

Durability of brush electrode in an electrostatic precipitator

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Abstract

An electrostatic precipitator (ESP) is suitable for collecting nano-order suspended particles. In order to clean the air in living spaces using ESPs, a low ozone concentration must be maintained. Therefore, the aim of this study is to investigate discharge electrodes that can achieve high collection efficiency for long periods of time at low ozone concentrations. In this study, the durability performance of a disk-shaped carbon brush electrode in long-term operation was investigated in positive and negative corona discharges. The ESP consisted of a discharge section, which had a disk electrode with 20 carbon brushes, and an electrostatic section. A positive or negative DC high voltage was applied to the discharge section and the ozone concentration was adjusted to 0.05 ppm, and the ESP was operated for 2,000 hours. Initially, the collection efficiency under negative corona discharge was 94%, and decreased to 83.6% after 2,000 hours. Conversely, under positive polarity, the initial collection efficiency was 99.5% and remained as high as 94% even after 2,000 hours. This indicates that positive polarity can maintain high collection efficiency over 2,000 hours with low ozone concentrations.

Keywords: Electrostatic precipitator (ESPs), ozone, carbon brush electrode, corona discharge, collection efficiency.

1. Introduction

Infectious diseases such as novel coronaviruses and influenza viruses have affected many people worldwide. These infections can spread through contact, droplets, or aerosols, highlighting the importance of clean air in infection control. Viruses range in size from 20 to 300 nm [1], while droplet viruses are between 50 nm and 500 μ m [2]. An electrostatic precipitator (ESP) is suitable for the removal of nano to micro-order suspended particles from the air. ESPs typically use corona discharge, which produces ozone capable of inactivating viruses and bacteria captured during filtration [3–4]. However, indoor and working environment evaluation standards limit ozone concentrations to below 0.05–0.1 ppm. Therefore, ESPs are required to achieve high collection efficiency at low ozone levels.

It is known that ozone generation can be reduced by using an electrode heating [5], a silver electrode [6], or insulation coated ground electrode [7]. Katatani and Mizuno proposed an ESP with carbon fiber [8–11]. Kim *et al.* achieved high collection efficiency greater than 85% at a low ozone concentration less than 0.15 ppb in an ESP with carbon fiber [12–14]. Ehara *et al.* also investigated the effect of a carbon fiber electrode [15].

Zukeran and Yasumoto investigated the effect of disk electrodes with knife edges [16] and carbon brush electrodes as a discharge electrode in an ESP. Carbon brush electrodes demonstrated a high collection efficiency ranging from 96% to 99.8% for virus-sized particles, while maintaining a low ozone concentration of 0.025 ppm for 150 hours of continuous operation [17]. The low ozone levels and high collection efficiency must be maintained for long periods of time for practical use.

Therefore, this study focuses on the durability of carbon brush electrodes, evaluating their performance for 2,000 hours of continuous operation while measuring ozone concentration and collection efficiency.

2. Experimental

A schematic diagram of the experimental system is shown in Fig. 1. The system was composed of a duct, an electrostatic precipitator (ESP), and a fan. The ESP consisted of a charging section and a collection section. The charging section featured a coaxial cylinder structure consisting of a disk electrode and a grounded cylindrical electrode (90 mm in diameter, 200 mm in length). Two types of disk electrodes were used: a carbon brush disk electrode and a cemented carbide disk electrode (ARS CORPORATION, CH-45) [17]. Details of the carbon brush disk electrode is shown in Fig. 2. Twenty brushes are attached to a disk electrode (35 mm in diameter). Each brush consists of 6,000 carbon fibers, each with a diameter of 6 μm and a length of 5 mm. The cemented carbide disk electrode consists of carbon (C), tungsten (W), cobalt (Co), and other materials, and has a hardness greater than steel, making it highly resistant to wear. The distance between the tip of the disk electrodes and the ground electrode is 22.5 mm.

