Capture of Ultrafine Particles Using a Film-Type Electret Filter with a Unipolar Charger

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ABSTRACT

Electret filters have been used widely to collect particles because of their low pressure drop and high collection efficiency due to the electrostatic attraction between the particles and filter. However, the collection efficiency of these filters decreases over time due to charge degradation. Therefore, a unipolar charger using a corona discharge was combined with an electret filter to overcome this decrease. The highest particle collection efficiency for 70 nm, uncharged particles occurred with a fresh electret filter was 34.0%, whereas a neutralized filter had a collection efficiency of 32.6%. However, when fresh and neutralized electret filters were used with a unipolar charger (electret field: 1.9 kV cm–1), the highest particle collection efficiencies of 99.8% and 98.2%, respectively, were obtained and appeared at the electrode-to-mesh distance, a distance similar to the duct diameter. The distance between the tip of the discharge electrode and filter, which can be predicted using Sigmond’s law, affected the charge density value on the filter surface. The ozone concentration was negligible under optimum conditions for particle collection. Therefore, using an electret filter combined with a corona discharge has good potential for improving air purifiers.

Keywords: Unipolar charger; Electret filter; Aerosols; Polarization; Sigmond’s law.

INTRODUCTION

Aerosol particles are commonly collected by filters or electrostatic precipitators (ESP). Particle collection during filtration is performed by conventional mechanical mechanisms such as diffusion, interception, and impaction (Yeh and Liu, 1974; Lee and Liu, 1982; Hinds, 1999). Fibrous filters have been used widely in filtration devices because of their low cost and high collection efficiency; however, they have an inevitable high pressure drop. Whereas an ESP, which has negligible flow resistance (Lehtimäki and Heinonen, 1994), uses electrostatic forces to collect particles, a corona discharge provides sufficient charges to particles (Hinds, 1999).

An electret filter, which is used commonly in air filtration, is created by applying electrostatic forces to a conventional filter (Lehtimäki and Heinonen, 1994; Wang, 2001). The electret filter fulfills the requirements for high filtration efficiency and low pressure drop (Van Turnhout, 1981; Brown, 1993a; Romay et al., 1998). Interest has grown in the usage of a polymer film-type electret filter due to its excellent electrical, thermal, and mechanical properties (Sahli et al., 2003). Previous studies that used the polymer, polytetrafluoroethylene (PTFE), showed excellent charge storage stability after corona charging (Nifuku et al., 2001). However, the film-type electret filter also experienced surface potential decay that resulted in a decrease in collection efficiency over time (Sahli et al., 2003).

Introducing an ionizer in an electret filter system overcomes this drawback of the electret filter by supplying additional charges (Noh et al., 2011). Previous studies that used an ionizer showed that the particle removal efficiency was improved from ~60% to 85% (Park et al., 2010; Noh et al., 2011). The efficiency could not be increased further, however, because of the upper limit of the unipolar ion concentration caused by mutual repulsion loss. Therefore, the addition of ionizers did not help to increase collection efficiency because of the ion concentration limit of around $1 \times 10^7$ cm–3 (Noh et al., 2011). On the contrary, a corona discharge can produce unipolar ions with a high enough concentration. In addition, to the best of our knowledge, we are not aware of any previous attempts to use corona discharge to improve the collection efficiency of filtration.

In this study, we tested how combining the film-type electret filter with a unipolar charger of corona discharge...
affected the collection efficiency of ultrafine particles. We focused on the relationship of various parameters, such as voltages and distances between two electrodes, with the collection efficiency. The combination of a corona discharge and an electret filter improved the particles collection efficiency up to 99.8%. The optimum distance for the collection efficiency was observed and analyzed with the current density by using Sigmond’s law (Sigmond, 1982).

EXPERIMENTAL DETAILS

The schematic setup, which consists of a particle-generation zone, collection zone, and measurement zone, is shown in Fig. 1.

