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Filtration of Submicron Aerosol Particles Using a Carbon Fiber Ionizer-assisted Electret Filter

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ABSTRACT

The effects of a carbon fiber ionizer on the collection efficiency of an electret filter for residential house ventilation were investigated with varying the face velocity, the number of ionizers, and the polarity of the ionizer. A Flimmer filter, which was made by a Swedish company, was used as the electret filter. The air ion concentration upstream of the filter gradually increased as the velocity increased. Under the same conditions of velocity and the same number of ionizers, the positive ion concentrations were slightly higher than the negative ones. The ion concentration at any location away from the ion source was only slightly affected by the number of ionizers. When ionizers were used in front of the Flimmer filter, the collection efficiencies for submicron particles increased by 10 to 25%. When positive ionizers were used, the collection efficiencies were 10 to 15% higher than with the negative ionizers. The increase in collection efficiency occurred because most of the generated air ions were captured on the surface of the electret filter fibers, thereby increasing the electrostatic potential inside the electret filter.

Keywords: Air ion; Carbon fiber ionizer; Collection efficiency; Electret filter; Submicron particle.

INTRODUCTION

Electret filters are deep-bed fibrous filters used in air filtration. They are composed of high porosity coarse fibers that allow for low flow resistance. Since the fibers are charged, electrical forces act between the fibers and any particles (Emi *et al*., 1987). The particle capture characteristics of electret filters rely on a combination of conventional mechanical mechanisms (i.e. impaction, interception, and diffusion) and electrostatic mechanisms. In general, the collection efficiency of an electret filter is higher than that of a conventional fibrous filter, particularly for submicron-sized particles. Many studies have been conducted in order to identify the characteristics of electret filter media. Romay *et al*. (1998) presented experimental data on the performance of three types of commercially available fibrous electret filters. Kim *et al*. (2007) studied nanoparticle penetration through commercial electret filter media. Podgórski and Bałazy (2008) proposed a numerical method for determining deposition efficiency for naturally charged submicron particles within bipolar charged fibrous filters. Ji *et al*. (2003) studied the effect of particle loading on the collection performance of an electret cabin air filter; they showed that the collection efficiency of the electret filter media degraded as more particles were loaded, and reached minimum efficiency at steady state. This degradation with operating time is a potential drawback of existing electret filter technology.

Recently, Noh *et al*. (2011) investigated the submicron-sized aerosol filtration and pressure drop of an electret filter (Flimmer filter), which was developed by a Swedish company for particle removal in natural ventilation systems. They showed that the pressure drop of a Flimmer filter was lower than that of a conventional mechanical filter having the same collection efficiency. Li and Jo (2010) reported that the filtration quality of a Flimmer filter was higher than that of a mechanical or a general panel-type electret one for a mechanical ventilation and air conditioning system in a subway station. However, they pointed out that the unstable collection efficiency for particles larger than 1 μm and the increase in penetration with time were the main disadvantages of a Flimmer filter. It has been reported that the collection efficiencies of Flimmer filters for particles smaller than 1 μm are not higher than those of other electret filters (Battelle Columbus Operations, 2008)

Recently, ionizer-assisted fibrous filter media have been designed to increase the removal efficiency of aerosol

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particles (Han, *et al*., 2008; Park, *et al*., 2009; Park, *et al*., 2011). Ionizers were operated by applying a few kilovolts to a bundle of carbon fibers to increase the collection efficiency of a filter without affecting the pressure drop. The ionizers produced stable unipolar ions in sufficiently high concentrations without generating particles and ozone. Thus, they have been considered for use in indoor air purifiers to generate air ions as an alternative to corona discharge. Park *et al*. (2009) installed carbon fiber ionizers in front of a fibrous medium filter to enhance the removal of submicron particles and bioaerosols. Han *et al*. (2008) examined the penetration and the charging efficiency of fine and ultra-fine particles using a brush-type ionizer with a bundle of micron-sized carbon fibers. Park *et al*. (2011) tested the increase in particle filtration with a pair of carbon fiber ionizers installed upstream of a glass fiber air filter. Lee *et al*. (2004, 2005) used facepiece respirator filters and continuous emission of unipolar air ions by corona-ionizing air purifiers in the vicinity of a disposable half-mask respirator enhanced its protection characteristics against fine and ultrafine particles of bacterial and viral size ranges. Agranovski *et al*. (2006) used low efficiency heating, ventilating, and air conditioning (HVAC) air filters. Huang *et al.* (2008) examined the effect of ion-induced enhancement on the filtration of an HVAC filter with biological aerosols, including aerosolized bacterial cells, bacterial and fungal spores, and viruses. Park *et al*. (2010) reported the effect of a carbon fiber ionizer-assisted cabin air filter on $PM_{2.5}$ reduction. They showed that a carbon fiber ionizer installed in front of an electret cabin air filter increased the $PM_{2.5}$ reduction by 20–21%. Kim *et al.* (2010) developed a novel Electrostatic Precipitator (ESP) that uses an anticorrosive carbon brush ionizer as a precharger, and plastic collection plates. Their experimental results showed that high collection efficiency and a low pressure drop in the ESP can be obtained by generating a large quantity of unipolar ions and producing negligible concentrations of ozone. Robert and Timothy (1988) experimentally studied to identify collection mechanism of 0.5 μm-sized particles in electret filter media and determined the effect of particle charging on penetration. Shuie *et al.* (2011) investigated effect of negative air ion on particles concentration in a test chamber and showed that continuous emission of negative air ions can efficiently control ultrafine aerosol pollutants in cleanrooms.