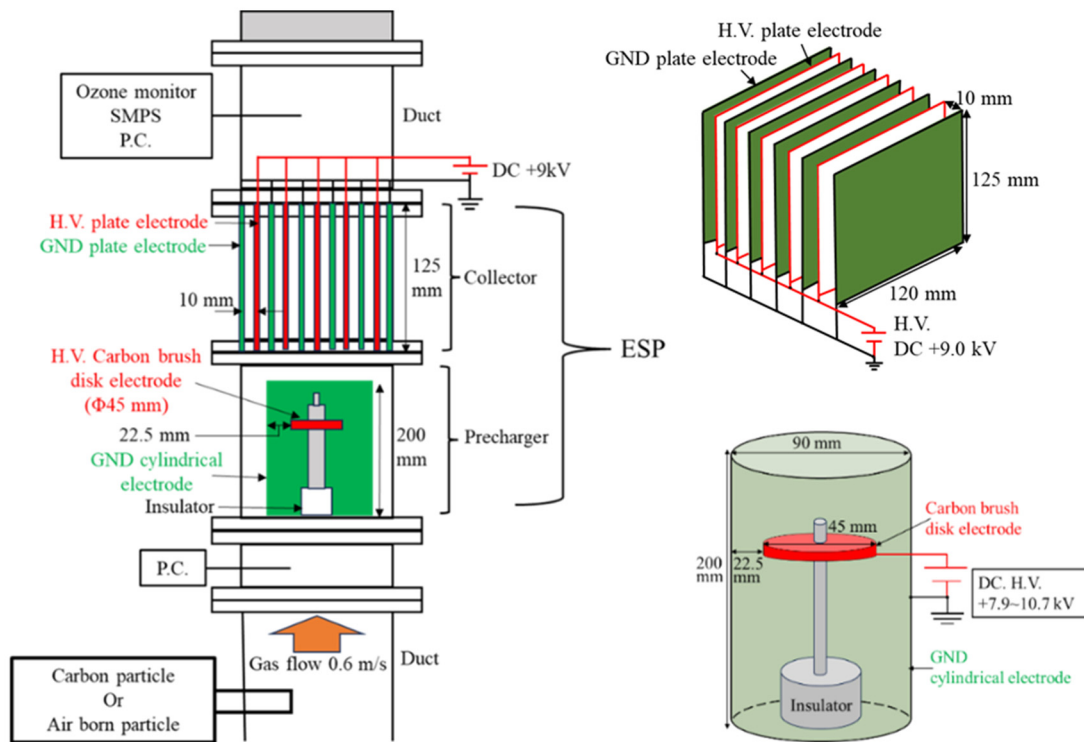


Fig. 1. Schematic diagram of experimental system.

A DC high voltage (up to 15 kV) of positive or negative polarity was applied to the carbon brush disk electrode using a DC power supply (Matsusada, HAR-20R15) to generate corona discharge. The collection section was a parallel plate electrode structure with grounded plate electrodes and high voltage application plate electrodes spaced at 10 mm intervals. A DC positive voltage of 9 kV was applied to the high voltage application plate electrodes to generate an electrostatic field. The corona onset voltages under positive and negative polarity were 5.5 kV and 4.0 kV, respectively.

Air containing test particles passed through the charging section, becoming charged, and was subsequently collected on the electrodes in the collection section due to the electrostatic field. The test particles were carbon particles or airborne particles. Carbon particles with a diameter of 24 nm or larger were generated using a particle generator (PALAS, DNP3000).

The gas flow velocity in the duct was 0.6 m s^{-1} (the gas flow rate: $7.26 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$), and the gas temperature ranged from 20 $^{\circ}\text{C}$ to 25 $^{\circ}\text{C}$. A portion of the gas was sampled to measure particle and ozone concentrations. Particle concentration was measured using a Scanning Mobility Particle Sizer (SMPS, TSI, Model 3936) capable of detecting particle sizes from 6 nm to 214 nm, and a light scattering particle counter (PC, RION, KC-01E) for measuring particles from 300 nm to approximately 10,000 nm.

Collection efficiency was calculated from the measured particle concentrations using equation (1). Ozone concentrations were monitored using an ozone monitor (Ebara Corporation, EG2001D).

$$\eta_d = \left(1 - \frac{N_{ud}}{N_{dd}}\right) \times 100\% \tag{1}$$

where N_{ud} and N_{dd} are the particle concentrations [parts m^{-3}] of diameter d [nm] at upstream and downstream sides of the ESP, respectively. The continuous operation for 2,000 hours was carried out to assess the durability of the carbon brush, where the current was set to a value at which the initial ozone concentration generated was 0.05 ppm, in line with previous studies [17]. The statutory durable years of air purifiers in Japan is six years (52,560 hours); however, in this study, it was set to 2,000 hours for convenience. The initial current values were 0.15 mA at applied voltage of 12.8 kV during the positive polarity corona discharge and 0.13 mA at 10.5 kV during the negative discharge. These current values were maintained for 2000 hours.

The shape of the electrode tips was periodically observed using a magnifying microscope (SHODENSYA, USH500CSU-H1) to check the deterioration of the electrodes. The lengths of the 20 carbon brushes were also measured and the average value was obtained.

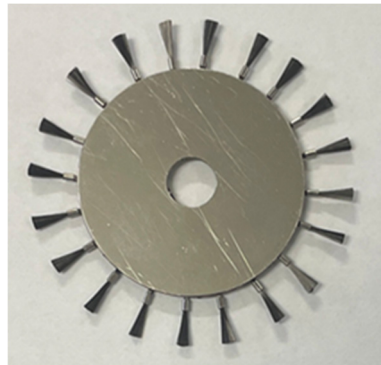


Fig. 2. Carbon brush electrode.

3. Results and discussion

3.1 Carbon brush shape degradation

The discharge luminescence at the elapsed time of 0 h and 2,000 h in the positive and negative polarities is shown in Fig. 3. For positive polarity, although the discharge luminescence appeared uniform at the elapsed time of 0 h, it became non-uniform after 2,000 hours. Similarly, the discharge luminescence under negative polarity also became non-uniform after 2,000 hours, showing more significant degradation compared to that under positive polarity.