Generation of Test Particles

The NaCl particles were generated by using a collision atomizer with 0.2 wt% NaCl solution under a pressure of 2 atm followed by a diffusion dryer and soft X-ray neutralizer (XRC-05, HCT CO., LTD). A flow rate of 3.2 lpm was maintained in the system. The particle size distribution, which had a geometric mean particle size of 81 (± 1.64) nm and total number concentration of 5.86 (± 0.835) × 10⁶ cm⁻³, is shown in Fig. 2. The generated particles had charges in...
the steady-state charge distribution (Hoppel and Frick, 1986). The charged particles were removed for the filtration test because the uncharged particles had the lowest collection efficiency in the electret filtration system.

**Corona Discharging Zone**

A plexiglass tube was used as the charger body with an inner diameter and length of 100 mm and 650 mm, respectively. A steel needle with a 3 mm diameter and tip angle of 10° was used as the central electrode, and a stainless steel mesh was configured as the grounded electrode. A high voltage DC power supply (+20 kV and 2 mA, Korea Switching) was connected to the needle. A polypropylene-film-embossed filter (C0425, Gumbo Industry, Republic of Korea) was prepared by rolling a corona charged embossed film with 25 mm in width, which was embossed with 5 mm in thickness and 4 mm in diameter. The morphology of the test filter was shown in Fig. 1(c). As shown in the figure, we can see that air resistance will be quite low because air stream is perpendicular to the filter media. The embossing area was 42.24% of the filter area. The embossed filter had a positive net charge of 9–15 kV on the surface. However, it had the same collection efficiency for either positive or negative particles, implying the same uniform charge distribution inside the filter medium. The effect of a filter was studied by utilizing a fresh film-type electret filter (FF) and a neutralized film-type electret filter (NF). The NF was prepared by soaking an electret filter in an ethanol solution and drying it at room temperature for 72 hours (Lee et al., 2002; Choi et al., 2015).

**Analytical Methods**

The corona current was measured by connecting an electrometer (PTI-2012, PointTech) to the grounded plate. An electrostatic classifier (3080, TSI) and a condensation particle counter (3775, TSI) were downstream of the charger to measure the NaCl particle size distribution. The collection efficiency was calculated using the following equation:

$$\eta = \frac{C_0 - C}{C_0}$$

where $C_0$ and $C$ are the upstream and downstream particle concentrations of the collection zone, respectively. The face velocity was fixed at 0.68 cm s$^{-1}$ throughout the experiments. The pressure drop at the filtration velocity was less than 2 Pa, as mentioned above. The ozone concentration was measured using a photometric ozone analyzer (T400, Teledyne Advanced Pollution Instrumentation).

**RESULTS AND DISCUSSION**

**Voltage-Current Characteristics**

The effect of the distance, $L$, between the discharge electrode and mesh upon the electric current was analyzed by removing the filter during the measurement. The voltage of corona inception increased with increasing distance. In addition, as the distance between the discharge electrode and mesh increased, the electric current decreased, as can be seen in Fig. 3. This tendency concurred with the results from previous research (Kulkarni et al., 2002). The relationship among electric field, voltage, and distance is explained as follows:

$$E = \frac{\Delta V}{L}$$

where $E$ is the electric field, and $\Delta V$ is the difference in voltage between the electrode and mesh (Hinds, 1999). It should be noted that the Eq. (2) only, strictly speaking, applies to the electric field in between two plates. However, the pseudo-homogeneous electric field strength has been used for ESPs because of its simplicity (Riehle, 1997). Eq. (2) shows that an increase in distance decreases the value of the $E$ at a constant voltage. Previous research explained the decrease in electric wind velocity by the increasing distance, which emphasized the localization of the electric force near an electrode (Drews et al., 2013).

**Fig. 2.** Particle size distribution generated from NaCl aqueous solution of 0.2 wt%.
Fig. 3. Current-voltage characteristics at various distances between electrode and grounded electrode.

**Collection Efficiency of Particles at 20 kV**

The collection efficiencies at various distances under the fixed voltage of 20 kV are shown in Fig. 4 for three cases: a) unipolar charger only, b) NF with a unipolar charger, and c) FF with a unipolar charger.

For the case of the unipolar charger only (Fig. 4(a)), the collection efficiency increased with particle sizes up to approximately 100 nm. The experimental collection efficiency was similar at various distances, except for 115 mm. The highest efficiency was at a distance of 105 mm. The experimental collection efficiency was compared with the theoretical collection efficiency by assuming the system is an ESP.

