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Filtration Efficiency of Electrically Charged Air Filters by a Corona Method

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Abstract

The influences of corona charging parameters on collection efficiency and surface potential of air filters were investigated. A polypropylene filter medium was electrically charged using a corona charger, and the resulting surface potential and filtration efficiency against neutralized KCl particles were measured. The filter media was charged under different conditions of applied voltage, voltage polarity, charging time, and distance between electrodes. In addition, we considered charging both sides of the filter as well as charging one side of the filter. As a result, electrical force obtained by charged fiber affected filtration efficiency when the apply voltage strength was higher than 7 kV. Negatively charged filter had higher filtration efficiency than positively charged filter while the surface potential of the negatively charged filter was slightly lower than those of positively charged filter. Moreover, the filtration efficiency increased as the charging time of filter fiber increased and the distance between electrodes decreased. The filtration efficiency was more sensitive to changes of charging time than to those of electrode distance, and the efficiency of both sides charged filter was higher than that of single side charged filter.

Keywords: Air filter, Corona charging, Applied voltage, Charging time, Filtration efficiency

1. Introduction

As the demand for cost-effective air filters increases, studies have been conducted on filters showing high efficiency at a low pressure drop. If the filtration efficiency is improved by changing the filter's physical structure, such as solidity, fiber diameter, and filter width, a consequent high pressure drop appears (Fisk, 2002; Ahn, 2006; Chuaybamroong, 2010). Thus, studies are being conducted to improve the efficiency of filters while retaining an almost constant pressure drop by providing electrical characteristics to the

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medium grade filter system. Methods that apply electric characteristics in filter systems include electrical charging of particles that flow into the filter (Lee et al., 2004; Agranovski et al., 2006; Park et al., 2009; Park et al., 2011), application of an external electric field to the filter (Thorpe and Brown, 2003; Park and Park, 2005), and electrical charging of filter media (Kim et al., 2007; Yang et al., 2007; Li and Jo, 2010; Chazelet et al., 2011; Sim et al., 2015). Because both the methods of particle charging and applying an external electric field require a high voltage supply system, disadvantages such as additional energy consumption and operational safety issues appear. On the other hand, the method of providing a quasi-permanent electric charge to filter fibers is simple and practical, and is thus being used in various residential and industrial filter systems (Boelter and Davidson, 1997; Grass et al., 2004).

Several methods to charge fibrous filters have been introduced, such as corona charging, triboelectric charging, induction charging, and hydro-charging (Gu and Schill, 1997; Romay et al., 1998; Tsai et al., 2002). Among these methods, using corona charging is suitable to produce a high volume of electrostatic energy in a short period of time (Chang, et al., 1991). A corona discharge occurs when a high potential difference is applied to two asymmetric electrodes such as wire to plate or pin to plate. This discharge generates a local strong electric field to the wire or pin. The electrons that were accelerated from the presence of the electric field produce an electron avalanche that ionizes the air, causing that the generated cations (i.e., positive ions), anions (i.e., negative ions), and electrons in the air to move along the electric field. If a filter medium made from insulating material is placed on the substrate, filter fibers can obtain a quasi-permanent electric charge by the attachment of air ions and electrons to the fiber surface.

Several researchers have conducted studies on fibrous electret filters using corona charging. Tabti et al. (2009) reported that if the voltage applied to the corona generator increases, the filter maintains an uncharged state, but if the applied voltage exceeds a given threshold, the surface potential of the filter rapidly increases. Nifuku et al. (2001) observed a limit in the increase of surface potential once a certain charge time is reached. Moreover, the effects of substrate temperature and humidity are also reported (Lin et al., 2004; Tabti et al., 2010). Even though the effects of various corona charging parameters, such as applied voltage, charging time, and substrate temperature and humidity, on the surface potential of fabricated electret filters were already addressed, there are still not enough studies about the influence on the surface potential of the distance between the two electrodes in the corona discharge generator. Moreover, currently available studies focus on the filter's surface potential according to the corona charging conditions without consideration of its filtration efficiency. Since the surface potential only represents charging level on the filter surface while filtration is occurred inside the filter medium, it is hard to identify the filtration ability using the surface potential.