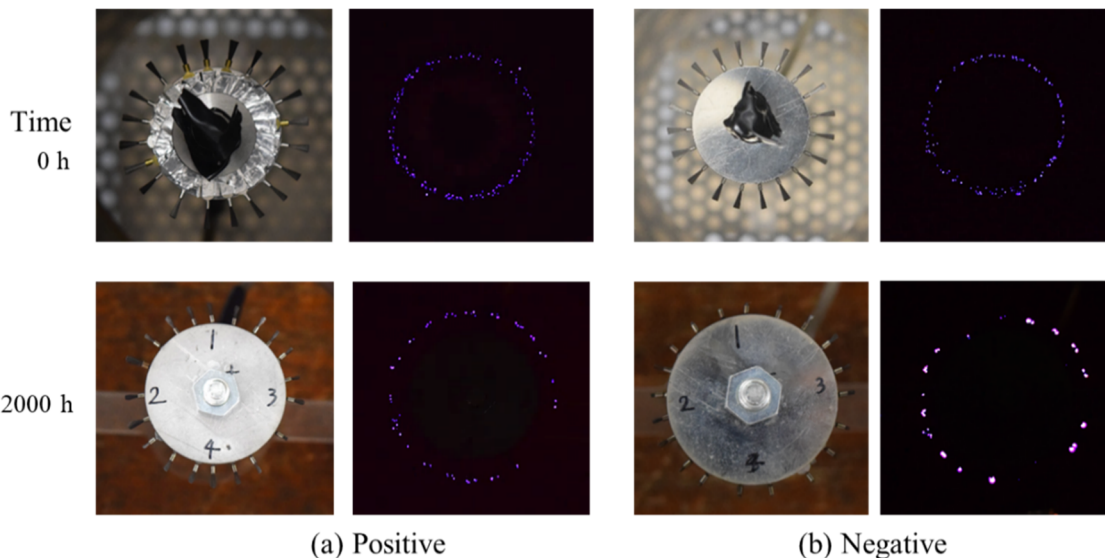


Fig. 3. Discharge luminescence. (Current:0.15 mA, the contrast was adjusted.).

The magnified photographs of the carbon fiber tip during the positive and negative polarity operation are shown in Fig. 4. During the positive polarity corona discharge, although the tips initially exhibited a rounded shape, they became sharper at the elapsed time of 2,000 h, indicative of deterioration. However, fibers with rounded tips were also observed. During the negative polarity corona discharge, the tendency was similar to the result in the positive polarity. This variation is presumed to result from the initial processing. Further investigation is necessary to elucidate the details.

The state of the carbon brush disk electrode is shown in the photos of Fig. 5. After 2,000 hours of positive polarity corona discharge, the carbon brushes showed noticeable deterioration compared to their initial state. Similarly, after 2,000 hours of negative discharge, the carbon brushes also exhibited significant deterioration compared to their initial condition.

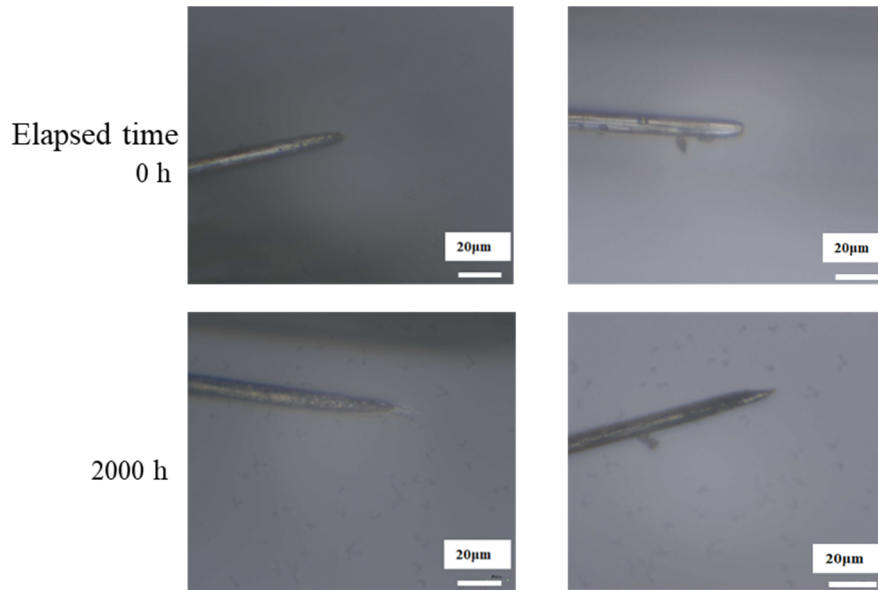


Fig. 4. Carbon brush tip shape.

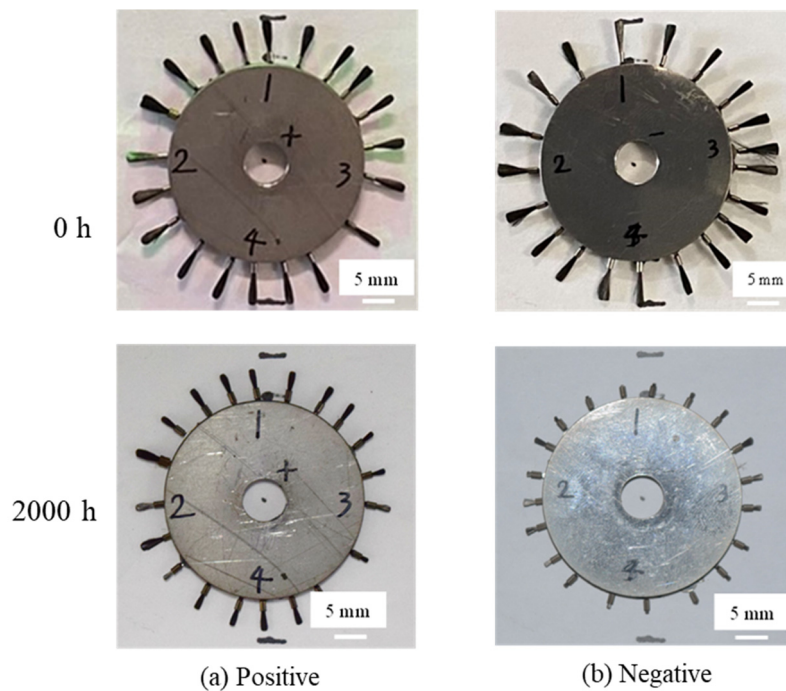


Fig. 5. State of the carbon brush disk electrode.

