A Study on Electrical Charge Distribution of Aerosol Using Gerdien Ion Counter

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ABSTRACT

The motion of charged particles strongly depends on its charge characteristics; as a result, information on charge distributions of target particles is an important variable in aerosol research. In this study, the charge distribution of atomized NaCl particles was measured using a Gerdien-type ion counter. Two particle charging conditions were used in this study. First, atomized NaCl particles were passed through an aerosol, resulting in a Boltzmann charge distribution. The charge distribution was experimentally determined, and the percentage of uncharged particles was compared to the percentage obtained from the theoretical Boltzmann charge distribution equation to verify the experimental method. The same experiment was conducted without the aerosol neutralizer to measure the charge distribution of the atomized and un-neutralized NaCl particles. The percentage of uncharged, negatively charged, and positively charged particles was 19%, 62%, and 20%, respectively, for the neutralized particles. For the atomized particles, which were generated without the aerosol neutralizer, a nearly zero charge state was observed, but the standard deviation in the charge distribution was larger than that of the neutralized particles. The experimental method proposed in this study is expected to be applicable to various aerosol research fields because it can be used to obtain simple information regarding the particle charge characteristics more easily and quickly than conventional methods.

Keywords: Aerosol particle; Charge distribution; Current measurement; Gerdien ion counter.

INTRODUCTION

Aerosol measurement and related studies are being increasingly conducted to meet the rising demand for understanding the charging characteristics of aerosol particles. Electrically charged aerosol particles move along a streamline and are subjected to an external electrical force. Thus, if an electric field exists around aerosol particles, the behavior of the charged particles differs from that of uncharged particles. For this reason, the charging characteristics of aerosol particles have a significant influence on the measurement, analysis, collection, and synthesis (Hinds, 1999).

Various studies have been performed to analyze the charge characteristics of aerosol particles. A study conducted

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in 1984 measured the quantity of particle charges as a function of particle size using a differential mobility analyzer (DMA) and optical aerosol spectrometer (Porstendörfer *et al.*, 1984). This technique can measure the quantity of charged particles in a relatively easy manner using the electrical mobility of aerosol particles, while the charge characteristics of nanoparticles with a diameter of ≤ 500 nm are difficult to analyze due to the limitations of the optical apparatus. In the 1990s, the integral mobility technique was proposed, which can analyze the charge of liquid- or solid-phase nanoparticles. Nevertheless, the polarity of the charged particles cannot be determined by the developed method (Adachi *et al.*, 1990; Wake *et al.*, 1991; Forsyth *et al.*, 1998). Ahn *et al.* (2001) and Kim *et al.* (2005) used a tandem differential mobility analyzer (TDMA) technique to measure the quantity of charged particles as function of particle size by connecting two DMAs in series. Although the TDMA technique is most widely used in analytical studies on charged particle characteristics, its analytical process is complicated and a long time is required to analyze the charge characteristics of a single specimen. Ahn and Chung (2010) proposed a different method to measure the quantity of charged particles in real-time using a DMA, particle condenser, and charge-coupled device (CCD) camera. This technique can analyze the charge distribution of the particles as a function of particle size with high precision.

However, in this technique the device configuration is complicated and the measurement results are sensitive to changes in the external environment due to the use of a condenser and camera.

Previous studies have proposed techniques that require a complicated device configuration to measure the charge quantity of aerosol particles as a function of particle size with high precision using a long-time measurement. However, studies on the design of particle collectors using an electric field require approximate information on the charge characteristics of aerosol particles discharged from a specific source within a short time in a simple manner. These applications are subject to temporal and spatial constraints in applying any analytical methods.