To calculate the theoretical collection efficiency, the number of charges on each particle was calculated first. The number of charges, $n(t)$, of a particle by diffusion charging is expressed as follows (Hinds, 1999):

$$n(t) = \frac{4\pi \varepsilon_0 d_p kT}{2e^2} \ln \left[ 1 + \frac{\pi d_p \bar{c} e^2 N_i t}{8\varepsilon_0 kT} \right]$$

(3)

where $\varepsilon_0$, $d_p$, $k$, $T$, $e$, $\bar{c}$, $N_i$, and $t$ represent the permittivity of a vacuum, diameter of a particle, Boltzmann constant, absolute temperature, elementary electron charge, mean thermal speed of ions (240 m s$^{-1}$), concentration of ions, and residence time, respectively. The $n(t)$ of a particle by field charging is expressed as follows (Hinds, 1999):

$$n(t) = \left( \frac{3e}{\varepsilon + 2} \right) \left( \frac{Ed_p}{4K_e e} \right) \left( \frac{\pi K_e e Z_i N_i t}{1 + \pi K_e e Z_i N_i t} \right)$$

(4)

where $\varepsilon$, $K_e$, and $Z_i$ are the relative permittivity of a particle, proportionality constant for Coulomb’s law ($9.0 \times 10^9$ N m$^2$ C$^{-2}$), and mobility of the ions (approximately 1.5 $\times$ 10$^{-4}$ m$^2$ V$^{-1}$ s$^{-1}$), respectively. The total $n(t)$ was summed for the subsequent calculations. $N_i$ was calculated from the following equation:

$$N_i = \frac{I}{eZ_i EA}$$

(5)

where $I$ and $A$ are the current in Fig. 3 and the area of the grounded electrode, respectively. The calculated $N_i$ values were on the order of $10^{15}$ s$^{-3}$, and these values were much higher than the corresponding values of approximately $10^{12}$ s$^{-3}$ generated by ionizers (Han et al., 2008). Therefore, we can expect the charging efficiency and consequent collection efficiency using a corona discharge to be much higher than those using an ionizer are.

Finally, the theoretical collection efficiency was calculated using the Deutsch-Anderson equation (Hinds, 1999):

$$\eta = 1 - \exp \left( -\frac{V_{TE} A_s}{Q} \right)$$

(6)

where $V_{TE}$, $A_s$, and $Q$ represent the terminal electrostatic velocity of a particle, area of the collection plate, and volumetric flow rate, respectively. $V_{TE}$ was calculated by multiplying $E$ by the electrical mobility of a particle, $C_n e^3/m \mu d_p$, where $C_n$ and $\mu$ represent the Cunningham slip correction factor and viscosity of air, respectively (Allen and Raabe, 1985). Because $E$ is not linear with distance, a correction factor is needed to represent the average $E$. It should be noted that an arbitrary correction factor of 0.4 was used to account for the effective drift velocity, a necessity because the effects of variations in the field strength and resuspension of particles make the theoretical calculation unreliable (Cooper and Alley, 2011).

The theoretical and experimental collection efficiencies were different. Based on current theories, the collection efficiency was supposed to decrease with particle size up to 100 nm because of the decreased electrical mobility of a particle that occurs by the reduced diffusion charging. First, the particle collection and resuspension on the mesh used in this study might be different from the plate used in ordinary ESPs. Second, the particle might be collected by dipole-dipole interaction. Dipoles are created in the dielectrics under $E$. 

![Graph showing current-voltage characteristics with distances](image-url)
The number of dipoles is proportional to the volume of the material. Therefore, the collection efficiency should increase as the particle size increases. On the other hand, the theoretical collection efficiency monotonically decreased as the distance increased. Therefore, theory cannot explain the high efficiencies at 105 mm (Fig. 4(a)). This discrepancy can be attributed to the uniform $E$ assumption during the calculation. This issue will be investigated further in the next paragraph.

