/m)
r	fiber radius
U	face velocity
W	filter weight (kg/m^2)
Z_p	particle electrical mobility
α	fiber packing fraction
ϵ_0	permittivity of free space ($8.85 \times 10^{-12} \text{ coulomb}^2/\text{Nm}^2$)
μ	gas velocity ($1.81 \times 10^{-4} \text{ Pa/s}$)
ν	air viscosity
ρ_f	fiber density
Δp	pressure drop across the filter

Stevens, 1989). Ikezaki et al. (1995) and Łokis and Motyl (2001) also noted that the surface potential of an electret filter fell as the RH increased.

Typically, the electret filters are charged by three main processes, including corona charging, triboelectric charging and charging by induction (Brown, 1993). Some researchers have shown that a fibrous filter coupled with an external electrical field also yielded high collection efficiency and low pressure drop, similar to those of an electret filter (Luckner et al., 1994; Lee et al., 2001). This work aimed to generate an electrically charged filter by using ionic surfactant. Ionic surfactants are commonly employed to charge the discharged filter in a water filtration system, to remove charged particles or ions. Pontière et al. (1997) showed that adding ionic or neutral surfactants increased the surface charges on a membrane. Kang and Shah (1997) stated that a polypropylene membrane pretreated with dimethyl dioctadecyl ammonium

bromide has a positively charged surface, and so removes negatively charged particles. However, the surfactant-pretreatment process has not yet been applied to air filtration. The goal of this study was to develop an electrically charged filter by pretreatment with anionic surfactants. In this study, the aerosol penetration through the ASPFs was challenged with the Boltzmann-equilibrium charged aerosol, which was similar to the environmental aerosols. The total charge of the common environment aerosols was close to zero. When aerosols were at Boltzmann-equilibrium charge distribution, the aerosols included uncharged, negatively charged and positively charged aerosols and the aerosols have zero net charge. The total charge of the common environment aerosols was close to zero. Furthermore, the singly charged and neutral (uncharged) aerosols were used to investigate the electrostatic filtration mechanism. The effects of the RH and the dielectric constant of the aerosol on the aerosol penetration through the fibrous filter pretreated with anionic surfactant were also explored.

2. Filtration theory

2.1. Single-fiber efficiency

The theoretical aerosol penetration through a filter, in terms of the total single-fiber efficiency is (Hinds, 1982)

$$P = \exp\left(\frac{-4\alpha E_{\Sigma} m}{\pi d_f(1 - \alpha)}\right), \quad (1)$$

where P is the aerosol penetration through the filter; E_{Σ} is the total single-fiber efficiency; d_f is the mean fiber diameter; m is the thickness of the filter, and α is the fiber packing fraction. The total single-fiber efficiency of an electret filter is the sum of mechanical and electrostatic single-fiber efficiencies, given by the following expression.

$$E_{\Sigma} = 1 - (1 - E_m)(1 - E_o)(1 - E_c), \quad (2)$$

where E_m , E_o and E_c are the single-fiber efficiency due to the total mechanical, the dielectrophoretic and the Coulombic capture mechanism, respectively. The overall mechanical mechanism involves diffusion, interception, impaction and gravitational settling. The mechanical mechanisms of an electret filter are insignificant, so the total mechanical mechanism is used to represent the effect of all mechanical mechanisms. Eq. (2) assumes that all mechanisms are independent.

2.2. Quality factor

A good filter is one that provides the highest collection efficiency with the lowest pressure drop. A useful index for comprising the different filters with better performance is the quality factor, q_F , defined as (Hinds, 1982)

$$q_F = \frac{\ln(1/P)}{\Delta p}, \quad (3)$$

where P is the aerosol penetration, and Δp is the pressure drop across the filter. A larger q_F corresponds to a better filter. Values of q_F can be compared only when the face velocity and size of the test aerosol are held constant.

Table 1
Characteristics of original untreated and electret filters

Type	Fiber material	measured weight of filter (g/m ²)	Filter thickness (mm)	Mean fiber diameter ^a (μm)	Calculated packing fraction ^b
Untreated	Polypropylene	166.78	5.0	30.1	0.040
Electret	Polypropylene	61.0	1.0	17.6	0.068
0.01 M SO	Polypropylene/Sodium oleate	186.15	5.0	30.1	0.040
0.05 M SO	Polypropylene/Sodium oleate	199.89	5.0	30.2	0.041
0.08 M SO	Polypropylene/Sodium oleate	208.44	5.0	30.3	0.041
0.01 M SDS	Polypropylene/SDS	180.95	5.0	30.1	0.040
0.05 M SDS	Polypropylene/SDS	192.44	5.0	30.2	0.041
0.08 M SDS	Polypropylene/SDS	200.37	5.0	30.2	0.041

^aDiameter was measured by SEM experiments.