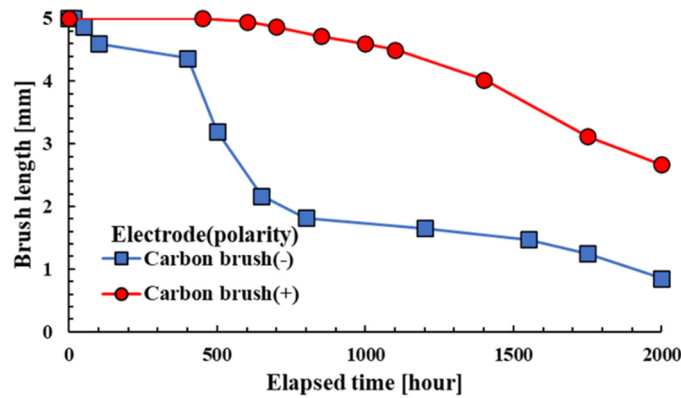


Fig. 6. Relationship between brush length and elapsed time under each polarity. (Discharge current: Positive: 0.15 mA, Negative 0.13 mA).

The relationship between the average length of the carbon brush and the elapsed time is shown in Fig. 6. The average brush lengths under positive and negative polarities decreased with the elapsed time. The average length, which was initially 5 mm for both polarities, decreased to 2.67 mm for the positive and 0.85 mm for the negative polarity after 2,000 hours. Especially, the negative polarity showed a deterioration rate 1.8 times faster than the positive polarity for 2000 hours. This cause may be due to positive ions, which have a mass greater than that of electrons and collide with the surface of the carbon fiber. While negative charges consist of both electrons and negative ions, in a negative polarity discharge, all positive charges collide with the electrode as positive ions, leading to faster electrode degradation. As a result, the carbon brush under negative polarity deteriorated faster than that under positive polarity. However, further investigation is needed to understand this phenomenon, including the reason why the length under negative polarity significantly decreased after 400 hours

3.2 Relationship between voltage current and ozone concentration

The relationship between voltage and discharge current under positive and negative polarities is shown in Fig. 7. Initially, under positive polarity (Fig.7 (a)), the corona onset voltage was approximately 5.5 kV, and the discharge current increased with increasing voltage. For instance, it reached 0.05 mA at around 9.0 kV at the elapsed time of 0 h. The corona onset voltage gradually increased with the elapsed time and reached approximately 9.0 kV after 2000 hours. Similarly, the voltage required to maintain a discharge current of 0.05 mA also increased with the elapsed time, reaching approximately 12.0 kV after 2000 hours. This is due to the fact that the brushes were deteriorated and became shorter, increasing the gap distance from the cylindrical electrode, as shown in Figs. 3 and 5. In contrast, under negative polarity (Fig. 7 (b)), the corona onset voltage was 4.0 kV. And the initial voltage was approximately 7.5 kV at 0 hours, with a corresponding discharge current of 0.05 mA. After 2,000 hours, the voltage significantly increased to approximately 13.5 kV for the same discharge current level. This substantial increase in voltage is attributed to faster electrode deterioration under negative polarity conditions, as illustrated in Figs. 5 and 6.

The relationship between discharge current and ozone concentration is shown in Fig. 8. Under positive polarity (Fig. 8 (a)), the ozone concentration increased with increasing discharge current at any elapsed time. For example, at the start of operation (0 hours), the discharge current of 0.1 mA resulted in an ozone concentration of 0.03 ppm, which increased to 0.15 mA or higher after 1,000 hours. This increase can be attributed to the narrowing of the spreads of the carbon fibers due to their deterioration with the elapsed time, although the corona discharges were generated at the tips of fibers as the fibers were spread by repulsion force at the beginning of operation as shown in Fig. 3 [14]. As the length of the brush decreases ($l_n > l_o$), the arc length becomes shorter ($L_n > L_o$) despite the same spread angle ($\theta_n = \theta_o$) as shown in Fig. 8 (c). Thus, it is considered that corona discharges were localized and the ozone generation efficiency decreased. After 2,000 hours, the discharge current needed to produce the same ozone concentration tends to decrease. This may be due to the further deterioration of the carbon brushes, which causes discharge from the brush fixtures. Due to the larger radius of curvature of the brush fixture corners compared to the carbon fiber, a higher concentration of ozone was generated [16, 17, 20].