Herein, we propose a method to analyze the charge distribution of aerosol particles in a simple manner using a Gerdien-type ion counter. The ratio of uncharged particles to total aerosol particles was calculated using the ratio of the number concentration of the aerosol particles flowing into the ion counter and the number concentration of the aerosol particles measured at the rear end of the ion counter. The ratio of positively charged to negatively charged particles was calculated using the micro-current measured from the ion counter. Furthermore, the validity of the proposed method was tested by comparing the experimental results with those predicted by theoretical calculation. The test method proposed in this study could be used in various aerosol research fields because it facilitates the simple and quick acquisition of information on the charge characteristics of particles.

METHODS

Method for Measuring Number Concentration and Charge Quantity of Aerosol Particles

To analyze the charge distribution of aerosol particles, the particle number concentration and quantity of charge were measured, and the test method is shown in Fig. 1(a). A total of 2.5 L min^{-1} of clean compressed air was injected into an atomizer (9302, TSI Inc.) to atomize a 1 wt% aqueous NaCl solution. The atomized NaCl droplets were granulated using a diffusion dryer installed downstream of the atomizer. The generated particles were diluted with 5.0 L min^{-1} of clean air to adjust the concentration, and a 1.0 L min^{-1} flow rate was used for the test. The charged state of the generated aerosol particles was controlled using an aerosol neutralizer (Model 5522, Grimm). When the aerosol neutralizer was used, the atomized aerosol particles were electrically neutralized to exhibit a Boltzmann charge distribution. When the aerosol neutralizer was not used, the charge state at the time of atomization was maintained. The proposed experimental method was verified by comparing the experimental results of electrically neutralized aerosol particles with the theoretically determined values, and the charge distribution of the atomized aerosol particles was further calculated based on the verified experimental method.

A Gerdien-type ion counter manufactured in the laboratory was used to measure the charge quantity of the

aerosol, and the operating principle is shown in Fig. 1(b). The ion counter used in this study contained an aluminum rod of inserted into the center axis of an aluminum circular tube. A copper tube was inserted inside the circular tube, and the insulation between the copper and aluminum tubes was formed using polytetrafluoroethylene (PTFE). The inner diameter of the copper tube was 38.2 mm, the diameter of the aluminum rod was 19 mm, the distance between the rod and tube was 9.6 mm, and the length of the copper tube was 150 mm. High voltage was applied to the aluminum rod using a high voltage power supply and the circular tube was grounded. When a high voltage was applied to the aluminum rod, an electric field formed inside the measuring device, and the charged particles flowing into the ion counter moved along the electric force line. Among the moving particles, the particles with the same polarity as the voltage applied to the aluminum rod were collected on the surface of the copper tube. An electrometer (Model 6514, Keithley) was installed between the copper and circular tubes to measure the micro-current generated when the charged particles adhered to the surface of the copper tube. The polarity of the voltage applied to the aluminum rod was changed to measure the micro-currents generated by the positively and negatively charged particles among the particles flowing into the ion counter. At the rear end of the ion counter, a scanning mobility particle sizer (SMPS) consisting of a DMA (Model 55-900, Grimm) and Faraday cup electrometer (FCE, Model 5.705, Grimm) was installed to measure the number concentration of particles.

Method for Calculating Charge Distribution of Aerosol Particles

When a high voltage is applied to the aluminum rod of the ion counter, an electric force forms inside the ion counter. As a result, only the charged particles can be selectively collected inside the ion counter. If the voltage applied to the aluminum rod is sufficiently large and particle deposition due to diffusion is negligible, all particles measured downstream of the ion counter can be assumed to be uncharged. The intensity of the voltage applied to the ion counter was gradually increased to measure the concentration of downstream particles. If the number concentration of the particles did not change even when the applied voltage was raised, all measured particles were assumed to be uncharged. The ratio of the uncharged to aerosol particles (P_0) was calculated using the number concentration and Eq. (1):

$$P_0 = \left\{ \left(\frac{C_{on}}{C_{off}} \right)_+ + \left(\frac{C_{on}}{C_{off}} \right)_- \right\} / 2 \qquad (1)$$