^bCalculated by the empirical model of Davies (1973).

Table 2
Properties of the anionic surfactants

Surfactant type	Chemical formula	Molecular weight	Hydrophile–lipophile balance (HBL)
Sodium oleate	C ₁₇ H ₃₃ COONa	304	18 ^a
Sodium dodecyl sulfate	C ₁₂ H ₂₅ NaO ₄ S	288	40 ^a

^aSchick (1987).

3. Materials and methods

3.1. Tested filters

Polypropylene fibrous filters were employed in this study. The characteristics of the polypropylene fibrous filters were presented in Table 1. Polypropylene filters were treated with the anionic surfactants, including sodium oleate (SO) and sodium dodecyl sulfate (SDS). These two surfactants have been widely applied in environmental engineering and they are nontoxic for human beings. Table 2 describes the basic properties of these two anionic surfactants. The weight of filters were measured by the electronic scale; the fiber diameter of the untreated and surfactant-pretreated filters was measured by the scanning electron micrograph (SEM) experiments; the filter thickness was measured by ruler; the packing fraction were calculated by the empirical model of Davies (1973),

$$\Delta p = \frac{vmUf(\alpha)}{r^2}, \quad (4)$$

$$f(\alpha) = 64\alpha^{1.5}(1 + 56\alpha^3), \quad (5)$$

where Δp is the pressure drop across the filter; v is the air viscosity; m is the filter thickness; U is the face velocity; r is the fiber radius, and α is the packing fraction.

Fig. 1. Schematic diagram of the experimental system.

Three concentrations (0.01, 0.05, 0.08 M) of two anionic surfactants solution, SO and SDS, were used. The surfactant solutions were prepared by dissolving surfactants in pure water. Then, the filters were soaked in the surfactant solution for 15 min and so became coated with the surfactants because the surfactants have one or several hydrocarbon chains that can hydrophobically bond to the surface of polypropylene (Kang and Shah, 1997). After they had been soaked, the filters were dried in an oven at 105 °C for 12 h. A manufactured electret filter was also used for comparison, to elucidate the performance of the ASPFs. Table 1 also presents the properties of the electret filter.

3.2. Aerosol generation system

Fig. 1 depicts the complete experimental setup. Sodium chloride (NaCl, dielectric constant, $k=5.9$) and aluminum oxide (Al_2O_3 , $k=9.6$) were employed as the test aerosols for various dielectric constants. These test aerosols were generated from a salt solution (NaCl) and a suspension of insoluble particles (Al_2O_3) by a Collision atomizer (model 3076, TSI Inc.). Then, the dried and neutralized polydisperse aerosol was electrically classified using a Differential Mobility Analyzer (DMA, model 3071, TSI Inc.), to obtain monodisperse singly charged aerosols in the submicron-sized range from 0.05 to 0.50 μm . The singly

charged particles were positively charged, because the inner electrical rod of the DMA was connected to a negative power supply and thus provided a precise negative potential that attracted positively charged particles. The aerosols from the DMA passed through a Kr-85 radioactive source (model 3077, TSI Inc.), which neutralized them to the Boltzmann-charge equilibrium. The aerosols from the Kr-85 passed through a homogenous electrostatic field, which removed all of the charged aerosols, leaving completely uncharged aerosols (neutral particle). An aerosol electrometer (model 3068, TSI Inc.) was used to monitor the neutralization of the charge of the aerosol.

3.3. RH control system

This study considered the effect of RH on the filtration characteristics. Two RHs were used in this work. The RH of the aerosol-flow stream was modified by changing the ratio of the flow rate of the dry gas stream to that of the humidified gas stream generated by the water vapor saturator. The final RH of the aerosol-flow stream was measured using a hygrometer (Hygromer A2, Rotronic Inc.). Two RH conditions for experiments were 30% and 70% that stood for dry and humid condition, respectively, in this study.