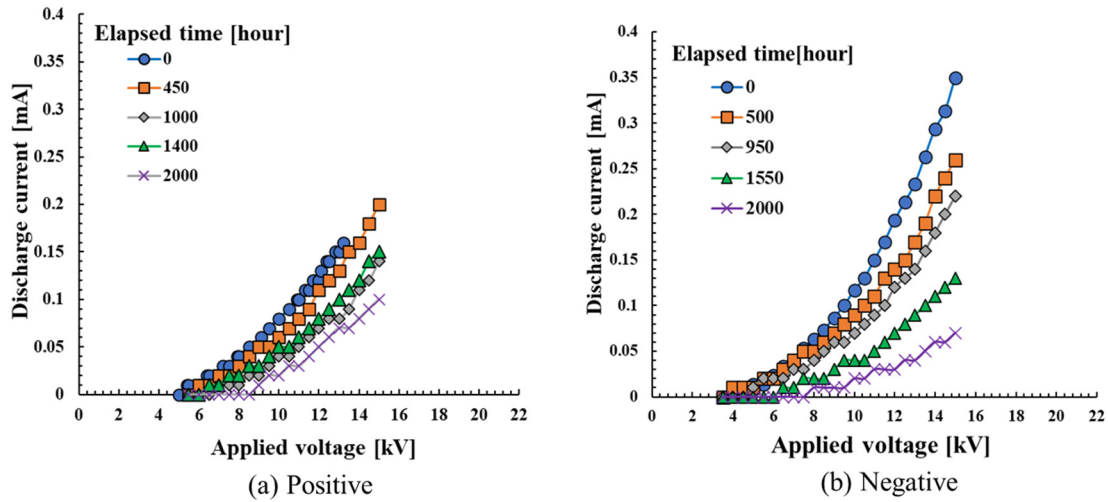
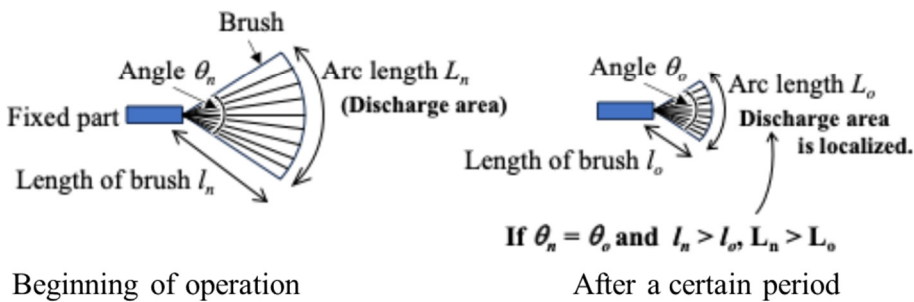
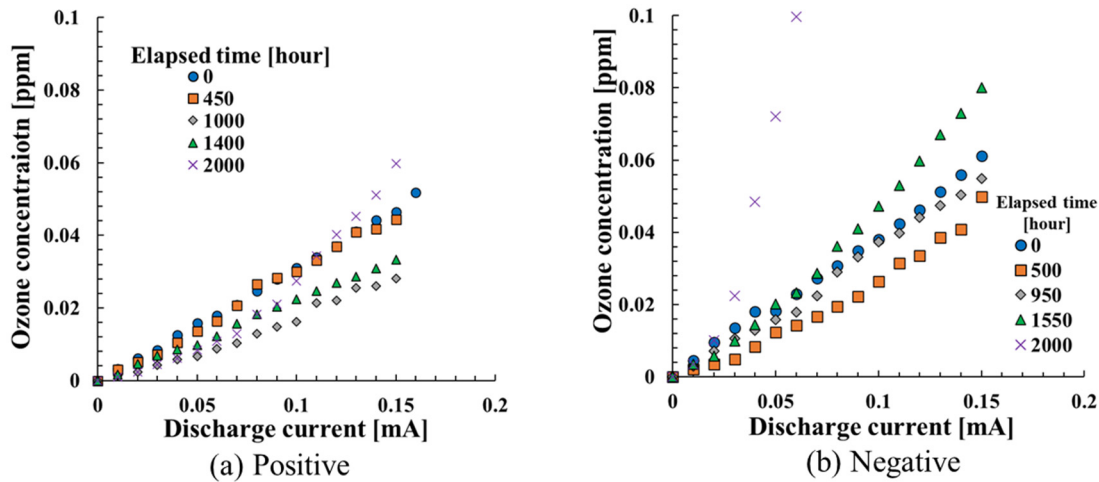


Fig. 7. Relationship between applied voltage and discharge current.



(c) Mechanism of corona discharge localizing

Fig. 8. Relationship between discharge current and ozone concentration.

Under negative polarity (Fig. 8 (b)), a similar tendency was observed to the result under positive polarity. However, the discharge current for the same ozone concentration was lower than that under positive polarity. For example, the discharge current for the ozone concentration of 0.03 ppm was 0.08 mA, which was lower than that required under positive polarity. Additionally, due to more rapid deterioration of the carbon brushes compared to positive polarity, there was a significant decrease in discharge current needed to maintain the same ozone concentration after 500 hours of operation.

The relationship between voltage and generated ozone concentration is shown in Fig. 9. Under positive polarity corona discharge at 0 hours of operation (Fig. 9 (a)), ozone was detected at voltages approximately 5.5 kV or higher, and the ozone concentration increased with increasing voltage. Due to the increase of the corona onset voltage as shown in Fig. 7, the voltage of ozone detection increased with the elapsed time.

Furthermore, after 1,000 hours of operation, the voltage required to maintain the same ozone concentration also increased. This increase is attributed to the increase of the distance between the tip of brushes electrode and the grounded electrode due to the deterioration of the carbon brush. Negative polarity corona discharge also exhibited a comparable tendency (Fig. 9 (b)). However, the voltage required to achieve the same ozone concentration increased earlier, around 500 hours of operation, due to the faster deterioration of the carbon brush compared to the positive polarity discharge.