The collection efficiencies for the cases of an NF with a unipolar charger and an FF with a unipolar charger are shown in Figs. 4(b) and 4(c), respectively. The collection efficiencies generally increased after the filters were installed. Strangely, the optimum distance was 105 mm, as it was in
the case of the unipolar charger only.

This phenomenon can be explained partly by the current density distribution, \( J \), in this system with Sigmond’s law:

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J = \frac{\varepsilon_0 Z V^2}{L^3} \left(1 + 2 \tan^2 \theta \right)^{-3/2}
\]

where \( V \) and \( \theta \) are applied voltage and a semivertical cone angle of a discharge, respectively (Sigmond, 1982; Mclean, 1988). The value of \( J \) at any point on the surface is estimated by the peak value of planar current distribution under an electrode (Sigmond, 1982; Mclean and Ansari, 1987; Mclean, 1988; Jones, 1997). Eq. (7) shows that the distance between the discharge electrode and mesh and the angle of a discharge electrode affect \( J \). A longer distance between the discharge electrode and mesh decreases the current density through the longer ion transport path. However, the longer distance increases the current density with the smaller angle. By taking the residence time of particles into account, the value of charge density per area at various distances is shown in Fig. 5. The theoretical calculation also showed that the optimum distance of 105 mm had the highest charge density. Previous research showed an increase in charge carrier number density as the distance increased at the fixed current density (Chen and Davidson, 2003). Therefore, the calculation results by using Sigmond’s law (Fig. 5) support the experimental results in Fig. 4.

The optimum distance of 105 mm was found for the cases of the charger with an NF and the charger with an FF. However, the NF did not collect particles as well as the FF did. This was due to the electrostatic forces, which were created by the electret filter, that increased the collection of particles on the filter. The higher particle collection values of the FF showed that additional charges on the filter improved the particle capture efficiency. Therefore, the performance of a filter was affected by the electrostatic force condition on the filter. Previous research showed that ethanol treatment to neutralize a filter significantly decreased the particle collection efficiency (Lee et al., 2002; Choi et al., 2015). The effect of diffusion and field charging did not significantly affect particle collection efficiency for the combination of the unipolar charger and electret filters because the short distance of 25 mm does not improve the collection efficiency. This can be attributed to the weakened corona discharge when the filter was installed during the collection of particles.

**Collection Efficiency of Particles at 105 mm**

After fixing the distance to 105 mm, the particle collection efficiency was studied at various applied voltages to investigate the effect of \( E \). Generally, an increase in applied voltage improved the collection efficiency of particles (Fig. 6). This result agreed with previous research that showed an increase in collection efficiency for ultrafine particles when the applied voltage was increased up to 25 kV (Zukeran et al., 1999). The bipolar ions created by the corona discharge was separated by the \( E \). That condition enhanced the unipolar ion atmosphere, which resulted in more efficient diffusion charging; and hence improved the deposition mechanisms (Kulkarni et al., 2002).

In comparison to Fig. 6(a), the addition of a filter generally showed higher collection of particles (Figs. 6(b) and 6(c)). The maximum collection efficiency was obtained at 20 kV for each case. The unipolar charger had a particle collection efficiency of 97.1% for 70-nm-sized particles, whereas the combination of the unipolar charger and electret filters had efficiencies of 98.2% and 99.8% for the NF and FF, respectively. The higher applied voltage improved the diffusion and field charging on particles for the unipolar charger only case. In addition, the polarization of a particle under the \( E \) improved the collection efficiency. The additional interaction of surface charges of an electret filter improved the collection efficiency for the unipolar charger and FF case.

![Fig. 5. Current density distribution at various distances from the electrode to the mesh (25 mm distance is not included in the graph because the position of the electrode was right on the surface of the filter; thereby, the charging area for the particles was lacking).](image)
Fig. 6. Particle collection efficiency at the fixed distance of 105 mm for a) unipolar charger, b) neutralized filter with a unipolar charger, and c) fresh electret filter with a unipolar charger.
The electrostatic deposition is the most important mechanism when both particles and a filter are charged (Hinds, 1999). The electret filter creates the $E$, which induces the charge separation in a particle. The non-uniform field around a filter allows for a greater attractive force on the near side of a particle than it does for a repulsive force on the far side of a particle; hence the particles migrated toward the filter (Brown, 1993b). The existence of a filter acted as a collector of particles and increased the efficiency of particle collection. The $E$ on the filters suppressed the reentrainment, which is the movement of particles back into the gas stream, by producing a gradient force at the fiber tip that reduced the ionic-wind-pushed particles to reenter the stream (Sung et al., 2006). The particles were deposited on the filter surface in irregular, bent chains when electrostatic force was absent, but were in straight chains with applied electrostatic force (Oh et al., 2002).

