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INVESTIGATION OF A CELL-TYPE ELECTROSTATIC PRECIPITATOR (CESP)

Taewon T. Han[1], Seongjin Yun[2], Jeanho Park[3], Donggi Kwag[4] and Youngjin Seo[5]
[1]Department of Environmental Sciences, Rutgers, The State University of New Jersey, New Brunswick, United States of America
[2]Yonsei Institute of Green Technology, Yonsei University, Seoul, Republic of Korea
[3]Research Institute of Industrial Technology Convergence, Korea Institute of Industrial Technology, Ansan, Republic of Korea
[4]Department of Aeromechanical Engineering, Hanseo University, Taean, Republic of Korea
[5]Environment and Bio Fluid Engineering Lab, Faculty of Department of Mechanical Engineering,Kumoh National Institute of Technology, Daehakro, Gumi, South Korea
E-Mail: yjseo@kumoh.ac.kr

ABSTRACT

Indoor air quality is increasing concern and people use air purifiers to enhance indoor air quality. An electrostatic precipitator as one of conventional methodologies has been widely usedto remove particulate matters, but it could generate ozone in the process of charging, which results in the need to investigate electrostatic precipitator systems (i.e., single- or two- stage) and their components (i.e., electrode material and polarity) for minimizing the amount of generated ozone. The test system is made of static disspipative material (e.g., Delrin), is shaped as an opened square channel, and contains acharging source. The charging electrode (carbon fiber brush or tungsten needle) is mounted on the ceiling of the collector, while its flat bottom section holds a collection plate made of stainless steel.The optimized configuration of the CESP was designed into a two-stage system (charging and collection sections) and a carbon fiber brush (~1000 fibers) was selected as an optimal charger of the CESP. As a result, the CESP had a collection efficiency of about 28% through a single pass air and around less than 15 ppb ozone concentration when sampling with 0.5 μm PSL particles at 1.1 m/s face velocity for 3 min sampling time. These results have a practically importance role for developinga multi-cell ESP system, which can improve its performance without any severe ozone production.

Keywords: electrostatic, air purifier, carbon fiber, aerosol,air pollution.

INTRODUCTION

Many researchers have said that the mortality and the respiratory disease are related with a concentration of aerosolized particles in ambient air. In China and neighborhood countries, the number of respiratory patients and deaths evidently increase with an increase of a concentration of ambient particulate matters (PMs) by the Asian dust storm (Chen *et al*., 2015; Vellingiri *et al*., 2015; Lee *et al*., 2015). In Malaysia, lots of people die or have lung diseases due to haze generated by forest fire every year (Dennekamp and Abramson, 2011; Payus *et al*., 2013; Sahani *et al*., 2014; Othman *et al*., 2014). In urban areas, fine PMs in ambient air cause huge social costs and health problems of city dwellers(Sun *et al*., 2013). Unfortunately, staying indoors is not a solution to prevent people from having respiratory illness because they are also exposed to indoor particles. From these reasons, household air purifiers are recently popular to improve the concentration in residences (Hart *et al.*, 2011; Wheeler *et al*., 2011). These products are generally classified into two types by a removal mechanism for aerosolized particles: mechanical and electrostatic precipitator (ESP) air purifier. The formers have non-woven fabric filters and the representatives are high efficient air particulate (HEPA) filters. These filters are comparably cheap and have very high collection efficiency for fine particles. To decrease their pressure drop, electret media are used most of the HEPA filters for a household use and these filters make the products ventilate large amounts of clean air. However, they are needed a regular exchange due to the increase of pressure drop and decrease of the efficiency for use withthe HEPA filters. Advantages of ESPs are generally low pressure drops and no need for periodically exchanging a filter, but they produce ozone during the ionization process. To reduce ozone generation from the ESP, various researches have been conducted. Tepper *et al*. (2007)developedanelectrospray-based air purification systemwhich did generate an imperceptible level of ozone. However, there are some disadvantages such as very sensitive to contaminants (e.g., salts), relative low ion currents, relatively complex hardware (Mann, 1990)

In this paper, we proposed a simple designed corona discharger with a background ozone level and approached to apply electrostatic collector to remove a fine aerosol (i.e., less than 2.5 μm). This ozone level is much less than the limit (i.e., produced by medical devices operated in closed spaces to 50 ppb) set by U.S. Food and Drug Administration (Britigan *et al*., 2006).The goal of this study is to investigate how operation parameters (e.g., polarity (positive or negative) of charging voltage, number of carbon fibers) affect its performance.