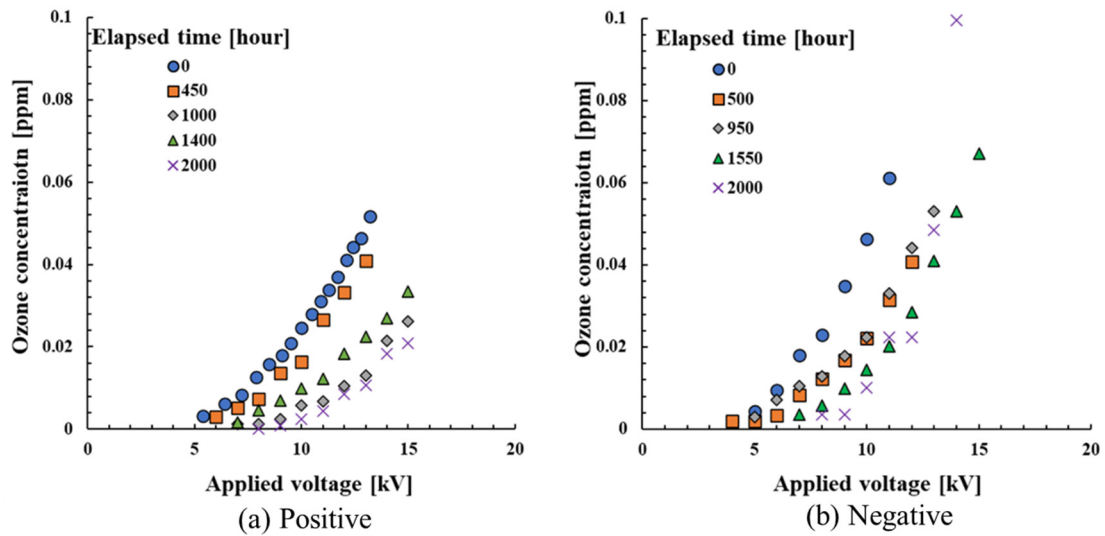


Fig. 9. Relationship between discharge current and ozone concentration.

The relationship between power consumption and generated ozone concentration is shown in Fig. 10. In both positive and negative polarity corona discharges, the ozone concentration increased with increasing power consumption. In the positive polarity discharge, the ozone concentration decreased over time at the same power consumption. This was due to a decline in ozone concentration under the same voltage and current conditions. In contrast, in the negative polarity discharge, the concentration increased rapidly after 2000 hours of operation. This was due to a sudden rise in ozone concentration under the same current conditions (Fig. 8).

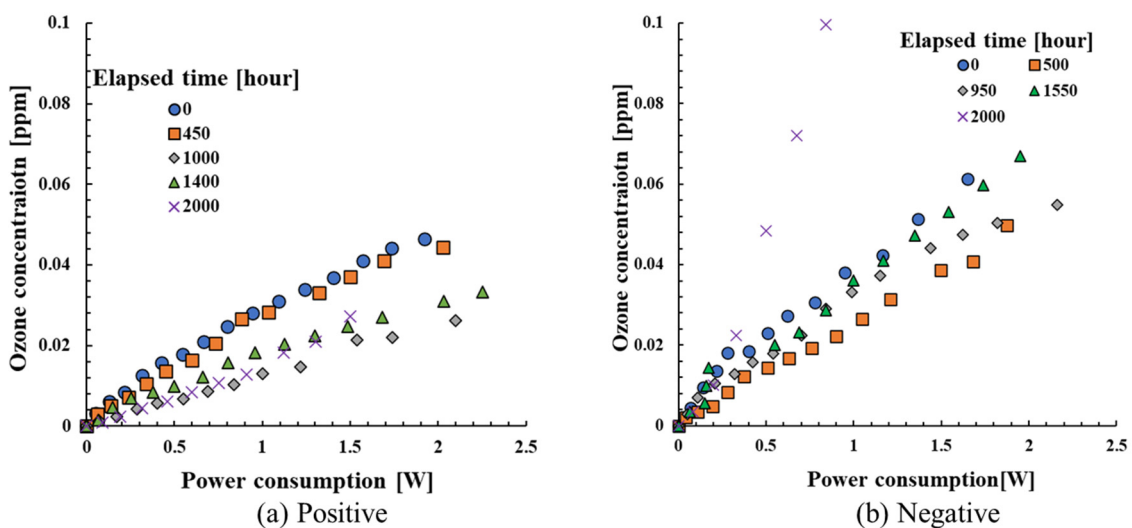


Fig. 10. Relationship between discharge current and ozone concentration.

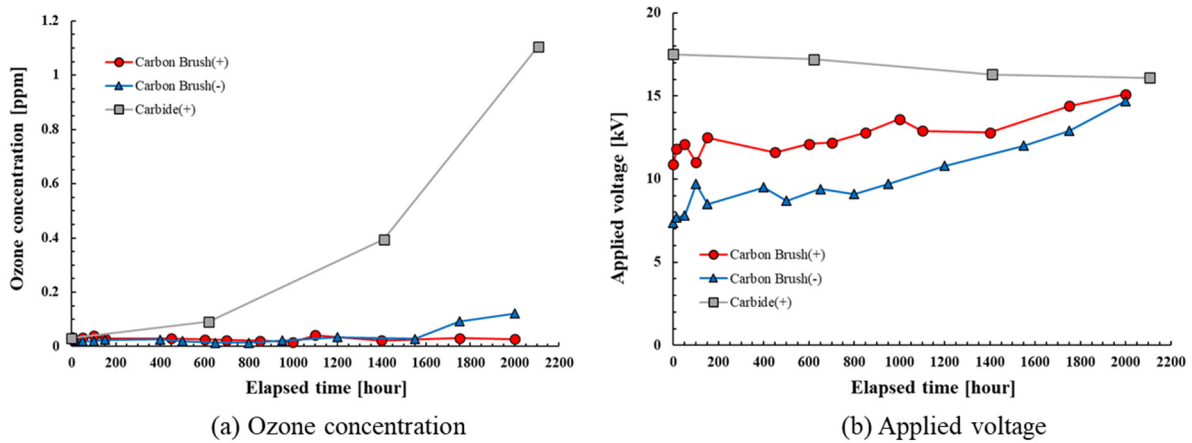


Fig. 11. Relationship between ozone concentration, applied voltage and elapsed time (Discharge current: Positive 0.10 mA, Negative 0.07 mA, Carbide 0.09 m).