In this study, the effects of a carbon fiber ionizer on the collection efficiency of a Flimmer filter were investigated with varying parameters of face velocity, the number of ionizers, and the polarity of the ionizer. By measuring the concentrations of particles and ions upstream and downstream of the filter, the main mechanism for increasing the collection efficiency with air ions was determined.

EXPERMENTAL

Electret Filter and Carbon Fiber Ionizer

A Flimmer filter is composed of electrically-charged polypropylene fibers (10–90 μm in diameter). These fibers are mostly dispersed toward the airflow direction, in contrast to a conventional fibrous filter or a conventional electret filter. The detailed structure of a Flimmer filter was introduced in our previous research (Noh *et al.*, 2011).

The carbon fiber ionizers were positioned 0.34 m upstream of the test filter as shown in Fig. 1. The diameter of the test duct was 0.1 m. We used 1, 2, 3, and 4 ionizers. Each ionizer consisted of an ion emission tip and a power pack. The ion emission tip consisted of a bundle of 300 ± 50 carbon fibers. The diameter of each carbon fiber was approximately 5–10 μm. The input voltage and frequency of the power pack were 220 V alternating current (AC) and 60 Hz, respectively. The output voltage was measured using a high voltage probe (6015A, Tektronix), an oscilloscope (6050A, LeCroy Corp), and a 10^7 Ω resistor. The output voltage had a saw tooth waveform, and its peak-to-peak value was about 2.8 kV regardless of its polarity. Figs. 2(a) and (b) show the waveforms of the positive input and negative output voltages, respectively.

Ion and Ozone Concentration Measurements

When the carbon fiber ionizer was turned on, ozone and positive or negative ions were generated. Using an ion counter (Air ion counter, AlphaLab, Inc., USA), gaseous ion concentrations were measured at sampling ports 1 and 2, as shown in Fig. 3. The ion counter measures up to 1.999×10^8 ions/cm^3 and the accuracy is ± 25% of the reading. Also, an O_3 monitor (OZ 2000G, SERES, France) was used to monitor O_3 at sampling port 2. The detection range of the O_3 monitor is 0.5–10,000 ppb and the precision is 0.5 ppb. All tests were carried out at the same output voltage. The total power consumption was less than 1 W.

Particle Filtration Test

A schematic of the experimental system used to test the

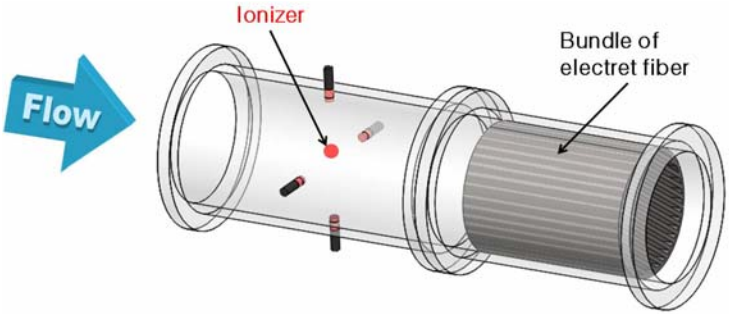
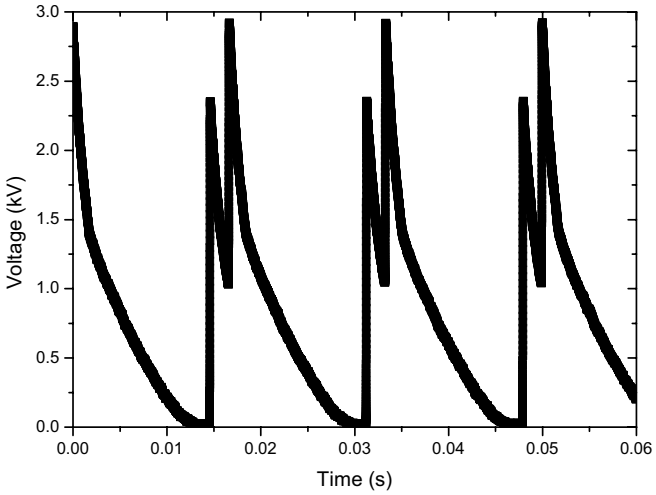
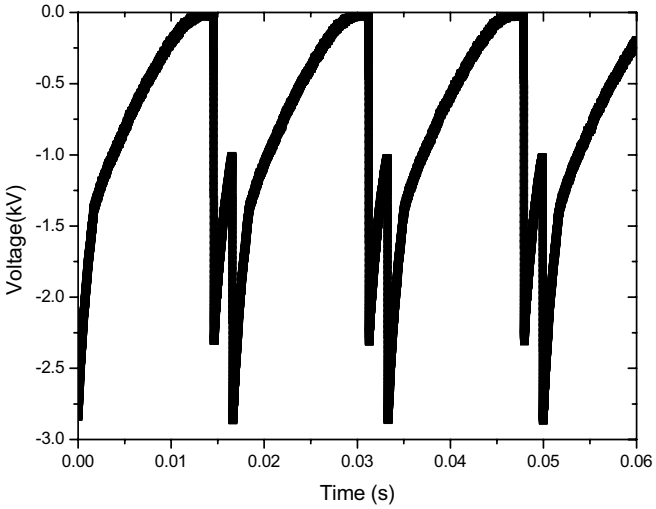


Fig. 1. Arrangement of carbon fiber ionizers and an electet filter.