In this study, an electrostatic charge was applied on a filter media made from polypropylene fibers considering several different corona charging conditions including applied voltage, voltage polarity, charging time, and distance between electrodes. Charging both sides of the filter and a single side of the filter were also considered. Surface potentials of fabricated electret filters were measured and filtration efficiency for the different conditions was evaluated and compared.

2. Material and Methods

2.1 Preparation of test filter samples

A commercial filter medium made from melt-blown fibers was used as test filter. The filter medium was made from polypropylene (PP) fibers and had 22.59 g/m^2 of average weight. The average thickness and fiber diameter of the filter medium were about 200 and 2 μm, respectively (Fig. 1). The filter medium was cut to 200×500 mm^2 size and then treated with

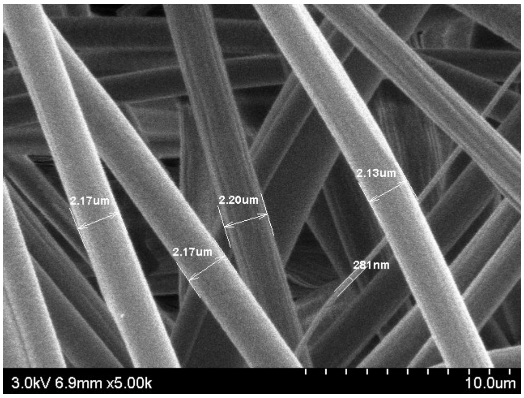

Fig. 1. SEM images of the filter sample.

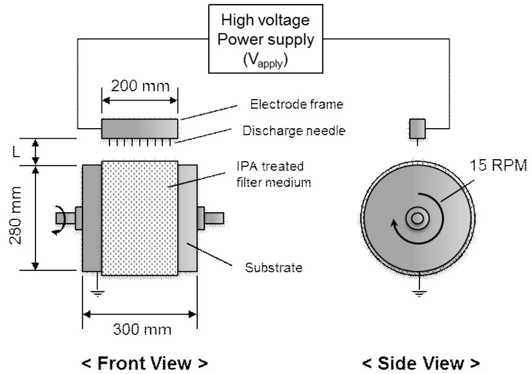

Fig. 2. Schematic of filter charging system.

isopropanol (IPA) following the electrostatic discharging procedure from the European Standard EN 779 (2012), in order to remove the initial electrostatic properties. The IPA treated filter medium was dried for 24 hours in a fume-hood under controlled temperature and relative humidity at 29 °C and 24%, respectively, and finally charged using a corona discharge generator.

2.2 Filter charging using corona discharge generator

The corona discharge generator used for this experiment included electrode frames with multiple discharge needles spaced 5 mm apart and a cylindrical steel substrate that can be rotated (Fig. 2). The needle length was approximately 7 mm, and the electrode frame was about 200 × 50 mm^2. The cylindrical substrate had a width of 300 mm and a diameter of 280 mm. Positive or negative high voltages were applied on the discharge needles, and the substrate was grounded. The IPA treated filter medium was wrapped to the cylindrical substrate and charged by corona discharging while rotating at 15 RPM. The filter charge level was controlled by adjusting the charging time at 0.5, 3.0, and 5.0 min. The voltage applied on the needles (V_{apply}) was set at ±5, ±7, and ±10 kV, and the distance between discharge needle and substrate (electrode distance, L) was set at 15, 20, and 25 mm. Further, to evaluate the influence of charging both sides and charging a single side on the filtration efficiency, both sides of the filter were electrically charged with an applied voltage of +10/+10, −10/−10 and +10/−10 kV. During the experiments, the temperature and relative humidity were maintained in the range of 21–23 °C and 20–30%, respectively. The charged filter medium was cut in samples of 100 ×