3.3 Relationship between ozone concentration and operating time

Relationship between ozone concentration, applied voltage and elapsed time is shown Fig. 11. The result of a similar experiment using the cemented carbide disk electrode [17] in a previous study was as shown in this figure. The discharge polarity was positive. The discharge current of the carbon brushes in positive and negative polarities and the carbide disk electrode were adjusted to 0.10 mA, 0.07 mA and 0.09 mA, respectively, which were values at the initial ozone concentration of 0.03 ppm. Meanwhile the current was adjusted to the value at the ozone concentration of 0.05 ppm in the experiment conducted over 2000 hours of continuous operation. The initial ozone concentration in the brush disk electrode during the positive-polarity corona discharge was 0.03 ppm and remained almost unchanged over the operating time and was still 0.027 ppm after 2000 hours. On the other hand, in the case of the negative polarity, although no significant change was observed up to 1500 hours of operation, the ozone concentration increased significantly at 1760 hours. This is because even though the brush length remained unchanged (as shown in Fig. 6), the carbon brushes deteriorated (as shown in Fig. 3), causing the voltage required to maintain the same current to increase (Fig. 11-b). In other words, discharge occurred from the brush fixture, altering the form of the discharge. In the case of the positive polarity cemented carbide disk electrode, the ozone concentration increased significantly at 600 hours and further increased with time. This is due to the generation of streamer discharges due to the deterioration of the electrodes [17]. The ozone concentration under negative polarity was higher compared to the positive polarity. An explanation of this tendency is that electrons generated in the ionization area do not pass through the dissociation area in the positive corona discharge, whereas they pass through the dissociation area in the negative corona discharge [21].

The above results indicate that the use of positive-polarity corona discharge with a carbon brush electrode is suitable for maintaining low ozone concentrations for long periods of time.

3.4 Relationship between collection efficiency and operating time

Elapsed-time-dependent collection efficiency, applied voltage, and discharge current at an ozone concentration of 0.03 ppm is shown in Fig. 12. The voltage and current were adjusted to the value of the ozone concentration of 0.03 ppm at this measurement. Meanwhile the current was adjusted to the value at the ozone concentration of 0.05 ppm in the experiment conducted over 2000 hours of continuous operation. The figure also shows the results of a similar experiment using the cemented carbide disk electrode [17] in the previous study. In the case of the positive polarity using the carbon brush electrode, the initial collection efficiency was as high as 99.5% and decreased slowly with the elapsed time yet remained as high as 92.7% after 2,000 hours. The reason for the decrease in collection efficiency is that the deterioration of the carbon brush, as shown in Fig. 3, made the discharge luminescence points non-uniform, reducing the charging efficiency. As shown in Figs. 12 (a) and (b), the discharge current and voltage required to maintain the same ozone concentration may increase over time; however, this is considered to be due to the decrease in charging efficiency. The same tendency was seen under negative polarity, although the collection efficiency was initially 94.0% and decreased to 79.9% after

2,000 hours of operation. The voltage and current at an ozone concentration of 0.03 ppm under negative polarity were lower than those under positive polarity, whereby the initial collection efficiency under negative polarity was lower than that under positive polarity. In the negative polarity corona discharge, the carbon brush deteriorated more quickly than in the positive discharge, resulting in a significant decrease in collection efficiency. The same tendency was observed in the case of the positive polarity cemented carbide disk electrode, with an initial collection efficiency of 99.9% which decreased to 78.8% after 2,000 hours of operation. This was due to the deterioration of the electrodes, which caused streamer discharge [17].