(a) Positive



(b) Negative.

Fig. 2. Voltage patterns induced in ionizers.

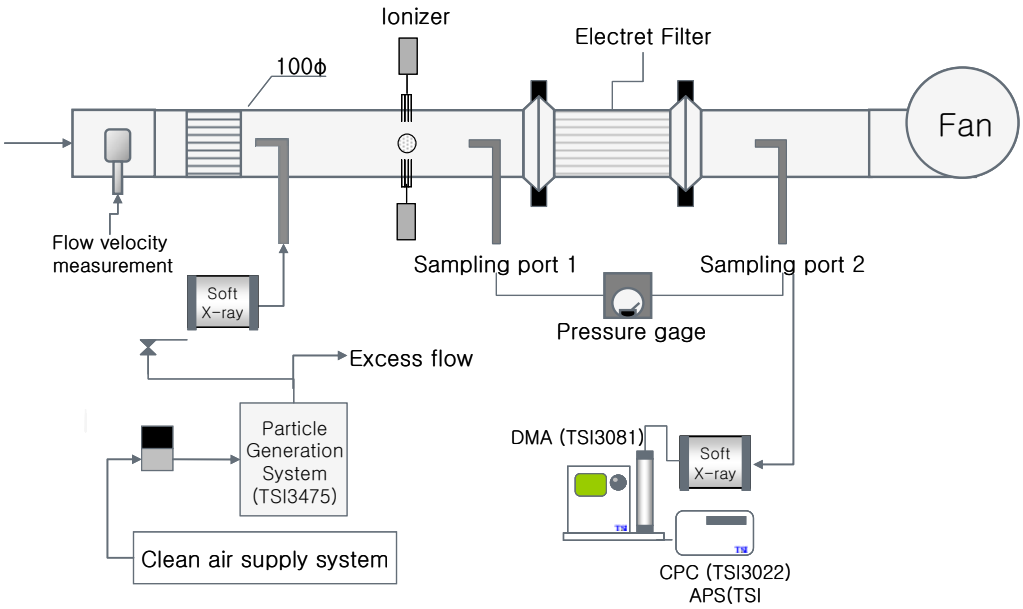


Fig. 3. Schematic of the experimental system for testing the performance of a Flimmer filter with carbon fiber ionizers.

performance of aerosol particle removal is shown in Fig. 3. The lab-scale test system consisted of a particle generation system, a test duct, and a measurement system. Diethylhexyl sebacate (DEHS) particles with nuclei of sodium chloride (NaCl) were used as test particles. The test particles were generated using a condensation monodisperse aerosol generator (CMAG, model 3475, TSI Inc., USA). Using nitrogen as the carrier gas, an atomizer inside the CMAG produced spray from a low concentration aqueous solution of sodium chloride. The droplets passed through a drying column where they were dried to form a high concentration nuclei aerosol. The condensation nuclei travelled to a thermostatically-controlled saturator vessel and bubbled through low volatility DEHS. The carrier gas, nuclei, and vaporized substance moved from the saturator into a reheater unit. The reheater was used to ensure that the aerosol material was completely vaporized. From the reheater unit, the nuclei and vapor moved into an air-cooled condensation chimney. Here, once a preset supersaturation level was reached, the controlled heterogeneous condensation process began, resulting in highly monodisperse aerosol particles. The test particles from the CMAG then entered a charge neutralizer (Soft X-ray charger 4530, HCT Co., Ltd., Korea) to realize a Boltzmann charge distribution using soft X-ray photoionization. A steady state concentration of test particles was supplied to the test duct. The test duct was made of acryl, and its outer diameter and length were 0.1 m and 1 m, respectively. Clean air was delivered to the test duct and mixed with the particle-laden air flow. The filter was installed in the middle of the test duct. Two isokinetic sampling probes made of 6.5 mm (in diameter) stainless steel were located upstream (sampling port 1) and downstream (sampling port 2) of the filter to measure aerosol concentrations. The longitudinal distance between the ionizers and sampling port 1 was 0.27 m. The desired concentrations of test particles were controlled using a laminar flow meter (LFM).

The face velocities upstream of the filter were controlled using a fan controller and measured with a flow anemometer (model AVM07, PROVA). The flow anemometer has a detection range of 0–45 m/s with an accuracy of ± 3%. The velocities were set to 0.5, 1.0, 1.5, and 2.0 m/s since the normal operating condition used in a mechanical ventilation system housing is 1.0 to 1.5 m/s. The pressure drop across the electret filter was monitored using a multi-function measuring instrument with an accuracy of ± 2% of 250 Pa (2001MV, DWYER Instrument). The particle concentrations were measured with a scanning mobility particle sizer (SMPS) (model 3936, TSI). The SMPS consisted of a classifier controller (model 3080, TSI), differential mobility analyzer (DMA) (model 3081, TSI), condensation particle counter (CPC) (3022A, TSI), and a neutralizer (Soft X-ray charger 4530, HTC) with a sampling airflow rate of 0.3 L/min. The SMPS measured particles from 14.6 to 763.5 nm with a mobility equivalent diameter. Fig. 4 shows the size distribution of the test particles measured at sampling port 1 for a filter face velocity of 0.5 m/s. The total particle concentration was about 2×10^4 #/cm^3. As the velocity increased, the concentration of the test particles gradually decreased since the concentration was diluted by an increased amount of clean air. The size distribution changed only slightly when the ionizers were turned on.