MATERIALS AND METHODS

Design Features of the Cell-type Electrostatic Precipitator (CESP)

TheCESP has an open channel (Figure-1) and was made of static dissipative material: homopolymer acetal (Delrin, Professional Plastics Inc., Fullerton, NY). In addition, a sharp edge inlet was added to theCESP to minimize inlet losses and turbulence in the entering aerosol stream. This CESPis also divided by its

mechanism (Figure-1); in a single-stage electrostatic collector, particle charging and collection take place simultaneously in the same chamber and two-stage collector is different in that particle charging takes place in a separate chamber which precedes collection. In Figure-1, the device has a shape of a square (12.5 mm × 12.5 mm) and in both configurations (single-stage versus two-stage) the length of the chamber was 50.8 or 111.6 mm. In the charging section (single-stage versus two-stage) the top part contains an ionizer (e.g., carbon fiber brush or tungsten needle) and the bottom part contains a thin stainless steel plate (width (*w*): 12.5 mm × length (l): 111.6 mm), while in the collection section the both parts (top and bottom) have the same size (12.5 mm × 111.6 mm) of stainless steel plates (Stainless Supply Co., Monroe, NC) as a collection electrode and a ground. The configuration presented in Figure-1 creates ions which charges the incoming particles and then deposits them onto the collection electrode. As the ion sources, the following two configurations were fabricated and installed at a distance of 25.4 mm (1.0 inch) away from the inlet: (a) three different numbers of carbon fiber brushes, ~10, 100, 1000 fibers/brush (VC-36S, Formosa Plastics Co., Taiwan) or (b) a tungsten needle (W91, Scientific Instrument Services Inc., Ringoes, NJ). The carbon fiber and tungsten wire diameters were ~7 µm and~76.2 µm, respectively. A negative (or positive) charging voltage (3.0-6.0 kV) was applied, and a positive collection voltage (3.0-5.0 kV) was used.

The single-stage or two-stage single-channel prototype can then be applied as an electrostatic air purifier which consists of multiple channels. The use of multiple small electrostatic collectors arranged in various layouts allows achieving uniform charging performance and thus high removal efficiency while sampling at high flow rates. In the 1st stage of each channel, a carbon fiber ionizer containing ~1000 individual fibers is positioned on the top of the channel and a collection plate (50.8 mm in length) is positioned on the bottom of the channel. The carbon fiber is connected to positive high voltage, while the plate is grounded. In addition, each channel also has the 2nd stage positioned behind the first stage and it consists of a long collection plate (203.2 mm in length) on the bottom and a ground electrode (203.2 mm in length) on the top. The 2nd stage is connected to high voltage of the sign (i.e., negative polarity) opposite to the high voltage connected to the 1st stage.

The performance of the CESPwas optimized by adjusting the following parameters: number of fibers in each carbon brush, strength of the electrical field in the first stage, and strength of the electrical field in the second. Use of carbon fiber ionizers allows application of low voltage (less than 5 kV) to achieve particle charging while producing low ozone emissions (under 20 ppb), thus alleviating the issues related to traditional ESPs and ozone production.

Experimental Setup for Testing the CESP

Test Set-up: The test system is shown in Figure-2, and it consisted of a flow control system, a particle generation system, an air-particle mixing system, and a particle monitoring system. The system was housed inside a Class II Biosafety cabinet (NUAIRE Inc., Plymouth, MN). A six jet Collision nebulizer (BGI Inc., Waltham, MA) was used toaerosolize test particles from a liquid suspension at a flow

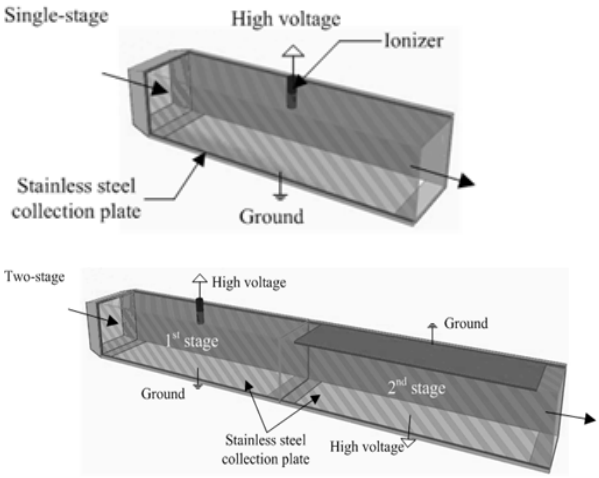

Figure-1. Schematic diagram of the cell-type electrostatic precipitator (CESP): a) single-stage and b) two-stage.

rate (Q_A) of 5 L/min (pressure of 14 psi). A HEPA-filtereddilution air flow, Q_D (105 L/min), provided by an in-house compressor was used to dilute the particle stream; it was controlled by a pressure regulator and monitored by a mass flow meter (TSI Inc., Shoreview, MN). The dilution air and aerosolized particle stream were combined and passed through a 2-mCi Po-210 charge neutralizer (Amstat Industries Inc., Glenview, IL) to reduce aerosolization-related particle charges to Boltzmann charge equilibrium. The electrically neutralized particles then passed through the first mixing box (Han *et al.*, 2005) which improved the uniformity of particle distribution across the flow cross-section of the test section. The second mixing box and a U-type duct connector further improved particle mixing. A well-mixed flow stream then entered a test duct (0.152 m (6 inches) in diameter and a 0.914 m (36 inches) in length), as shown in Figure-2. A flow straightener was placed at the exit of the second mixing to eliminate large scale turbulence and flow swirl generated by the mixing boxes. The CESP was positioned in parallel six duct diameters downstream of the exit of the flow straightener in order to provide uniform cross-sectional profile of test particles. The coefficient of variation (i.e., the ratio of the unbiased standard deviation of a set of measurements to the mean of the set of measurements, *COV*) of 0.5 µm PSL concentration across the test duct was about 2.7% at the measurement location. The *COV* was measured over five equally distributed sampling points in the cross-sectional area of the duct in triplicate.