where C_{on} is the total number concentration of particles downstream of the ion counter when a voltage is applied, and C_{off} is the total number concentration of particles measured when no voltage is applied. The subscripts + and – represent the polarity of the voltage applied to the ion counter. The test results were verified by comparing the ratio of the uncharged particles measured under the
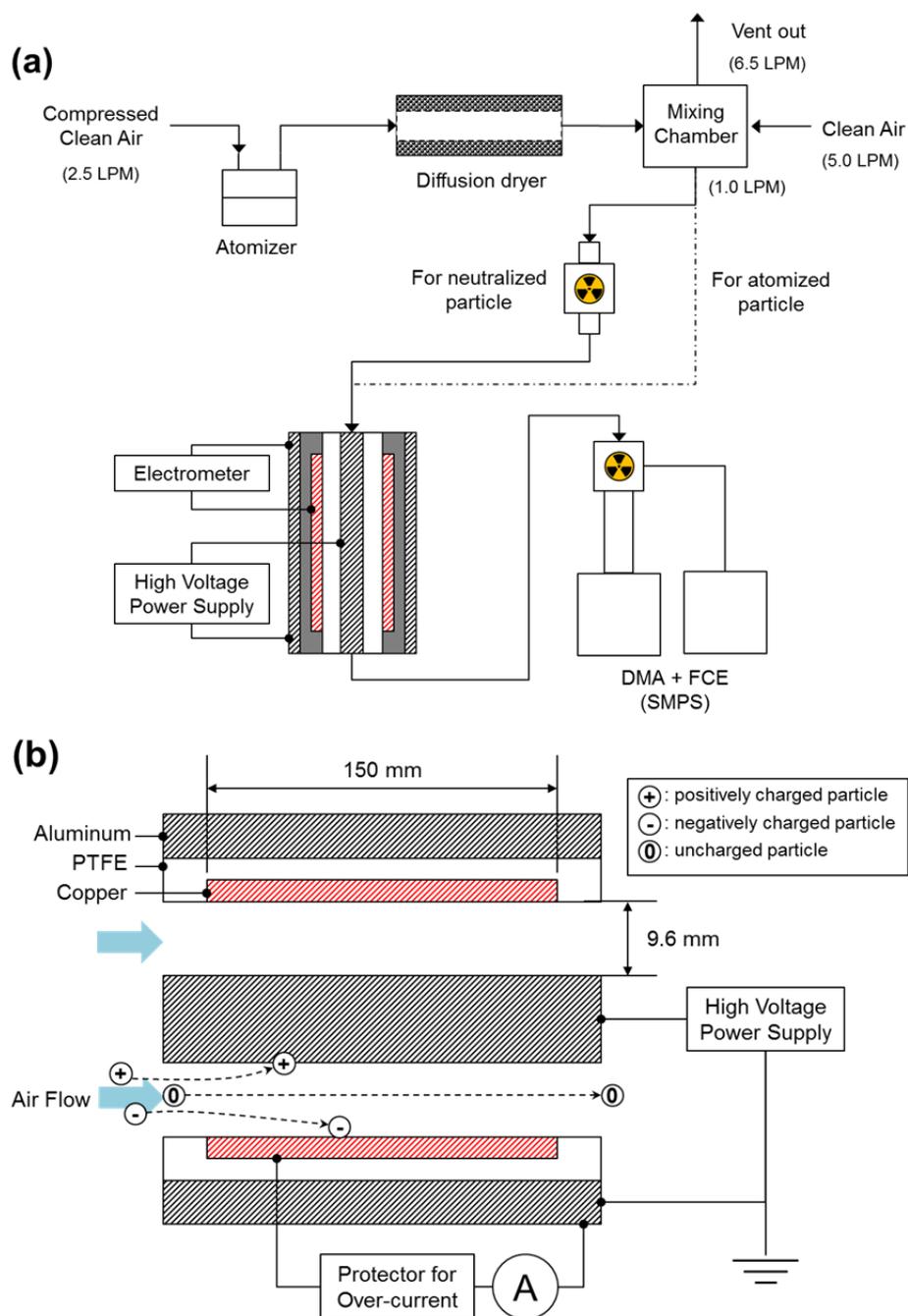
Fig. 1. Schematic diagrams of (a) the experimental setup and (b) lab made Gerdien-type ion counter.