The fractional particle collection efficiency $\eta(d_p)$ of the filter, based on particle number concentration, is defined as

$$\eta(d_p) = 1 - \frac{C_{down}(d_p)}{C_{up}(d_p)} \tag{1}$$

where C_{up} and C_{down} represent the aerosol number concentrations measured upstream and downstream of the filter, respectively, and d_p is the mobility equivalent diameter.

RESULTS AND DISCUSSION

Ion and Ozone

Figs. 5(a) and (b) show the positive and negative ion concentrations, respectively, measured at sampling port 1 when the face velocity and the number of ionizers were varied.

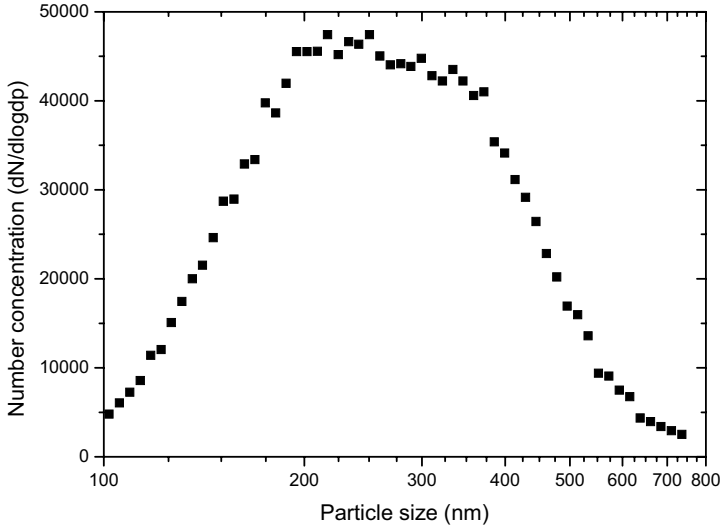


Fig. 4. Size distribution of the test particles measured at the sampling port 1 when the face velocity of the filter was 0.5 m/s.

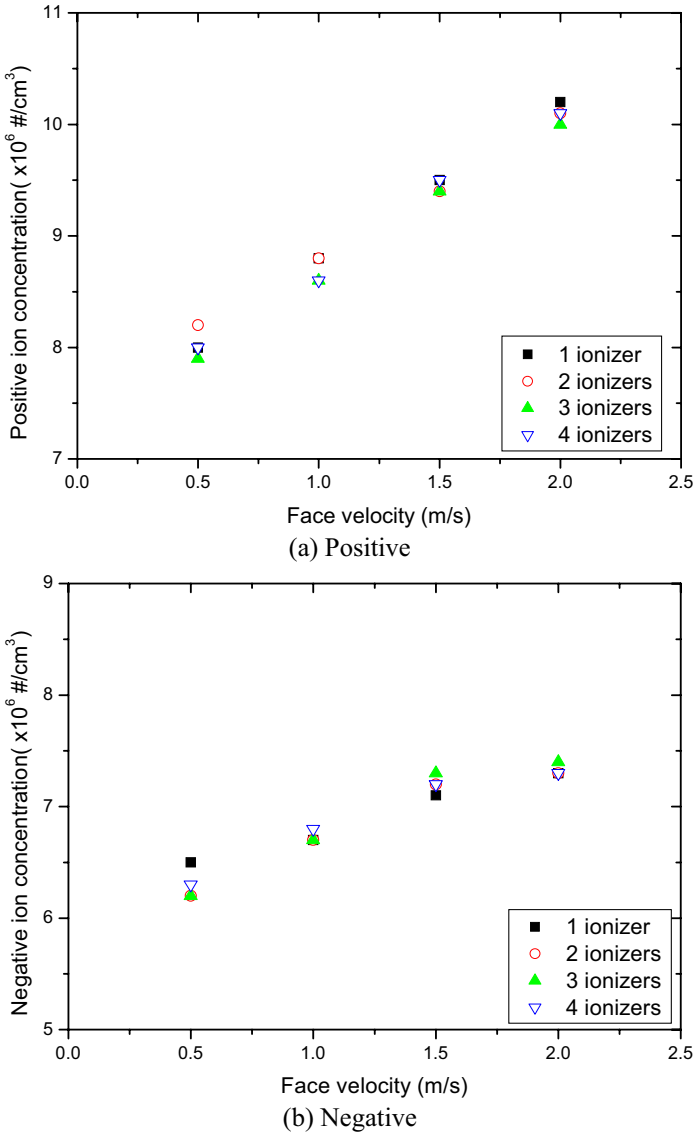


Fig. 5. Positive and negative ion concentrations measured at the sampling port 1 for various velocities and number of ionizers.

The averaged values were plotted, and the relative errors were under 6% for all measurements. As the velocity increased, the air ion concentration increased for any number of ionizers used. For the same velocity and number of ionizers, the positive ion concentrations were slightly higher than the negative ones. This phenomenon can be explained using the following charge drift equation (Sigmond, 1982):

$$\frac{1}{N}-\frac{1}{N_0}=\frac{e}{10^{-6}}\frac{\mu}{\varepsilon_0}t \tag{2}$$

where N is the ion concentration at the measuring point (#/cm^3), N_0 is the initial ion concentration, e is the charge of an electron (1.6×10^{-19} C), 10^{-6} is the conversion factor, μ is the electrical mobility of a positive or negative ion (m^2/V·S), and ε_0 is the permittivity of air (8.85×10^{-12} F/m). t is the ion drift time, which can be approximated by d/U where U is the face velocity in m/s and d is the distance from the carbon fiber ionizer to any position where the ion concentration was measured. This charge drift equation was derived from the rate of change of charge concentration along the path of ions and the continuity equation of charge concentration without considering the diffusion effect. The equation describes exactly the spreading out of the charge concentration along the path of a cloud of unipolar ions drifting with constant mobility in an arbitrary and time-dependent electric field (Sigmond, 1982).