Table 1. Experimental condition

Charging side	Applied voltage (kV)	Charging time (min)	Charging distance (mm)	Filtration velocity (cm/s)
Single	±5, 7, 10	0.5	15	3, 5, 10
	-10	0.5, 3, 5	15	
	-10	0.5	15, 20, 25	
Both	+10/+10 +10/-10 -10/-10	0.5	15	

100 mm^2 for filtration tests. Since the performance of the charged filters could vary according to the time of exposure to external air (Nifuku, et al., 2001), the filtration test was conducted 24 hours after the corona charging was completed. Details on experimental conditions are summarized in Table. 1.

2.3 Measurement of surface potential of filter sample

The filtration efficiency of non-electret filters is only dependent on mechanical movement of particles, such as diffusional, interception, and inertial motions, whereas additional electrical forces influence the efficiency of the electret filter. In particular, the trajectory of entering particles to the electret filter is affected by Coulomb and dielectric forces produced by charged fibers. These forces can be calculated by (Donovan, 1985)

$$F_{electric} = \frac{Qq_p}{2\pi\epsilon_0 r} - \left(\frac{k_p - 1}{k_p + 2}\right)\frac{d_p^3 Q^2}{[\![8\pi\varepsilon_0 r]\!]^3} \qquad (1)$$

where q_p is the particle charge, ε_0 the vacuum permittivity, k_p the dielectric constant of the particle, d_p the particle diameter, and r the distance between the center of the particle and central axis of the fiber. The first term on the right side of the Equation (1) represents the attractive Coulomb force between charged fiber and charged particles, while the second term represents dielectrophoretic force, which occurs between a charged fiber and neutral particles. Q represents the unit length charge of the fiber and can be calculated using the Equation (2) with the assumption that the distance between the filter and substrate is negligible.

$$Q = \frac{C_m^2 V}{(C_m + C_c)A} \qquad (2)$$

where C_m and C_c are the electrostatic capacity of filter material and air, respectively, V is the surface potential and A the surface area of the filter medium. As shown in Equations (1) and (2), the electrical forces in the electret filter are strongly affected by the charge strength of the fiber. Since the direct measurement of the unit length charge of the fiber is difficult to obtain, the surface potential of the filter, which is proportional to the unit length charge was measured and used as an indicator of strength of the electrical forces in the electret filter. The surface potential was measured using an electrostatic voltage monitor (Model EVM 102, Sunje Electrostatics, Korea). The distance between the detection probe of electrostatic voltage monitor and the filter sample was fixed at 10 mm with a detection area of 39.25 mm^2.

2.4 Filtration test

The experimental setup for the filtration test of fabricated electret filter samples is shown in Fig. 3. A solution of KCl at 0.1 wt% was aerosolized by an atomizer (9302A, TSI Inc., USA) and the generated particles flowed into a diffusion dryer (3062, TSI Inc., USA) to remove moisture. It is known that neutral aerosols present Boltzmann equilibrium charge distribution. Since atomized particles have high charge (Johnston et al., 1987; Yeh et al., 1988; Emets et al., 1991), a neutralizer (GRIMM Model 5.621, Germany) was installed right-after the diffusion dryer outlet to alter the charge of the atomized particles to the Boltzmann equilibrium charge distribution. The particles entered an acrylic test duct (with cross-section area of 100 × 100 mm^2 and length of 240 mm) in which a tested filter media was installed. The number concentrations at each particle size (d_p) were measured by a scanning mobility particle sizer (SMPS) consisting of an electrostatic classifier (Model 3080, TSI Inc.), a DMA (Model 3081, TSI inc.) and a condensation particle counter (CPC, Model 3025A, TSI Inc.). The flow rate in the atomizer was fixed at 5 lpm and the filtration velocity was controlled at 3.0, 5.0 and 10.0 cm/s by adjusting the flow rate of a clean air. The partial (η_f) and overall (η_o) filtration efficiencies of the filter sample were calculated by