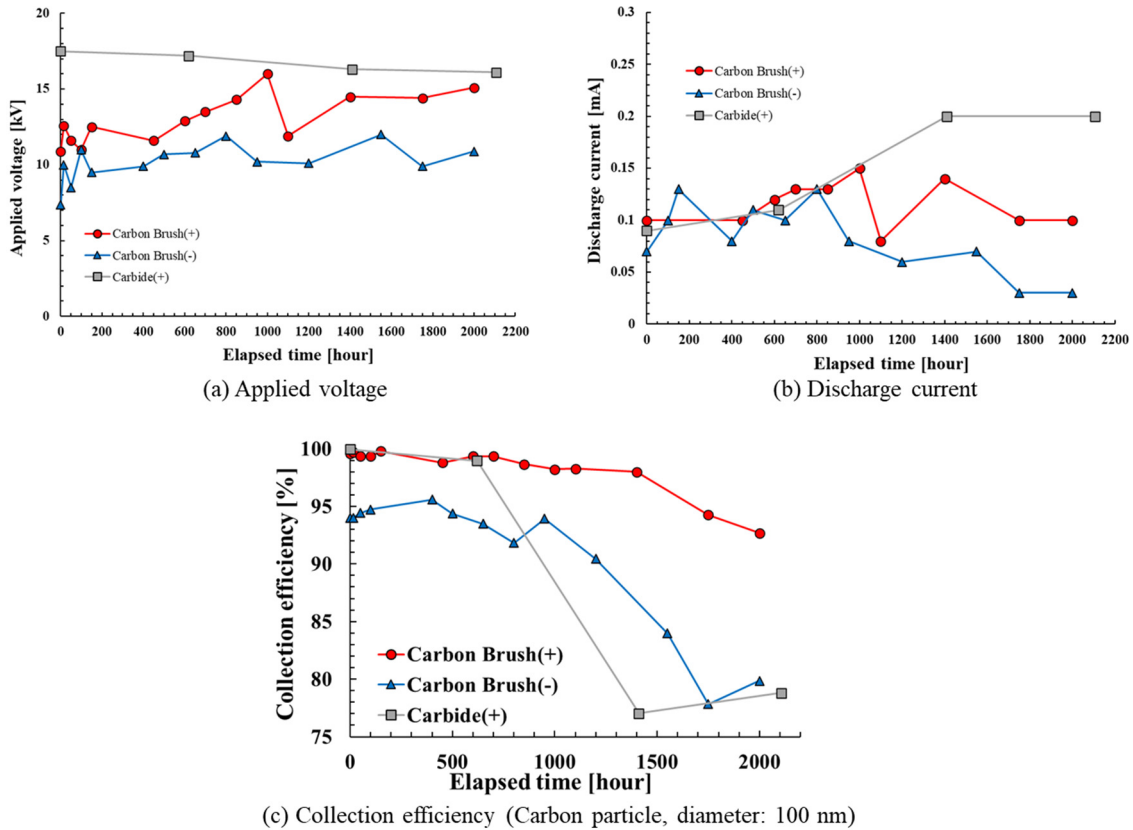


Fig. 12. Elapsed-time-dependent collection efficiency, applied voltage, and discharge current at an ozone concentration of 0.03 ppm.

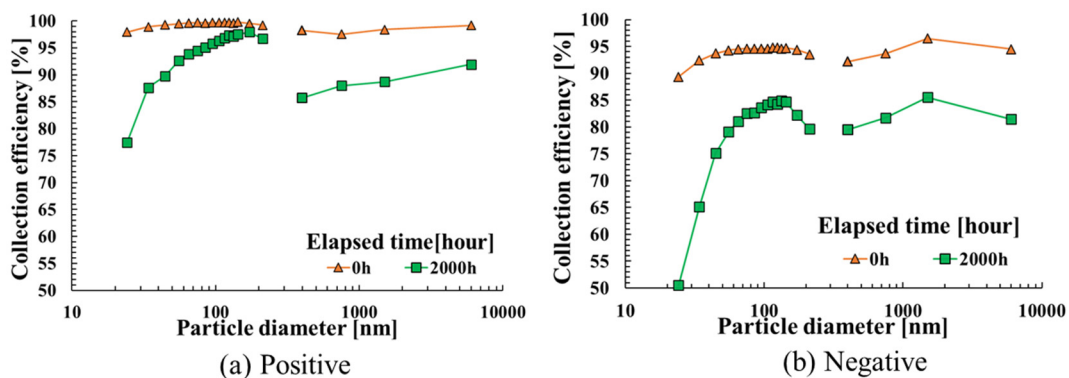


Fig. 13. Collection efficiency as a function of particle diameter.

Positive (Voltage: 0 h - 10.9 kV, 2000 h - 15.1 kV. Current: 0 h - 0.1 mA, 2000 h - 0.1 mA)
 Negative (Voltage: 0 h - 7.4 kV, 2000 h - 10.9 kV. Current: 0 h - 0.07 mA, 2000 h - 0.03 mA).

The collection efficiency as a function of particle diameter in the ESP with the carbon brush disk electrode is shown in Fig. 13. Under positive polarity (Fig. 13 (a)), the collection efficiency decreased from 6,000 nm to approximately 400 nm due to the reduced particle surface area and resulting lower charge. The collection efficiency for particles smaller than 300 nm increased. The fluid drag force decreases as the particle diameter

decreases, since the particle diameter approaches the mean free path of air molecules (Cunningham's correction factor). Thus, this results in an increase in particle migration velocity as the particle diameter decreases, despite the decrease in particle charge. However, the collection efficiency decreased again for particles smaller than approximately 100 nm. This is most likely because the number of charges is lower than one [18] or nanoparticles were formed by the ion-induced nucleation [19]. Initially, the collection efficiency for all sizes was approximately 98% or higher, which decreased to around 85% after 2,000 hours, particularly noticeable for 24 nm particles. Negative polarity (Fig. 13 (b)) shows a similar tendency but with lower initial collection efficiencies ranging from 89% to 94%. After 2,000 hours, the efficiency decreased to a maximum of 85%, lower than under the positive polarity.

These results indicate that the positive polarity corona discharge with a carbon brush electrode is suitable for maintaining high collection efficiency for long periods of time.

4. Conclusion

In this study, the durability performance of an electrostatic precipitator using a carbon brush disk electrode under each polarity was investigated. The following results were obtained and it became clear that low ozone concentration and high collection efficiency can be maintained by using the carbon brush electrode with positive polarity corona discharge.

- (1) For both polarities, the discharge luminescence was uniform at the beginning of operation but became non-uniform after 2,000 hours.
- (2) For both polarities, the carbon fiber tips deteriorated and became from a round shape to a pointed shape. The durability of the brushes was higher under the positive polarity.
- (3) For both polarities, the voltage values at the same current increased with operating time. This was due to deterioration of the carbon fiber.
- (4) The current values at the same ozone concentration under both polarities initially increased with operating time and then showed a tendency to decrease. This is due to an increase in the electrode spacing and a change in the discharge form due to the deterioration of the carbon brushes.
- (5) The ozone concentration under the positive polarity showed little change with the elapsed time. Under the negative polarity, the ozone concentration increased significantly at 1760 hours.
- (6) The collection efficiency decreased with the operating time under both polarities, although the positive polarity still had a high collection efficiency of 85% or more after 2,000 hours. Under negative polarity corona discharge, the collection efficiency decreased significantly due to the rapid deterioration of the carbon brush.

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