From Eq. (2), the ion concentration at the measuring point is only affected by the ion drift time t when the initial ion concentration N_0 is fixed. The data shown in Fig. 5 were obtained for a fixed d of 27 cm; thus, the increase in ion concentration with face velocity can be theoretically predicted using Eq. (2). A higher electrical mobility of negative air ions (≈1.9×10^{-4} m^2/V·S) compared to the mobility of positive air ions (≈1.1×10^{-4} m^2/V·S) will cause the positive ion concentration to be higher than the negative one, as experimentally validated and shown in Fig. 5 (Kim *et al.*, 2011).

Fig. 5 shows the interesting result that the number of ionizers seldom affected the air ion concentrations. This result can be explained using Eq. (2), which shows that the ion concentration N at any drift time t is dependent only on the initial ion concentration N_0, which is expected to be affected by the number of ionizers. Fig. 6 shows calculated results of ion concentrations with various initial ion concentrations and drift times. The ion concentration increased with the initial ion concentration, for any drift time, when the initial ion concentration was lower than 10^5 #/cm^3. However, the ion concentration decreased with drift time when the initial ion concentration was higher than 10^6 #/cm^3. For constant drift time, we note that the ion concentration was saturated for an initial ion concentration higher than 10^7 #/cm^3. We measured initial concentrations for positive and negative applied voltages 3 cm downstream from an ionizer. The measured values for the positive and negative voltages were 2×10^8 ions/cm^3 and 8×10^7 ions/cm^3, respectively. Assuming that these concentrations represent the initial concentrations N_0, the initial concentrations would increase with an increase in the number of ionizers. However, according to the results shown in Fig. 6, the ion concentration at any location away from the 3 cm position would not be affected by the number of ionizers. This explains the results shown in Fig. 5: the ion concentration at the same sampling point and face velocity increased only slightly, even when the number of ionizers increased from 1 to 4.

Near the tip of a carbon fiber ionizer, the detected ozone concentration was in the range of 60 to 300 ppb when either a positive or negative ionizer was operated. However, the ozone concentration downstream of the electret filter was reduced to as low a value as the background concentration (< 0.8 ppb) for all face velocities of 0.5 to 2.0 m/s, since the ozone generated at the tip of the ionizer was diluted with ambient air having an ozone concentration below 0.8 ppb. Our results are in good agreement with the previous results (Han *et al.*, 2008; Park *et al.*, 2009; Kim *et al.*, 2010; Park *et al.*, 2010; Park *et al.*, 2011).

Particle Filtration Efficiency

Aerosol particles in ambient air tend to be naturally charged by collisions with positive or negative ions that are naturally present in the air due to their random thermal motion. Such charged aerosol particles will lose their charge slowly as the charged particles attract oppositely-charged ions. These competing processes eventually lead to an equilibrium charge state called the Boltzmann equilibrium charge distribution (Hinds, 1999). In this study, the particle filtration test was carried out using equilibrium charged particles that were generated in the laboratory (see Fig. 3).

Fig. 7 shows fractional particle collection efficiencies of the positive ionizer-assisted electret filter for face velocities of 0.5 to 2.0 m/s. In order to obtain the average values and standard deviations of fractional particle collection efficiencies, experiments were repeatedly carried out over 5 times for each velocity. The averaged values for each particle size were plotted. Their sample standard deviations were lower than 4% for all experimental cases. When the ionizers were not used, the collection efficiencies for all tested particle sizes were in the range of 50 to 60% at a face velocity of 0.5 m/s. For face velocities of 1, 1.5, and 2 m/s, the collection efficiencies were not affected by the face velocities, but were reduced to 40 to 50%. When the positive ionizers were used, the collection efficiencies for all face velocities increased and became 75 to 85%. As expected, the number of ionizers did not affect the collection efficiency since the air ion concentrations did not change with the number of ionizers.

Fig. 8 shows the collection efficiency of the negative ionizer-assisted electret filter for face velocities of 0.5 to 2.0 m/s. In order to obtain the average values and sample standard deviations of fractional particle collection efficiencies,