3.4. Measuring penetration of aerosol

The aerosol penetration through the pretreated and untreated filters was measured using two condensation particle counters (CPCs, model 3025, TSI Inc.), which measured the aerosol concentrations upstream and downstream of the filter holder. Each aerosol penetration test was performed in triplicate for each filter. The pressure drop across the tested filter was measured using a pressure gauge (Model 2000, Dwyer Instruments Inc). The face velocity through the tested filter was controlled using a flow meter and a pump. The testing face velocities ranged from 0.1 to 1.0 m/s and were applied to study the effects of the face velocity. Tests were performed at least in triplicate for each type of filter, face velocity, RH and species of aerosol. Fig. 1 schematically depicts the complete experimental setup.

3.5. Surface charge on the filter

This study examines the surface charge of the ASPFs. An electrofieldmeter (EFM 022, Wolfgang Warmbier Instruments Inc.) was used to measure the electric field (E) of the ASPFs. The distance between the sensor and the surface of the filter was maintained at 1 cm. The surface charge of the ASPFs contributed to the electric field (1 cm distance) on the surface of the filter. Ten pieces of the ASPFs in each pretreated concentration were used to measure the electrical field. The electric field at a distance r from a charged fiber that carries a uniform charge Q per unit length acts purely in the radial direction and has magnitude expressed as follows (Brown, 1993; Wang, 2001),

$$E = \frac{Q}{2\pi\epsilon_0 r}, \quad (6)$$

where Q represents the charge per unit length of the fiber; r is the distance from the fiber (1 cm) and ϵ_0 is the permittivity of free space. Accordingly, the charge on the filter is,

$$Q = 2\pi\epsilon_0 r E. \quad (7)$$

Fig. 2. Pressure drop of the tested filters versus face velocity.

4. Results and discussion

4.1. Preliminary experiments

Fig. 2 shows the pressure drop across the tested filters, including untreated filter, SO-pretreated filters, SDS-pretreated filters and manufactured electret filter, versus the sampling face velocity. The pressure drop increases with the face velocity, indicating that the airflow through the tested filters is laminar. As shown in Fig. 2, the pressure drop across the ASPFs pretreated with various concentrations slightly exceeds that across the untreated filter, but the difference is insignificant. The pressure drop across the filter has been known to be associated with its fiber diameter, its packing fraction and its filter thickness. Hence, the fiber diameter, the packing fraction and the thickness of the ASPFs are almost the same as those of the untreated filter as indicated in Table 1. These results agree with the fact that the anionic surfactants coat the fiber, forming thin surfactant membranes. The results also suggest that the mechanical filtration forces of a filter pretreated with anionic surfactants should be almost the same as those of untreated filter. The surfactant membrane does not significantly change the fiber diameter, the packing fraction and the fiber thickness. It does increase the weight of the ASPFs, so the surfactant membrane on the filter fiber increases the density of the filter fiber. The pressure drop across the ASPFs is lower than that of the manufactured electret filter according to the comparison of the pressure drops across the ASPFs and manufactured electret filter. At a face velocity of 0.1 m/s, the pressure drop across the ASPFs is approximately 5.75 Pa, whereas that across the electret filter is about 12.05 Pa.

4.2. Collection performance of anionic surfactant-pretreated filter

Fig. 3 plots the experimental results on aerosol penetration through the untreated filter and that pretreated with three different concentrations of SO for “Boltzmann equilibrium” NaCl aerosols. In each test, the face velocity was maintained at 10 cm/s. The penetrations of the 0.3 μm aerosol through 0.01, 0.05 and 0.08 M SO-pretreated filters, and through the untreated filter were 53%, 45%, 40% and 78% respectively. The penetrations through these three SO-pretreated filters were lower than that of the original untreated

Fig. 3. Aerosol penetration through SO-pretreated filters at different surfactant concentrations.