The collection efficiency of particles by an FF and NF are summarized in Fig. 7. The collection efficiencies of the NF and FF were 32.6% and 34%, respectively, for particles 70 nm in size at 0 kV. Without the applied voltage, the film-type electret filter could not remove particles efficiently because of the large gaps between the rolled films. The NF and FF showed minimum efficiencies for particles with a diameter of 70 nm. The electrostatic force on a filter shifted the minimum penetration particle size (MPPS) toward the smaller sized particles, which has been shown in previous studies (Chazelet et al., 2011; Sanchez et al., 2013). In addition, strangely, although the tested NF was prepared by soaking an FF into ethanol solution, it still has electrostatic charges. When the applied voltage increased to 20 kV, the collection efficiencies increased for the FF and NF to 99.8% and 98.2%, respectively, for particles with a diameter of 70 nm. The applied voltage provided electrostatic charge for the particles, which facilitated their charging. Based on the experimental results, the combination of a corona discharge and an electret filter increased the efficiency of particle collection.

**Ozone Concentration**

The generation of ozone is a disadvantage of a corona discharge, especially for a negative corona discharge. The commercial air cleaner showed an ozone generation rate of $2.5 \times 10^{-3}$ mg s$^{-1}$, even though this generation was affected by the relative humidity, kind and dimension of the electrode material, and current (Boelter and Davidson, 1997). To reduce ozone generation, a positive corona discharge was used in this experiment. The ozone concentration measured at 25 mm showed exponential increase with respect to the applied voltage (Fig. 8). The highest ozone concentration was 505 ppb, and the ozone generation rate was $5.38 \times 10^{-5}$ mg s$^{-1}$ at 20 kV. This is smaller than the value reported for the commercial air cleaner and in previous research (Moon et al., 1998). For a positive corona discharge in the point-plane configuration, Moon et al. (1998) showed that the ozone concentration and generation rate were 3 ppm and 1 $\times 10^{-4}$ mg s$^{-1}$, respectively, at a distance of 25 mm. The ozone concentration was around 13 ppb at a distance of 105 mm. These ozone concentrations were measured without a filter. When the filter was installed, the ozone concentration had much smaller value less than 10 ppb as shown in the Fig. 8 because of the reduced corona discharge. Considering the optimum condition to collect particles of using a combination of an electret filter and a corona discharge, the ozone concentration was not practically a problem in our system. Therefore, the combination of an electret filter with a corona discharge has the advantages of high particle collection efficiency and low ozone generation.

**CONCLUSION**

Ultrafine particles were collected using a combination of a unipolar charger and an electret filter. The applied voltage was an important factor for the collection efficiency. Generally, higher voltage and shorter distance between the electrode and mesh showed higher collection efficiencies. The supply of ions and creation of dipoles under the $E$ are the

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**Fig. 7.** Particle collection efficiency at the voltages of 0 kV and 20 kV for the fresh electret filter and neutralized filter.

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important mechanisms to high collection efficiency. However, there was also the effect of current density distribution presented by Sigmond’s law where the optimum distance existed. The additional electrostatic interaction between particles and the charged filters was also important. Therefore, the combination of the unipolar charger and FF showed a high particle collection efficiency of 99.8% for 70-nm-sized particles at the optimum distance of 105 mm and voltage of 20 kV. Because this distance is relatively far, the ozone generation by the corona discharge was regarded as negligible. The combination of the unipolar charger and electret filter provides a solution for capturing ultrafine particles, leading to improved indoor air quality. The low ozone concentrations and high collection efficiency are additional attractive benefits that give this system great potential to address the health risks associated with ultrafine sized pollutants.

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