electrically neutralized condition to the ratio of uncharged particles calculated using the theoretical Boltzmann charge distribution. The ratio of uncharged particles at a specific particle size, d_p, can be theoretically calculated using Eq. (2) (Yeh and Cheng, 1983):

$$P_{0,d_p} = \left(\frac{K_E e^2}{\pi d_p kT} \right)^{\frac{1}{2}} \exp\left(\frac{-K_E n^2 e^2}{d_p kT} \right)\Bigg|_{n=0} = \left(\frac{K_E e^2}{\pi d_p kT} \right)^{\frac{1}{2}} \quad (2)$$

where K_E is the electrostatic constant of the particles ($9 \times$

10^9 N × 10^9 N m^2 C^{-2}), e is the unit charge (1.6×10^{-19} C), k is the Boltzmann constant (1.38×10^{-23} J K^{-1}), T is the absolute temperature, and n is the charge of the particles.

The proportions of positively charged particles (P_+) and the ratio of negatively charged particles (P_-) in the aerosol were calculated based on the current measured by the electrometer using Eq. (3):

$$P_+ = (1 - P_0) \times \frac{\left| I^+ - I_0^+ \right|}{\left| I^+ - I_0^+ \right| + \left| I^- - I_0^- \right|} \quad (3)$$

$$P_- = (1 - P_0) \times \frac{\left|I^- - I_0^-\right|}{\left|I^+ - I_0^+\right| + \left|I^- - I_0^-\right|} \tag{4}$$

where I^+ and I^- refer to the intensities of the micro-current measured when the high voltages of positive and negative polarity were applied to the ion counter, respectively. The subscript 0 refers to the initial current value observed in the electrometer under the conditions where particle injection into the ion counter was prevented and no voltage applied.

RESULTS AND DISCUSSION

Charge Distribution Analysis of Neutralized Aerosol Particles

Fig. 2 shows the changes in the particle size distribution and total number concentration according to the applied voltage when the electrically neutralized aerosol particles flowed into the ion counter. The number concentration of the generated NaCl particles was approximately 6.8×10^6 #/cc and the modal diameter was approximately 69 nm. When voltage was applied to the ion counter, the number concentration of NaCl particles significantly decreased and further maintained from the 500 V level of the applied voltage. Furthermore, polarity of the applied voltage did not lead to significant differences in the number concentration and modal diameter of the particles.