$$\eta_f(d_p) = \left(1 - \frac{C_{down}(d_p)}{C_{up}(d_p)}\right) \times 100\% \tag{3}$$

$$\eta_o = \left(1 - \frac{\Sigma C_{down}(d_p)}{\Sigma C_{up}(d_p)}\right) \times 100\% \tag{4}$$

where, C_{up} and C_{down} are particle concentrations upstream and downstream of the filter sample, respectively. Moreover, we defined four parameters to perform a quantitative analysis of the effects of charging time and electrode distance on the filtration efficiency by considering

$$\Delta\eta_{\tau} = \frac{\eta_{o,charge} - \eta_{o,IPA}}{\tau} \tag{5}$$

$$q_T = \frac{V_{charge} - V_{IPA}}{\tau} \tag{6}$$

$$\Delta\eta_L = \frac{\eta_{o,charge} - \eta_{o,IPA}}{L} \tag{7}$$

$$q_L = \frac{V_{charge} - V_{IPA}}{L} \tag{8}$$

where $\Delta\eta_{\tau}$ and $\Delta\eta_L$ are the charging effectiveness by charging time and electrode distance, respectively, q_T and q_L represent the average increase of surface potentials with respect to charging time and electrode distance, respectively, and τ is the charging time of the filter. Subscripts *charge* and *IPA* represent the electret filter sample and IPA treated filter sample, respectively. Since particle loading on the electret filter leads to degradation of filtration efficiency (Tabti et al., 2010a; Plopeanu et al., 2011; Rengasamy et al., 2013), all experiments were conducted within a 10 min timeframe.

3. Results and Discussion

3.1 Effects of applied voltage

The size distribution of inlet particles and partial filtration efficiencies of fabricated electret filter samples are shown in Fig. 4a. When filtration velocity was 3 cm/s, the concentration and mode diameter of

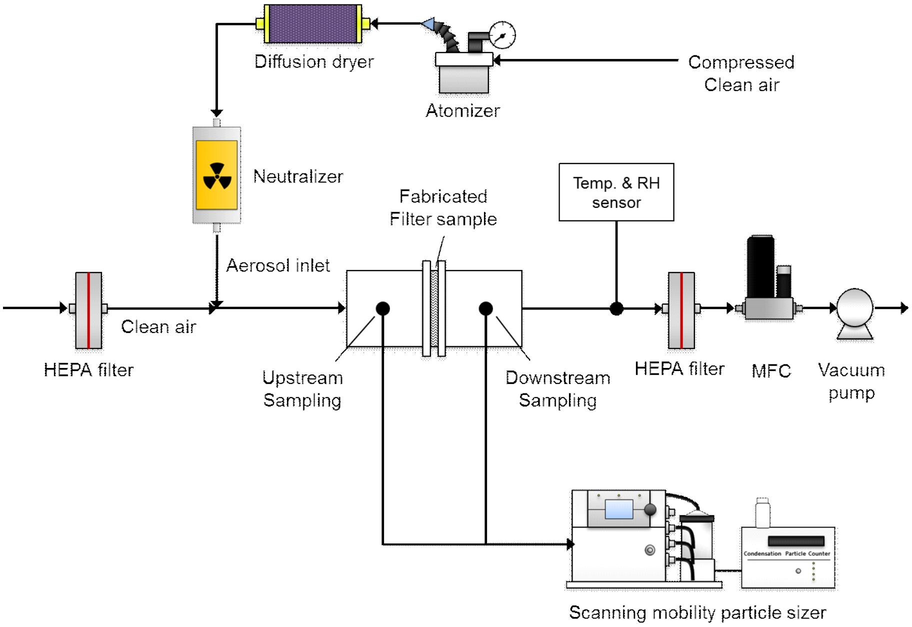

Fig. 3. Experimental setup for filtration test.