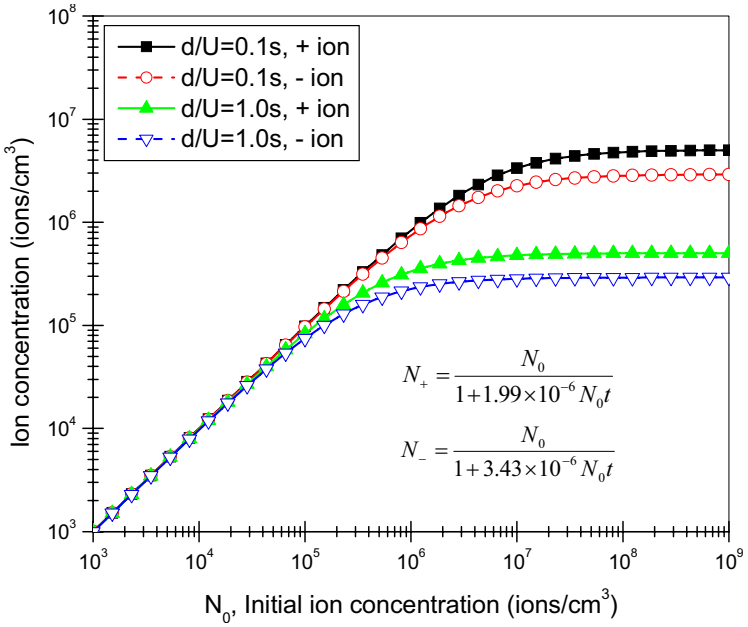
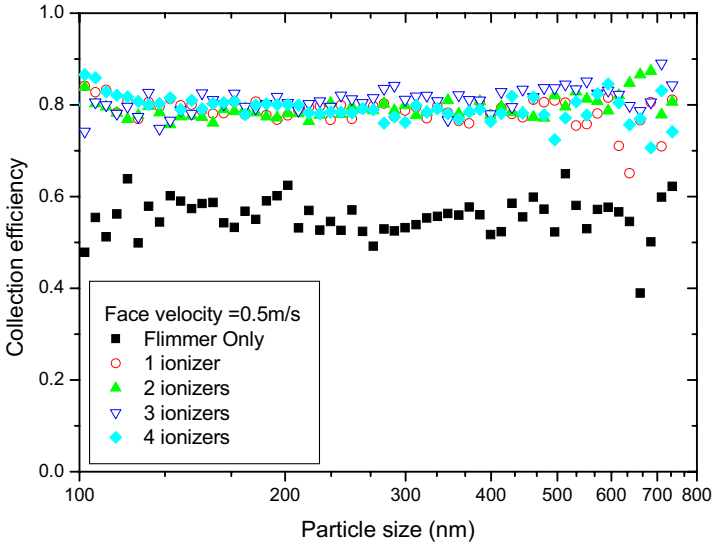
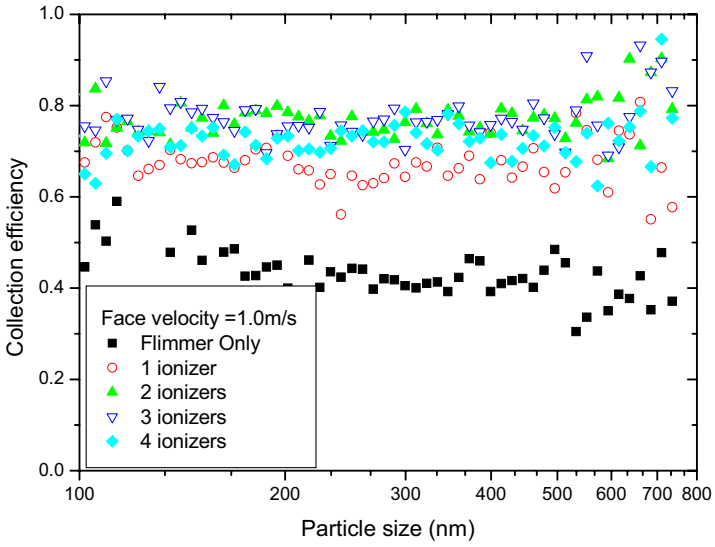


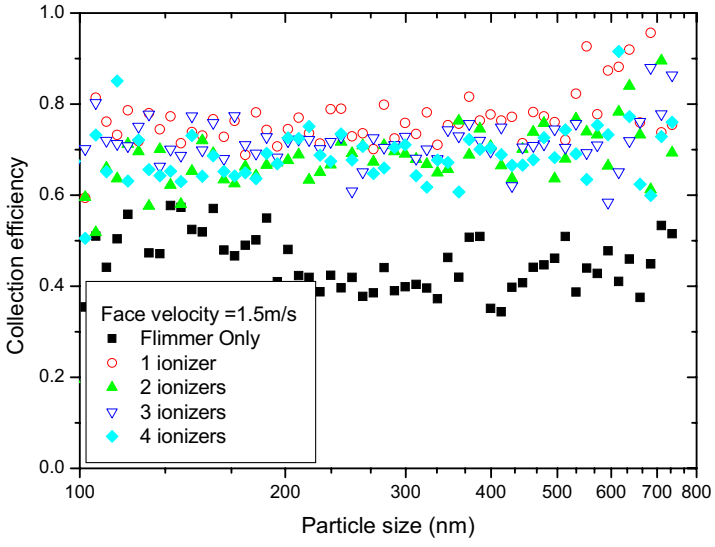
Fig. 6. Positive and negative ion concentrations for initial ion concentration and drift time, which were predicted by Eq. (2).