When the intensities of applied voltage were 500 and 1000 V, the ratio of the uncharged particles calculated using Eq. (1) was compared to the results obtained using the theoretical equation, Eq. (2) (Fig. 3). According to the Boltzmann charge distribution equation, the percentage
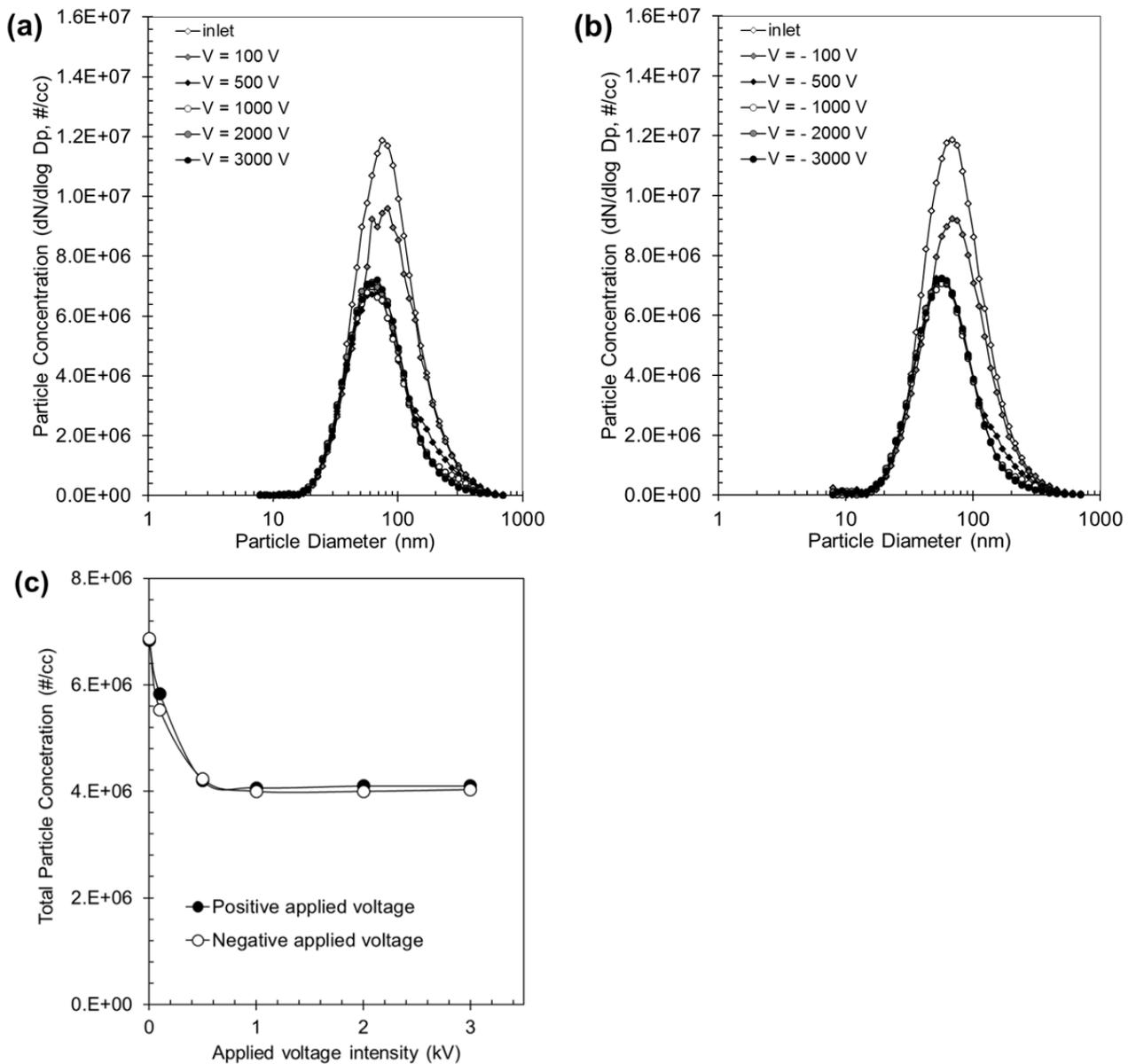
Fig. 2. Particle number concentrations of the neutralized particles with (a) positive and (b) negative applied voltages. (c) Total particle concentration with various applied voltage intensities.
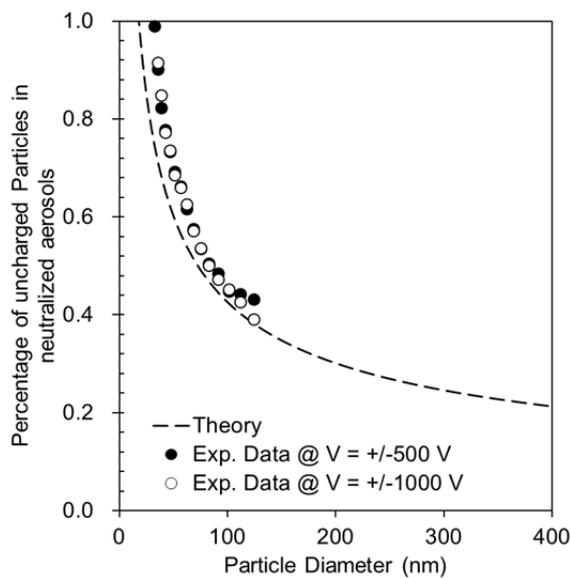
Fig. 3. Experimental and theoretical percentages of uncharged particles in the neutralized aerosols.