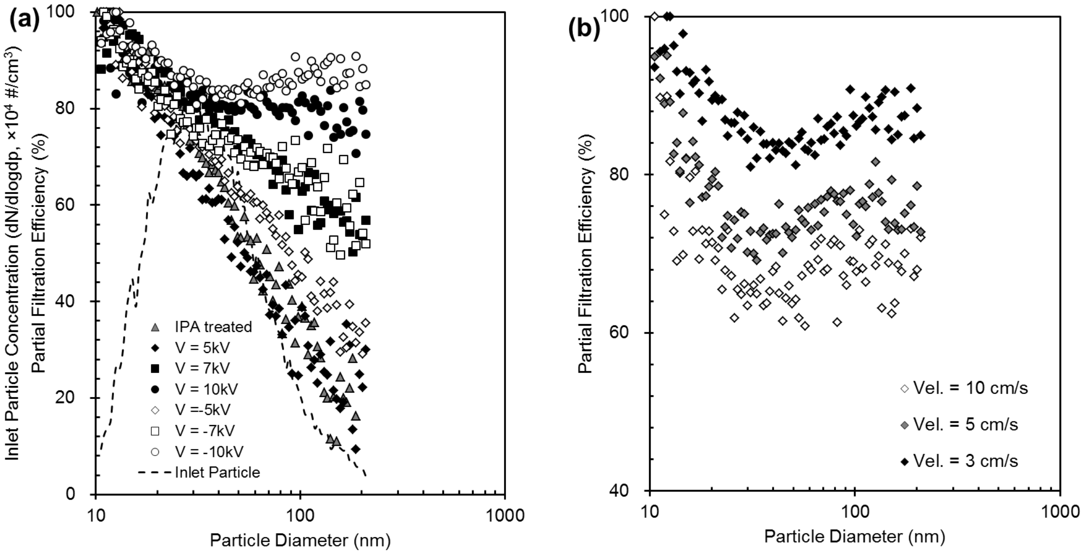

Fig. 4. (a) Size distribution of inlet particles and partial filtration efficiency of fabricated electret filters at 3 cm/s of filtration velocity, and (b) the efficiency under various filtration velocities when applied voltage, charging time, and charging distance were of −10 kV, 5 minutes, and 15 mm, respectively.

inlet particles were of 5.6×10^5 particles/cm^3 and 31 nm, respectively. Surface potentials of the electret filter sample were of 4.51, 7.64, and 8.99 kV when applying voltages of +5, +7, +10 kV, respectively, whereas surface potentials of −2.44, −5.98, and −9.84 kV were present when applying the corresponding negative voltages. The filtration efficiency increased with the applied voltage, but no electrical filtration effect was apparent when the applied voltage was ±5 kV. The efficiency of the negatively charged filter was slightly higher than that of the positively charged filter, even though the magnitudes of surface potentials were slightly lower than those of positive apply voltage cases. It is known that number concentration of negative ions generated by corona discharge is much higher than that of positive ions (Chen and Davidson, 2003; Intra and Tippayawong, 2010). Moreover, the mobility of negative air ion, which represents the drift velocity component in the electric field direction of unit strength, is larger than that of positive air ion (2.1 m^2/V·s for negative air ion, 1.36 m^2/V·s for positive air ion) (Kuffel et al., 2000). The negative ions having high number concentration and the mobility might affect the charging of filter fiber located deep in the filter medium. Thus, negatively charged filter might have superior filtration ability rather than positively charged filter, if they were fabricated under same corona discharge condition except the polarity of applied voltage. However, the surface potential did not represent the difference in the filtration efficiencies of two filters when they had different polarities.