(a) U = 0.5 m/s

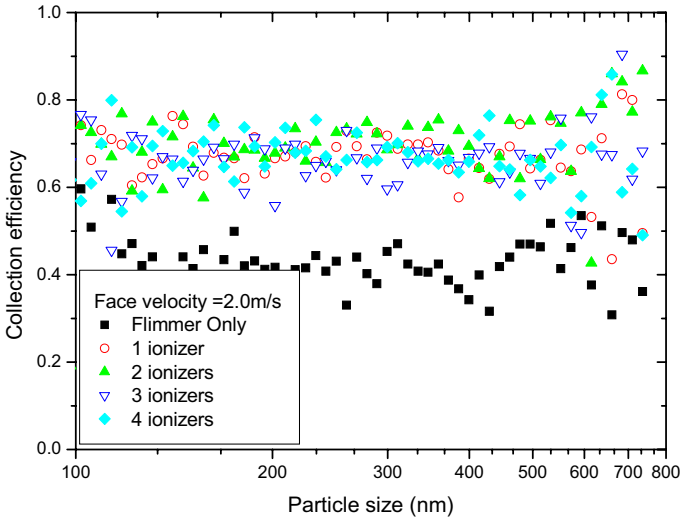


(b) U = 1.0 m/s



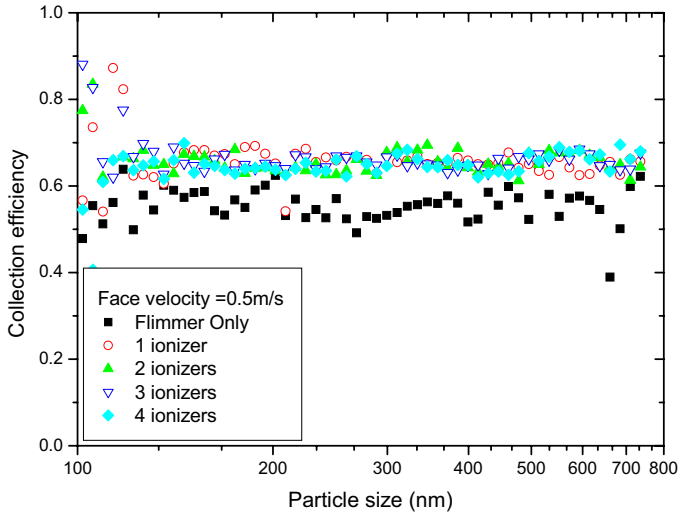
(c) U = 1.5 m/s

Fig. 7. Fractional particle collection efficiencies of the positive ionizer assisted electret filter for face velocities of 0.5 to 2.0 m/s.

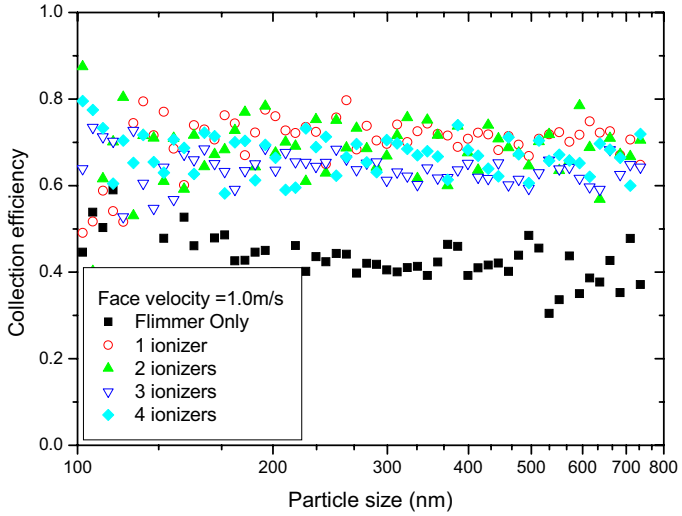


(d) U = 2.0 m/s

Fig. 7. *(continued).*

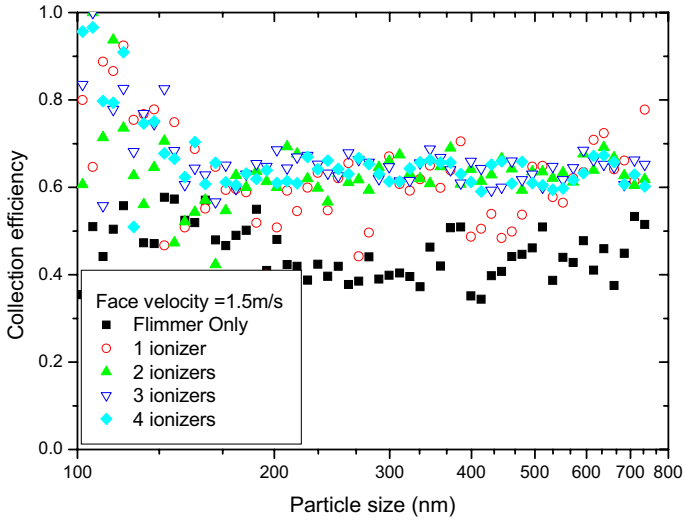


(a) U = 0.5 m/s

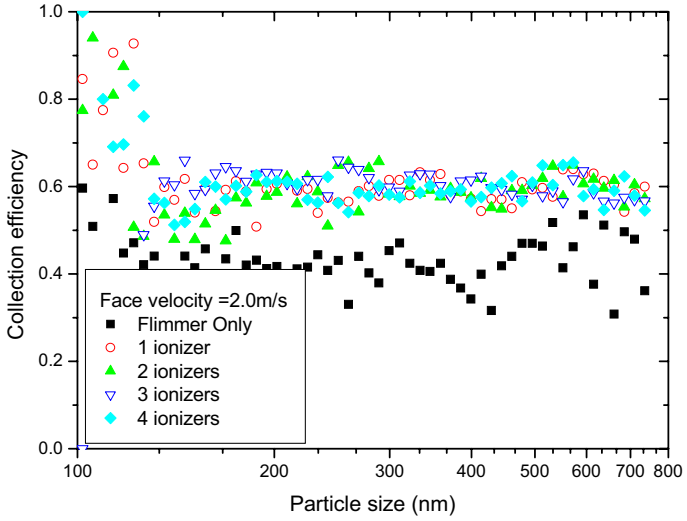


(b) U = 1.0 m/s

Fig. 8. Fractional particle collection efficiencies of the negative ionizer assisted electret filter for face velocities of 0.5 to 2.0 m/s.