of uncharged particles is inversely proportional to the particle diameter and the experimental results showed a similar inversely proportional tendency. Thus, in the subsequent experiment, when the intensity of the applied voltage was higher than 500 V, it was assumed that all charged particles among the particles flowing into the ion counter were collected in the ion counter and all particles observed downstream of the ion counter were uncharged.

Fig. 4 shows the current measured by the electrometer according to the polarity and intensity of the applied voltage. The "ON" and "OFF" modes shown in Fig. 4 indicate whether or not the particles were injected where the voltage was continuously applied. When the particles were

injected into the ion counter, the current measured by the electrometer increased. When the particle injection was prevented, the current significantly decreased. When a positive voltage of ≥ 500 V was applied, the current increase due to the increased applied voltage was not significant, while the amount of measured current increased as the applied voltage exceeded 2000 V. When a highly negative voltage was applied, the amount of current measured at the voltage intensity of ≥ 2000 V abnormally increased, and current was observed even when the particle injection was prevented. This phenomenon is inconsistent with the results of previous uncharged particle measurements. In the uncharged particle measurement experiment, when the intensity of the applied voltage was higher than 500 V, no significant change in the number of particles measured downstream of the ion counter was observed. This suggests that most of the charged particles are collected in the ion counter. Thus, the measured current should not significantly vary when the intensity of the applied voltage is higher than 500 V. Although there may be many causes of the abnormal current increase measured at high voltage intensities of ≥ 2000, the increase could be due to ground sharing between the high voltage power supply and electrometer (see Fig. 1(b)).

In this study, ± 500 V of applied voltage were chosen as the operating voltages of the ion counter because at this applied voltage intensity, the charged and uncharged particles can be effectively separated and the current can be measured in a relatively stable manner. The experimental results and Eqs. (1), (3), and (4) were used to calculate the charge distributions of the electrically neutralized aerosol particles. The ratios of uncharged, negatively charged, and positively charged particles to the electrically neutralized aerosol particles were 62%, 19%, and 20%, respectively, which corresponds to the theoretical Boltzmann charge distribution.
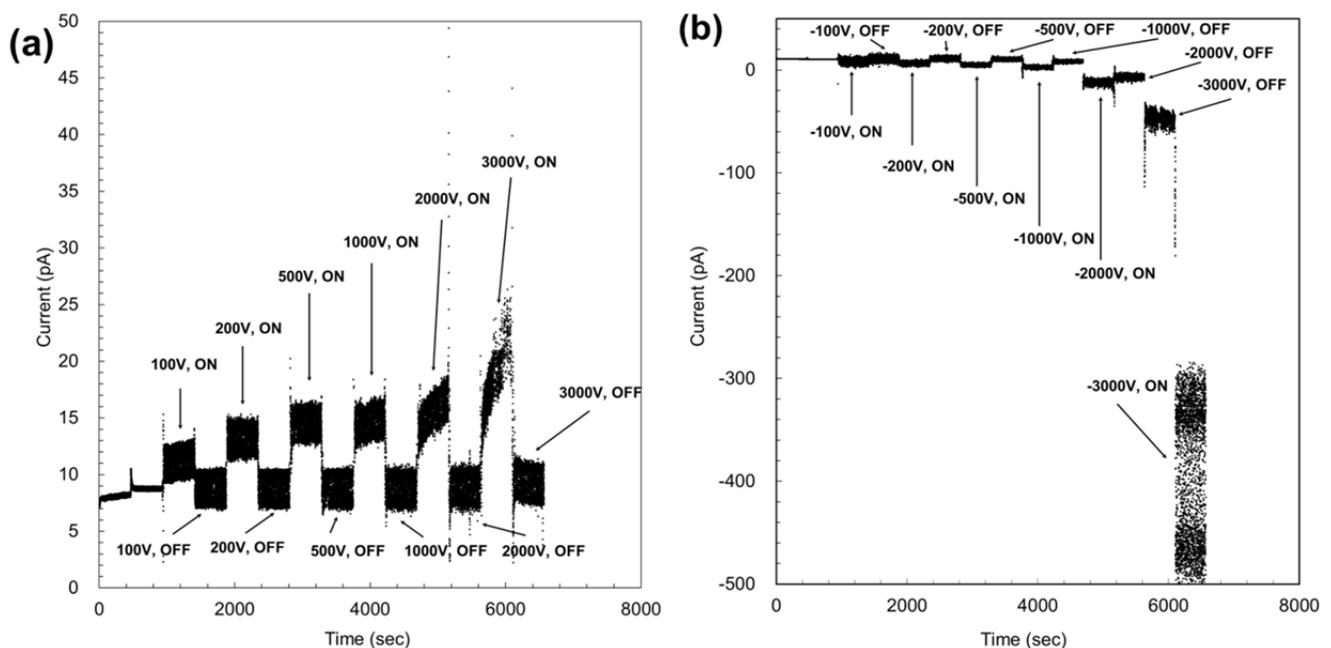
Fig. 4. Currents when (a) positive and (b) negative voltages were applied.