The partial filtration efficiency of the electret filter sample for various filtration velocities is shown in Fig. 4b. The filtration efficiency decreased as its velocity increased. In fact, the mechanical filtration mechanisms such as diffusion, interception, and inertial motions are strongly affected by filtration velocity. Moreover, the velocity represents the residence time of the charged particle inside the electric field. Since, the dominant mechanical and electrical filtration mechanisms affecting particles with a diameter under 0.1 μm are particle's diffusional and electrical motions, which are inversely proportional to filtration velocity, the increasing of filtration velocity resulted in decreasing of filtration ability of the electret filter.

3.2 Effects of charging time and charging distance

Figure 5a shows the overall filtration efficiency for various charging times under an applied voltage and electrode distance of −10 kV and 15 mm, respectively. As charging time increased, the filter surface potential also increased. When charging time was 5 min, the surface potential was approximately of −9.94 kV, which is close to the voltage that was applied to the discharge needles. Here, the efficiency was of 72.5, 78.7, and 86.3% at filtration velocity of 10, 5.0, and 3.0 cm/s, respectively. On average, there was a 25% increase in efficiency compared to the IPA treated filter sample. Moreover, the efficiency also followed the tendency that the efficiency decreases with increased filtration velocity. When electrode distance increased, the surface potential of the filter decreased, leading to a decrease in filtration efficiency (Fig. 5b).

Major factors that affect filter fiber charging are ion concentration near the filter fiber and exposure time of the filter fiber to the ions. Since the ion concentration generated by corona charging is inversely proportional to the distance between the discharge needle and the grounded substrate, charging time and charging distance can be considered to represent exposure time and ion concentration, respectively. The effects of charging time on filtration efficiency and surface potential were calculated by Equations (5 - 6) and shown in Fig. 6(a). An increase of charging time led to a decrease of both the average increasing rate of surface potential and the filter charging effectiveness. It might result from decreasing of electric field strength between filter surface and discharge needles by charged filter fiber. Since the polarity of filter fiber is same with that of discharge needles, the electric field strength would have gradually decreased during corona charging process. For this reason, the electrical velocity of ions decreased, thus the attaching ions on the filter fiber might decrease with a corresponding increase of charging time. The effect of electrode distance on filtration efficiency was similar to that of charging time, but its effect was much smaller (Fig. 6(b)). This suggests that charging time is a more

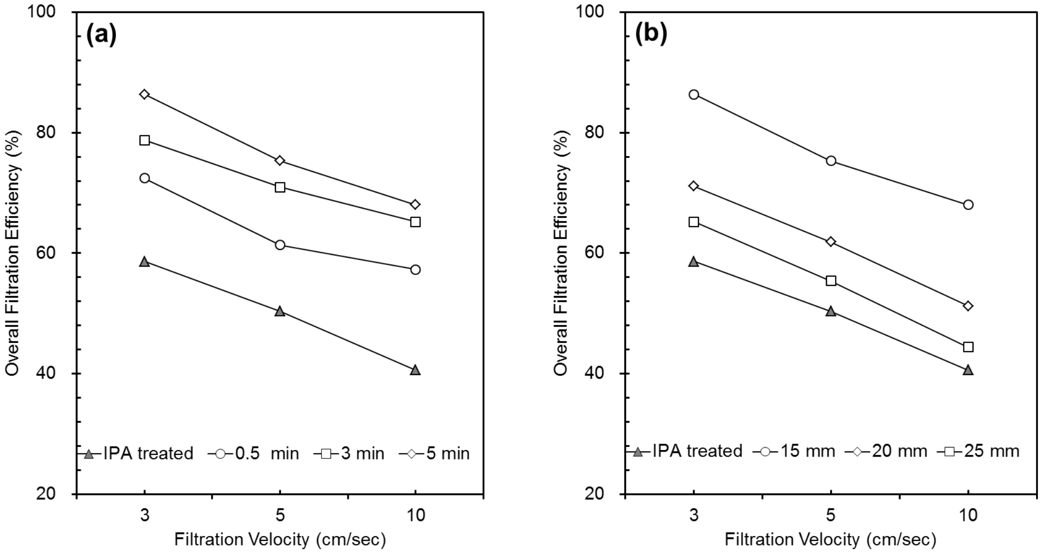

Fig. 5. Overall filtration efficiency with (a) various charging time and (b) various electrode distance.