Fig. 4. Aerosol penetration through SDS-pretreated filters at different surfactant concentrations.

filter. Fig. 4 reveals similar results from the experiments on aerosol penetration through SDS-pretreated filter at three different concentrations. The penetration through the untreated filter was also higher than that through the three SDS-pretreated filters. These experimental results imply that some additional aerosol-capturing forces should be created when the filter is pretreated with the anionic surfactants. The aerosol-capturing forces between the “Boltzmann-equilibrium” aerosol and the uncharged fiber are only the mechanical capture force and weak electrostatic force (image force). The findings from our experiments indicate that pretreating a filter with SO or SDS anionic surfactant does not change the original mechanical capture force. Accordingly, the electrostatic forces should be the additional aerosol-capturing forces, suggesting that the uncharged filter would possible be charged when being pretreated with anionic surfactants. An electrofieldmeter was used to sample directly the electric filed on the surface of ASPFs to prove this assertion. The ASPFs that were just taken from the oven and conditioned at room temperature were selected for sampling. Table 3 presents the data of the electric field (E , measured at 1 cm from the filter fiber) of the untreated filter and ASPFs. According to Eq. (7), the surface charge

Table 3

Surface charge of the tested filters

Filter type	Electric field (V/m)	Surface charge (C/m)
Untreated	$-1.10 \pm 0.10 \times 10^2$	-6.12×10^{-12}
0.01 M SO	$-5.50 \pm 0.60 \times 10^3$	-3.06×10^{-9}
0.05 M SO	$-9.72 \pm 0.51 \times 10^3$	-5.15×10^{-9}
0.08 M SO	$-1.22 \pm 0.03 \times 10^4$	-6.23×10^{-9}
0.01 M SDS	$-2.51 \pm 0.52 \times 10^3$	-1.39×10^{-9}
0.05 M SDS	$-4.83 \pm 0.74 \times 10^3$	-2.67×10^{-9}
0.08 M SDS	$-6.13 \pm 0.81 \times 10^3$	-3.39×10^{-9}
Electret	$1.54 \pm 0.33 \times 10^4$	8.33×10^{-9}

(Q , C/m) can also be derived from the electric field. The results indicated that the surface charge of the untreated filter is -6.12×10^{-12} C/m, and those of the filters pretreated with 0.01, 0.05 and 0.08 M SO, and 0.01, 0.05 and 0.08 M SDS are about -3.06×10^{-9} , -5.15×10^{-9} , -6.23×10^{-9} , -1.39×10^{-9} , -2.67×10^{-9} , and -3.39×10^{-9} C/m, respectively. These data reveal that pretreatment with anionic surfactant increases the surface charge of the filter. In other words, the filters become negatively charged by being treating with the anionic surfactant because the polypropylene fiber may be bonded with the carbon-chain group ion of the surfactant. Anionic surfactant molecules (SO or SDS) dissociate in water to form carbon-chain group ions ($C_{17}H_{33}COO^-$ or $C_{12}H_{25}O_4S^-$) and the complementary ions (Na^+). When an untreated filter is immersed in a surfactant solution, the carbon-chain group ion interacts with the polypropylene fiber. The bonding force between the polypropylene fiber and the carbon-chain group ion exceeds that between the carbon-chain group ion and its original complementary ion. Hence, when the filters were removed from the surfactant solution, some of the surfactant molecules that coated on the filter are only negative carbon-chain group ions, which charge the filter negatively.

Figs. 3 and 4 also show that aerosol penetration through ASPFs declines as the surfactant concentration increases. The sampling of surface charge reveals that the surface charge of the ASPFs increases with the concentration of surfactant. These results indicate that the ASPF had a larger charge when the filter was pretreated with surfactant at a higher concentration. This is due to the number of carbon-chain-group ions that coat the filter increases with the concentration of surfactant. The surface charge of the SO-pretreated filter exceeds that the SDS-pretreated filter given the same pretreatment concentration. For instance, the surface charges of the 0.05 M SO and SDS-pretreated filters are -5.15×10^{-9} and -2.67×10^{-9} C/m. The anionic surfactant charges the filter probably because of the negatively carbon-chain-group ions. Accordingly, the surface charge of the SO-pretreated filter exceeds that on the SDS-pretreated filter because more negatively carbon-chain-group ions are present on the surface of the SO-pretreated filter than on the surface of the SDS-pretreated filter, since the hydrophile–lipophile balance (HLB) of SO (18) is smaller than that of SDS (40). The HLB value evaluates the balance between the hydrophilic and lipophilic characteristics of the anionic surfactant. A surfactant with a higher HLB is more hydrophilic, and one with a lower HLB is more lipophilic (hydrophobic). The force between the polypropylene fiber and the carbon-chain group is the hydrophobic force. The HLB of SO is smaller than that of SDS, so the hydrophobic force between SO and polypropylene fiber is stronger; therefore more carbon-chain-group ions are present on the SO-pretreated filter.