Charge Distribution Analysis of Atomized Aerosol Particles

In order to measure the charge distribution of the aerosol particles generated from the atomizer, the experiment was performed after removing the aerosol neutralizer (see Fig. 1), and Fig. 5 shows the size distributions and total number concentrations according to applied voltage. The experimental results were similar to the experimental results of the electrically neutralized aerosol particles. When voltage was applied to the ion counter, the number concentration of NaCl particles significantly decreased and the number concentration was constant at ≥ 500 V of applied voltage in intensity. When the intensity of the applied voltage was 500 V, the current measured by the electrometer was approximately 13.9 pA with positive

polarity and was approximately –12.4 pA with negative polarity. Based on the above results, the charge distribution of the aerosol particles generated from the atomizer was calculated, and the obtained ratios of uncharged, negatively charged, and positively charged particles were 33%, 32%, and 36%, respectively.

Table 1 summarizes the charge distributions of the neutralized and atomized aerosol particles. In both cases, the proportions of negatively and positively charged particles were not significantly different. However, the uncharged particle proportion of the neutralized aerosol particles was higher than that of the atomized particles, suggesting that the standard deviation of the charged particle distribution decreases when the atomized aerosol particles pass through the aerosol neutralizer.
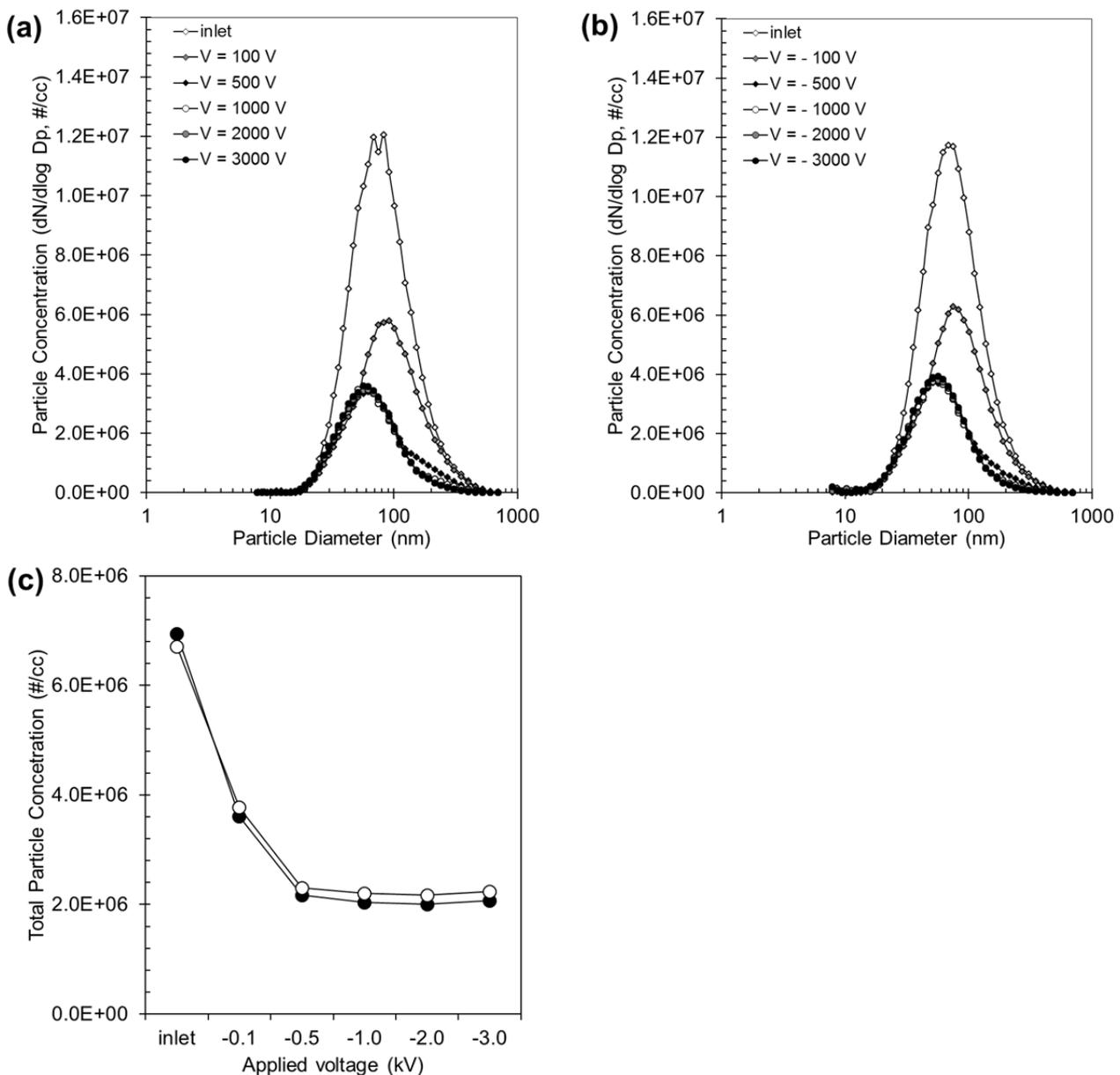
Fig. 5. Particle number concentrations of the atomized particles with (a) positive and (b) negative applied voltages. (c) Total particle concentration with various applied voltage intensities.

Table 1. Calculation results of the charge states of the neutralized and atomized particles.

Condition	Charge state of the particles		
	Negatively charged	Uncharged	Positively charged
Neutralized particle	19	62	20
Atomized particle	32	33	36

CONCLUSION

This study analyzed the charge distribution characteristics of particles using a Gerdien-type ion counter. The experimental results were verified by comparing the percentage of electrically neutralized aerosol particles with that determined via the theoretical Boltzmann charge distribution equation. The charge distribution of the atomized aerosol particles was calculated based on these results. The NaCl aerosol particles generated from the atomizer were uncharged on average regardless of the application of the aerosol neutralizer. However, the standard deviation of the aerosol particle charge distribution decreased when the aerosol neutralizer was used. Future studies will develop a solution to the measurement problem of abnormal current values in the electrometer, which occur when high voltages are applied to the ion counter. In addition, the charge distribution calculation of charged particles in the aerosol as a function of particle size will be further refined. This study can be applied to various studies on aerosols, including aerosol synthesis, electrical collector design, and atmospheric aerosol particle characterization.

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