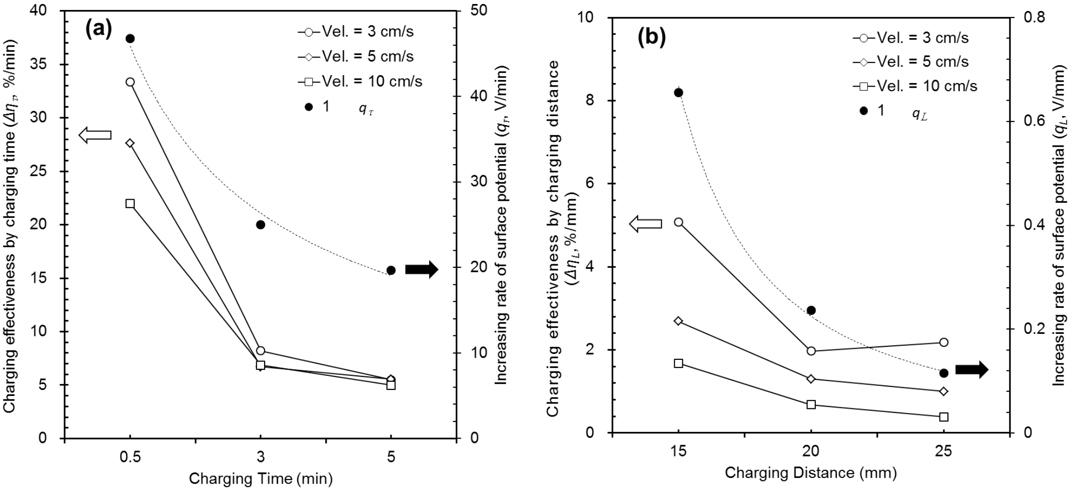

Fig. 6. Charging effectiveness and increasing rates of surface potentials (a) by charging time and (b) by electrode distance.

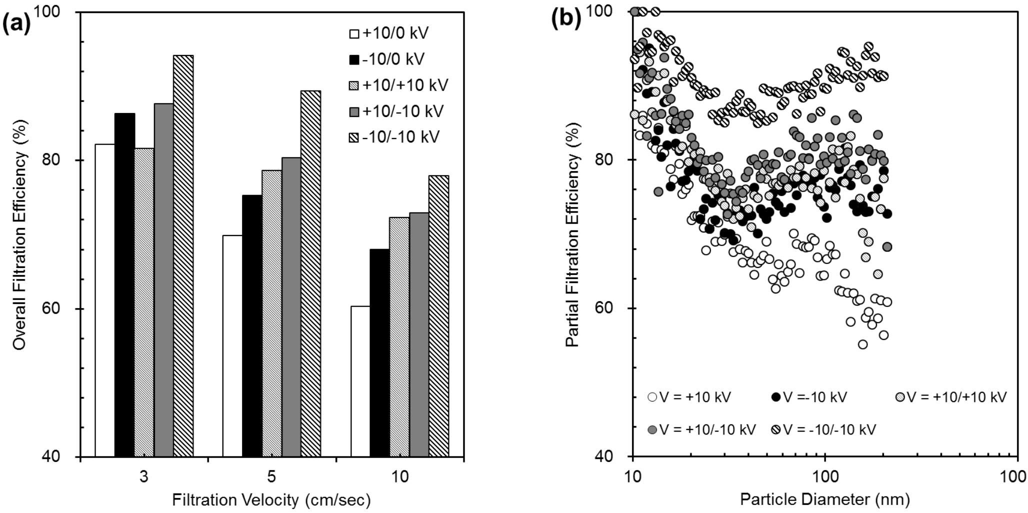

Fig. 7. (a) Overall filtration efficiency for single-side and both-side charged electret filters and (b) partial filtration efficiency for each particle size when filtration velocity is 5 cm/s.

dominant factor for improving electret filter performance rather than distance between two electrodes. However, since the effectiveness of charging time is slightly reduced during corona charging process, the improvement of the filtration efficiency by charging time increasing is limited.