Fig. 5. Aerosol penetration through manufactured electret filter versus aerosol size.

This study seeks to further elucidate the performance of ASPFs, so an electret filter is used for comparison. As revealed in Table 3, the surface charge of the electret filter is approximately 8.33×10^{-9} C/m. According to the experimental results, the surface charge of the electret filter is higher than that of the six ASPFs. Only the 0.08 M SO-pretreated filter has a surface charge (-6.23×10^{-9} C/m) that is close to that of the electret filter. Consequently, the surface charge of the ASPFs increases with the concentration used in the pretreatment. Hence, if the filter pretreated with a higher concentration, the surface charge of the ASPF could probably reach the charge-level of the manufactured electret filter. Fig. 5 plots the aerosol penetration through the manufactured electret filter against the aerosol size at a face velocity of 0.1 m/s. The results demonstrate that the penetration of the 0.3-μm aerosol of manufactured electret filter is about 22%, which is smaller than that of any ASPFs. However, a good filter does not only perform high collection efficiency but also low pressure drop. Eq. (3) shows that the value of aerosol penetration and pressure drop are combined in the quality factor (q_F) that the value of q_F could be used as a good indicator for comprising the performance of filter in considering the pressure drop and aerosol penetration in the same time. Figs. 6a and b plot the q_F of the ASPFs and the electret versus the size of the aerosol at a face velocity of 0.1 m/s. The experimental results reveal that only the 0.08 M SO-pretreated filter has a larger q_F than the electret filter at the whole range of aerosol sizes investigated and all other pretreated filters perform the better q_F s than electret within ultrafine aerosols (smaller than 0.1 μm). Although the aerosol penetration through ASPFs is higher than that through electret filter, the pressure drop across the ASPFs is lower than that across the electret filter, so the q_F of the ASPFs still exceeds the electret. Except the 0.08 M SO-pretreated filter, all other ASPFs perform higher q_F s in the ultrafine aerosol range, while the electret filter has the largest q_F when the aerosol is larger than 0.1 μm. It is suggested that the surface charge of the manufactured electret filter is higher than the ASPFs. The capture force, dielectrophoretic force, between the charged fiber and the neutral particle is significant when the aerosol is larger than 0.1 μm.

4.3. Charge stability of filter pretreated with anionic surfactant

The charge stability is an important index of the performance of an electret filter. Hence, the dried ASPFs were stored under atmospheric conditions for 60 days and the electric field was measured. After 60 days

Fig. 6. Quality factor of the tested filters versus aerosol size (a) SO-pretreated filters and electret filter and (b) SDS pretreated filters and electret filter.

of sampling, the electric fields of the 0.01, 0.05 and 0.08 M SO-pretreated filters were approximately $-5.46 \pm 0.57 \times 10^3$, $-9.62 \pm 0.39 \times 10^3$ and $-1.18 \pm 0.06 \times 10^4$ V/m, respectively. Over 60 days, the electric fields of the filters treated with the three concentrations of SO were almost identical. SDS-pretreated filters were observed to exhibit similar behavior. The electric fields of the 0.01, 0.05 and 0.08 M SDS-pretreated filters after 60 days were around $-2.34 \pm 0.39 \times 10^3$, $-4.69 \pm 0.58 \times 10^3$ and $-6.02 \pm 0.49 \times 10^3$ V/m, respectively. The variations of the electric fields of the filters treated with the three different concentrations of SO over 60 days of testing were very small. These experimental results reveal that the electric fields of the ASPFs are almost the same when placed under the atmospheric conditions over a period of 60 days. Therefore, the charge on the fibers of ASPFs is quite stable.

4.4. Effect of aerosol charge on aerosol penetration

For elucidating the Coulombic and dielectrophoretic capture mechanism, the negatively charged ASPFs were tested with the singly charged (positive) and neutral aerosols to compare with the result of the untreated filter tested with neutral aerosol. Fig. 7 plots the aerosol penetration through the 0.08 M SO-pretreated filter with singly charged and neutral NaCl aerosols, and that through the untreated filter with neutral aerosol at a face velocity of 10 cm/s. The aerosol penetration of the 0.08 M SDS-pretreated filter tested with singly charged and neutral NaCl aerosols, and that of the untreated filter with neutral aerosol at a face velocity of 10 cm/s was also shown in Fig. 8. In each figure, there are two curves for singly charged and neutral aerosol with ASPFs (curves 1 and 2) and one curve for neutral aerosol with untreated filters (curve 3).