(c) U = 1.5 m/s



(d) U = 2.0 m/s

Fig. 8. *(continued).*

experiments were repeatedly carried out over 5 times for each velocity. The averaged values for each particle size were also plotted. Their sample standard deviations were lower than 4% for all experimental cases. These results show that the effect of the ionizers and face velocity on collection efficiency was similar to the case with the positive ionizers. When negative ionizers were used, the collection efficiencies were 55 to 70%, which were 10 to 20% higher than the values of the case without ionizers. The collection efficiencies were 10 to 15% lower than the values of the positive ionizers for the same velocities.

Table 1 shows the positive and negative ion concentrations measured downstream of the electret filter (sampling port 2) before and after the electret filter was installed. Before the filter was installed, the ion concentrations were in the range of 0.2×10^6 to 0.45×10^6 ions/cm^3. However, the ion concentrations were reduced by about 99% after the electret filter was installed. This suggests that the air ions generated at the tip of the ionizers were captured on the surfaces of the electret filter fibers. The attached ions definitely increased the electrostatic potential at the surface of the electret fibers compared to the case of the ionizers being turned off. This result is in a good agreement with Agranovski *et al.* (2006). They explained how air ions with high mobility were deposited on fibers forming a macroscopic electric field, which shielded out some incoming unipolar charged particles due to repelling forces.

It would be interesting to know whether the generated ions still tend to attach to the filter surface even in the presence of aerosol particles. Considering only a diffusion charging mechanism between the ionizers and the electret filter, the theoretical average number of charges per particle ($n(d_p)$) with respect to the charging time t is defined as follows (Reist, 1993):

$$n(d_p) = \frac{d_p kT}{2e^2} \ln\left[1 + \frac{\pi d_p v_{rms} e^2 N \cdot t}{2kT}\right] \quad (3)$$

where k is Boltzmann's constant (1.38×10^{-16} erg/K), T is

Table 1. Positive and negative ion concentrations measured at the sampling port 2 before and after the electret filter was installed.

Velocity (m/s)	Average ion concentration (#/cm^3, ×10^6)			
	Without the electret filter		With the electret filter	
	Positive	Negative	Positive	Negative
0.5	0.20	0.20	0.0015	0.0015
1.0	0.30	0.25	0.0015	0.0015
1.5	0.35	0.30	0.0015	0.0020
2.0	0.45	0.35	0.0015	0.0030

the temperature (293 K), e is the elementary unit of charge (4.8×10^{-10} esu), v_{rms} is the root-mean-square velocity of the ions (2×10^4 cm/s at 293 K), and N_i is the average ion concentration near a particle (#/cm^3). When the charging time was lower than 0.54 s, the ion concentration was 10^6 to 10^7 ions/cm^3, the total particle concentration was about 2×10^4 #/cm^3, and the average number of charges per particle (0.5 μm) was calculated to be lower than 0.01. Then, the number of ions attaching to the particles would be as low as 400 #/cm^3, and most of the ions will move toward the filter.

Based on these calculations, we suggest that particle charging due to the carbon fiber ionizers was not the main mechanism to increase the filtration efficiency in our experimental conditions, and the filtration efficiency for the equilibrium-charged particles increased because the electrostatic potential accumulated inside the electret filter. However, if the power to the ionizers were increased such that air ions are generated at a concentration higher than 1.6×10^9 #/cm^3, the particles would be charged in the space between the ionizers and the electret filter, and then the collection efficiency would increase as reported by Park *et al.* (2010) and Park *et al.* (2011).

CONCLUSIONS

The influence of a carbon fiber ionizer on the collection efficiency of an electret filter was characterized for varying parameters of face velocity, the number of ionizers, and the polarity of the ionizer(s). From our theoretical and experimental results, the following conclusions were drawn:

1) As the velocity increased, the ion concentration upstream of the electret filter increased for any number of ionizers used. For the same velocity and number of ionizers, the positive ion concentrations were slightly higher than the negative ion concentrations. The air ion concentration at the same sampling point and face velocity increased only slightly, even when the number of ionizers was increased from one to four.
2) Near the tip of a carbon fiber ionizer, the ozone concentration was 60 to 300 ppb, but the ozone concentration downstream of the Flimmer filter was reduced to the background concentration (< 0.8 ppb) since the ozone was diluted with the air having an ozone concentration below 0.8 ppb.
3) When the positive or negative carbon fiber ionizer was installed in front of the electret filter, the collection efficiency for submicron particles increased noticeably. When the positive ionizers were used, the collection efficiencies for all face velocities increased and became 75 to 85%. When the negative ionizers were used, the collection efficiencies were 55 to 70%, which were 10 to 20% higher than the values for the case without ionizers.
4) When a carbon fiber ionizer was used in front of the electret filter, the ion concentrations were reduced by about 99% through the electret filter. We suggest that the air ions generated at the tip of the ionizers were captured on the surfaces of the electret filter fibers. Consequently, the electrostatic potential accumulated inside the electret filter increased the filtration efficiency for equilibrium-charged particles.

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