3.3 Effects of charging both sides

To verify the effects of both-side and single-side charged filter, the overall filtration efficiency was compared and evaluated using filter samples charged with an applied voltage of +10 kV or −10 kV on a single side, filter samples charged with an applied voltage of +10 kV or −10 kV on both sides, and filters charged on both sides with an applied voltage of +10 kV on one side and −10 kV on the other side (Fig. 7a). In this experiment, the charging time and charging distance were fixed at 5 min and 15 mm, respectively. The overall filtration efficiency of both-side charged filter was superior to that of single-side charged filter regardless of the charging polarity. Filters charged on both sides or charged with negative voltage showed higher filtration efficiency than filters charged with positive voltage. Likewise, filters charged with different polarity on each side showed a better filtration efficiency than filters charged with +10 kV applied voltage on both sides. This shows that degradation of the efficiency of positively charged filter fibers might be compensated by the efficiency of negatively charged filter fibers, which had higher filtration ability. The partial filtration efficiency with a fixed filtration velocity of 5 cm/s is shown in Fig. 7b. In general, the tendencies were similar except for the case of single side with applied voltage of +10 kV. The efficiency decreased with an increase of particle size until reaching most penetration particle size (MPPS) at approximately 30 nm, and from that particle size and above, the tendency is inversed. The efficiency of both-side charging with −10 kV was superior for all particle sizes, while the efficiency of the other cases showed slight differences for particle sizes larger than 30 nm. It is known that the amount of charged particles in neutralized particles increases with particle size (Hinds, 1999). For this reason, relatively large particles might be more sensitive to changes of fiber charging conditions.

4. Conclusion

This study examined the filtration efficiency of electret filters under various corona charging conditions. Moreover, the surface potential which is directly proportional to the unit length charge of electret filter fiber was measured and used as an indicator of electrical forces in the filter medium. The surface potentials increased with apply voltage increasing. There is no significant change in filtration efficiency when strength of applied voltage was lower than 5 kV, but the filtration efficiency proportionally increased with the apply voltage strength when the strength was higher than 7 kV. In the polarity test, the surface potentials were slightly lower than those of positive apply voltage cases. On the other hand, negatively charged filters showed higher filtration efficiency under all filtration velocity conditions than positively charged filters. It is known that electrical mobility of negative ion is higher than that of positive ion in the same electric field. By this reason negative ions might affect the charging of filter fiber located deep in the filter medium and result in the inversely tendency between surface potential and filtration efficiency. As the charging time of filter fiber increased, the filtration efficiency also increased. However, the amount of the increase was reduced over time. As electrode distance increased, filtration efficiency decreased due to a decrease in ion concentration resulting from corona charging, and the increment in filtration efficiency is reduced for longer distances. For tested electret filters using corona charging, the influence of charging time on the filter's filtration efficiency was higher than that of charging distance. Moreover, when both sides of the filter were charged, filtration efficiency was higher compared to that obtained when a single side was charged, and filtration efficiency was the highest when both sides were negatively charged. The results of this study can be used as basic data for the determination of charged polarity and the configuration of filter charging device in electret filter manufacturing. However, in this study, the filtration ability of fabricated filter was tested using pristine filter sample, even though the ability is strongly affected by dust loading on the filter surface. As result of this study, it can be expected that both sides charged electret filter have higher robustness to dust loading comparing with single side charged electret filter, because back side of the filter is relatively less exposed to dust loading. Thus, filtration characteristics of the electret filter fabricated under various corona discharge conditions should be studied with dust loading in the future works.

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