In comparison with curves 1 and 3, the aerosol penetration through the 0.08 M SO- and SDS-pretreated filters with singly charged aerosol is much lower than that through the untreated filter with neutral aerosol, that indicating the Coulombic capture mechanism dominates the performance of these two charged ASPFs. This phenomenon could also be found on other ASPFs. Aerosol penetration through the untreated filter with neutral aerosol is in the range of 44–77%. For the 0.01, 0.05 and 0.08 M SO-pretreated filter, the overall penetrations reduce by a factor ($\text{penetration}_{\text{curve 3}}/\text{penetration}_{\text{curve 1}}$) of 1.4–3.9, 1.6–7.5 and 1.8–12.5, respectively. Similarly, the overall penetrations of the 0.01, 0.05 and 0.08 M SDS pretreated

Fig. 7. Filtration characteristics of the 0.08 M SO-pretreated filters.

Fig. 8. Filtration characteristics of the 0.08 M SDS-pretreated filters.

filter decrease by the reduction factor of 1.3–3.1, 1.3–3.3 and 1.5–5.3. These results indicate that the reduction of the penetration of the each type surfactant (SO and SDS)-pretreated filters increases with the pretreated surfactant concentration. In other words, the Coulombic effect becomes stronger with the pretreated surfactant concentration. As the results shown in Table 3, when the filter was pretreated with higher surfactant concentration, the pretreated filter had the higher surface charge. It is the main reason that has the stronger Coulombic effect works on the filter pretreated with higher surfactant concentration. From the results shown in Figs. 7 and 8, the most penetrating aerosol size of curve 1 is about 0.3 μm and that of curve 3 is also 0.3 μm . The results also show that the aerosol penetration through the charged ASPFs is very low at aerosol size smaller than 0.1 μm , but increases rapidly with aerosol size. For the 0.08 M SO-pretreated filter, the penetration reduction factor of the 0.05, 0.10, 0.20 and 0.30 μm singly charged aerosols were 12.5, 2.4, 1.8 and 2.0. These data indicate that the Coulombic effect is significant for the smaller aerosol and becomes weaker as the aerosol size increases, which are consistent with

Fig. 9. Aerosol penetration through 0.05 M SO-pretreated filter versus aerosol size for different face velocity.

those of Kanaoka et al. (1987) and Romay et al. (1998). From the results also reveal that the maximum penetration reduction factor is shown at the smallest aerosol size ($0.05\ \mu\text{m}$), and the penetration reduction factor decreases sharply with the aerosol size. When the ASPF has the higher surface charge, the maximum penetration reduction factor is larger and the tendency of the sharply decrease of the penetration reduction factor is more obvious.

When comparing the curves 2 and 3, the aerosol penetration through 0.08 M SO- and SDS-pretreated filters with neutral aerosol is lower than that through the untreated filter with neutral aerosol, that revealing the dielectrophoretic mechanism works on these two charged ASPFs. The tendency could be observed when testing with other ASPFs. For the 0.01, 0.05 and 0.08 M SO-pretreated filter, the overall penetrations reduce by a factor ($\text{penetration}_{\text{curve 3}}/\text{penetration}_{\text{curve 2}}$) of 1.2–1.5, 1.3–1.7 and 1.5–1.9, respectively. Similarly, the overall penetrations of the 0.01, 0.05 and 0.08 M SDS-pretreated filter decrease by the reduction factor of 1.1–1.2, 1.2–1.3 and 1.2–1.6. The results also indicate that the reduction of the penetration of each type surfactant (SO and SDS)-pretreated filters increases with the pretreated surfactant concentration. The dielectrophoretic effect works stronger with the pretreated surfactant concentration. From the results shown in Figs. 7 and 8, the most penetrating aerosol size of curve 2 is about $0.2\ \mu\text{m}$, which is smaller than that of curve 3 ($0.3\ \mu\text{m}$). The results also indicate the difference between these two curves increases with the aerosol size and become larger as the aerosol size increases above $0.2\ \mu\text{m}$. For instance, the reduction factor ($\text{penetration}_{\text{curve 3}}/\text{penetration}_{\text{curve 2}}$) for 0.08 M SO-pretreated filter of the 0.05, 0.10, 0.20 and $0.30\ \mu\text{m}$ neutral aerosol were 1.5, 1.5, 1.6 and 1.9. It is indicating that the dielectrophoretic force acts at larger aerosol size ($> 0.2\ \mu\text{m}$) and dominates increasingly as the aerosol size increases. Comparing with the curves 1 and 2 from Figs. 7 and 8 the difference decreases with the aerosol size. These results also reveal that the Coulombic effect is dominant for the smaller aerosol and the dielectrophoretic force works at larger aerosol size.

4.5. Effect of face velocity on aerosol penetration

Fig. 9 depicts aerosol penetration against aerosol size for the neutral NaCl aerosol at various face velocities (0.1, 0.3, 0.5 and $1.0\ \text{m/s}$), through the 0.05 M SO-pretreated filter. Fig. 9 reveals an increase

Fig. 10. Aerosol penetration through the 0.05 M SO-pretreated filter against NaCl and Al₂O₃ aerosol.

in the penetration of 0.3 μm-aerosol through the SO-pretreated filter from approximately 47% to 77% as the face velocity increases from 0.1 to 1.0 m/s. The SDS-pretreated filter also has the same tendency. The 0.3 μm-aerosol penetrations through the SO-pretreated filter increase from 60% to 88%, as face velocity increases from 0.1 to 1.0 m/s, indicating that the aerosol penetration through the ASPFs increases with the face velocity from 0.1 to 1.0 m/s. This results follows from the fact that the principal mechanisms by which the submicron-size aerosol are filtered through the charged filter are electrostatic attraction and diffusion. A higher face velocity leads to a shorter residence time associated with aerosol deposition by electrostatic attraction and diffusion. The data are consistent with the results from previous studies by Kanaoka et al. (1987) and Chen and Huang (1998).

4.6. Effect of dielectric constant of aerosol on aerosol penetration

Fig. 10 plots the aerosol penetration through 0.05 M SO-pretreated filters versus aerosol size for neutral NaCl ($k = 5.9$) and Al₂O₃ ($k = 9.2$) particles. The results reveal that the aerosol penetration challenged with Al₂O₃ particles exceeds that challenged with NaCl particles. For instance, the penetration of 0.3-μm particles through 0.05 M SO-pretreated filters is 53% with NaCl particles and 47% with Al₂O₃ particles. Similarly, the aerosol penetration through 0.05 M SDS-pretreated filter against Al₂O₃ particles exceeds that against NaCl particles. These experimental results demonstrate that the penetration through ASPF declines as the dielectric constant of the aerosol increases. The principal electrostatic capture force between the ASPFs and neutral the aerosol is dielectrophoretic. The dielectrophoretic capture mechanism is that the charged fibers would polarize the neutral aerosols to cause the attraction between fibers and aerosols. Therefore, an aerosol with a higher dielectric constant can be more easily polarized by the charged fiber of the filter.

4.7. Effect of RH on aerosol penetration

Fig. 11 plots the aerosol penetration through the 0.05 M SO-pretreated filter versus aerosol size at two values of RH (30% and 70%). The experimental findings reveal that the aerosol penetration through the

Fig. 11. Aerosol penetration through 0.05 M SO-pretreated filter at different relative humidity.

0.05 M SO-pretreated filter is almost the same at RH 30% and 70%. Similarly, the aerosol penetrations through the 0.05 M SDS-pretreated filter at two RH are nearly identical. These results are not consistent with those published elsewhere (Ackley, 1982; Moyer and Stevens, 1989), in which the aerosol penetration through the electret filter increased as RH increased. The surface charge reduced as the humidity increased (Ikezaki et al., 1995; Lokis and Motyl, 2001). Those electret filters were charged by corona charging or triboelectric charging. Those processes would give a lot of ions or electrons on the fibers to make them become charged. The ions and electrons on the fibers are probably reduced by the water molecules easily, causing the surface charge decreased with the increasing RH. However, in this work, the ASPFs were charged by coating with the negatively carbon-chain-group ions, which were covered on the fiber surface stronger. Therefore, the surface charge of the ASPFs is not affected by the water molecules. This is probably the reason that the aerosol penetrations through the ASPFs were nearly the same at different RHs.

4.8. Comparison of the effect of different parameters on aerosol penetration

A regression equation was used to understand the effects of different parameters on aerosol penetration. The aerosol penetration would nearly not be affected by the different RHs. Thus, the RH would not be regressed in the equation. The regression equation considered the most relevant parameters, including aerosol size (0.05–0.5 μm), electric field of the ASPF (-2.51×10^3 to -1.22×10^4 V/m), face velocity (0.1 to 1.0 m/s), dielectric constant of aerosol (5.9 and 9.2), and aerosol charge (0 and 1). The experimental results can be fitted to the following equation:

$$P = ad_p^b E^c U^d k^e (f + n)^g, \quad (8)$$

where a , b , c , d , e , f and g are constants, P is aerosol penetration, d_p is the aerosol size, E is the electric field of the ASPF, U is the face velocity, k is the dielectric constant of aerosol, and n is the aerosol charge. Since n is either zero or one, $(f + n)$ was used to take the place of (n) . According to the regression analysis, the regression equation is shown as follows:

$$P = 1.35d_p^{0.17} E^{-0.12} U^{0.23} k^{-0.11} (1.32 + n)^{-0.42}. \quad (9)$$

As the results of regression analysis, the correlation coefficients R^2 is about 0.79. Comparison of the coefficients of b , c , d , e , and g , we can find the effects of different parameters on aerosol penetration. The result shows that the largest value is g , indicating the influence of the aerosol charge on aerosol penetration is the highest. The second value of the coefficient is d , and the following values are b , c , and e in sequence. Thus, the effect of face velocity on aerosol penetration is the second, and the following parameters are aerosol size and electric field of the ASPF. The effect of the dielectric constant of aerosol on penetration is the lowest.

5. Conclusions

The experimental results showed that aerosol penetrations through ASPFs were lower than through the untreated filter with Boltzmann-equilibrium charged aerosol. The 0.3 μm -aerosol penetrations through an untreated, 0.01, 0.05 and 0.08 M SO-pretreated filters were about 78%, 53%, 45% and 40%. The penetration of 0.3- μm aerosol of 0.01, 0.05 and 0.08 M SDS-pretreated filters were, 62%, 58% and 51%. The overall collection efficiency of the ASPFs is much higher than that of untreated filter, depending on aerosol size and surfactant concentration. The pretreatment of the filter with anionic surfactants did not change the structure of the filter and the mechanical capture force. As the results of the surface charge sampling, the surface charge of the ASPFs is much larger than that of untreated filter. These findings revealed that pretreatment with anionic surfactants, SO and SDS, charged uncharged filters. The penetration and surface data also indicated that the surface charge of the ASPFs increased with the concentration of surfactant used in the pretreatment and the SO-pretreated filter has a higher surface charge than the SDS-pretreated filter in the same pretreating surfactant concentration.

Comparing between the aerosol penetration through the ASPFs with singly charged aerosol and that through the untreated filter with neutral aerosol, the penetration of the ASPFs with singly charged aerosol decreases by a factor of 1.3–12.5. For the 0.08 M SO-pretreated filter, the reduction factor of the 0.05, 0.10, 0.20 and 0.30 μm singly charged aerosol were 12.5, 2.4, 1.8 and 2.0, indicating that the Coulombic effect is significant for the smaller aerosol and becomes weaker as the aerosol size increases. In contrast with the penetration through the ASPFs to that through the untreated filter with neutral aerosol, the penetration reduction factor of the ASPFs is in the range of 1.1–1.9. The reduction factor for 0.08 M SO-pretreated filter of the 0.05, 0.10, 0.20 and 0.30 μm neutral aerosol were 1.5, 1.5, 1.6 and 1.9. It is indicating that the dielectrophoretic force acts at larger aerosol size ($> 0.2 \mu\text{m}$) and dominates increasingly as the aerosol size increases. Therefore, the Coulombic capture force is dominant for the smaller aerosol ($< 0.1 \mu\text{m}$) and the dielectrophoretic capture mechanism works at larger aerosol size.

The aerosol penetration through the ASPFs increases with the face velocity, because the short retention time for aerosol deposition by electrostatic capture and diffusion in the submicron region. The aerosol penetration through ASPFs decline as the aerosol dielectric constant increases, because the principal electrostatic capture force between the ASPFs and the neutral aerosol is dielectrophoretic; the aerosol with a higher dielectric constant is more easily polarized by the charged fibers of the filter. RH does not affect the performance of the ASPFs.

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