Tests with PSL Particles: The CESP was tested with 0.5 µm green fluorescent polystyrene latex (PSL) particles (Duke Scientific Corp., Palo Alto, CA) and at

~11 L/min sampling flow rates (i.e., 1.1 m/s face velocity) for 3 min sampling

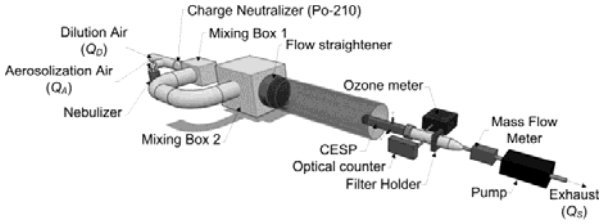

Figure-2. Schematic diagram of the experimental setup.

time by an optical particle counter (model 1.108, Grimm Technologies Inc., Douglasville, GA,USA). The airborne average concentration of fluorescent PSL particles was approximately 6.1×10^4/Liter. The prototype was tested at charging/collection voltages of (+ or −) 3-6 kV/3-5 kV. The reference aerosol concentration was determined by the optical counter (OPC) when the power was turn off. The ozone concentration (background subtracted) was also measured using a UV photometric ozone monitor (MODEL202, 2B Technologies Inc., Boulder, CO) at the outlet of the collector in the CESP system (Figure-2).

Determination of the CESP Collection Efficiency: The overall collection efficiency of the CESP was determined by comparing particle concentration downstream of the collector with its power ON and OFF using a Grimm OPC.

The overall collection efficiency from the collection electrode, $\eta_{OVERALL,\ PSL}$, was determined as follows:

$$\eta_{OVERALL,\ PSL} = 1 - \frac{C_{ON}}{C_{OFF}} \quad (1)$$

where$C_{ON}$and C_{OFF} are airborne particle concentrations downstream of CESP with its voltage ON and OFF, respectively; this metric does not take into account particle losses inside the collector.

RESULTS AND DISCUSSIONS

Figure-3 shows the collection efficiency and ozone concentration as a function of charging voltage (positive or negative 3.0-6.0 kV) at different configurations of the charger (carbon fiber brushes with varying numbers of fibers (~10 to ~1000/brush) and a tungsten needle). Firstly, one can observe that the collection efficiency and ozone concentration as a function of charging voltage are quite different depending on the change of charger polarity (positive and negative). In particular, the average collection efficiency at 3-4.5 kV compares the effects due to different polarity (positive versus negative): 2.0±0.8% vs. 6.3±2.3% (at 3 kV), 3.9±1.2% vs. 13.9±6.7% (at 3.5 kV), 9.4±4.7% vs. 21.2±7.5% (at 4.0 kV), and 14.9±5.8% vs. 32.0±9.3% (at 4.5 kV). Based on t-test results, the difference of average collection efficiency between positive and negative polarities was statistically significant at 3.0 and 3.5 kV ($P<0.05$). The average ozone concentration at 3-4.5 kV also compares: 2.3±1.0 ppb vs. 8.8±2.7 ppb (at 3.0 kV), 5.9±1.9 ppb vs. 21.3±6.4 ppb (at 3.5 kV), 12.3±4.0 ppb vs. 30.3±10.3 ppb (at 4.0 kV), and 18.8±6.6 ppb vs. 44.7±12.1 ppb (at 4.5 kV). The difference between two polarities was statistically significant ($P < 0.05$) except the 4.5 kV operating condition.

The difference between positive and negative polarities is that the overall collection efficiency with the negative polarity is about 2.3 times higher than that with the positive polarity at the full range of conditions (3.0-6.0 kV), while the overall ozone concentration with the negative polarity is also approximately 2.3 times higher (i.e., negatively affected) compared to that with the positive polarity.

Secondly, the number of fibers also affects the CESP performance. The average collection efficiency at positive or negative 3.0-4.5 kV ranged 1.5±1.6%-12.9±0.9% vs. 7.4±0.1%-30.6±1.4% (for ~10 fibers), 1.6±0.8%-15.9±2.8% vs. 8.0±0.3%-30.8±2.2% (for ~100 fibers), and 1.8±0.4%-22.3±2.2% vs. 7.4±0.1%-44.6±2.2% (for ~1000 fibers), respectively. When the number of carbon fibers were increased, the ozone concentration was also increased at both polarities: 1.2-25.3 ppb vs. 5.3-33.6 ppb (~10 fibers), 2.2-21.4 ppb vs. 11.4-43.0 ppb (~100 fibers), and 2.2-18.7 ppb vs. 7.9-61.9 ppb (~1000 fibers), respectively. With the tungsten needle, the average collection efficiency as a function of charging voltage (3.0-6.0 kV) was 3.2±1.5%-

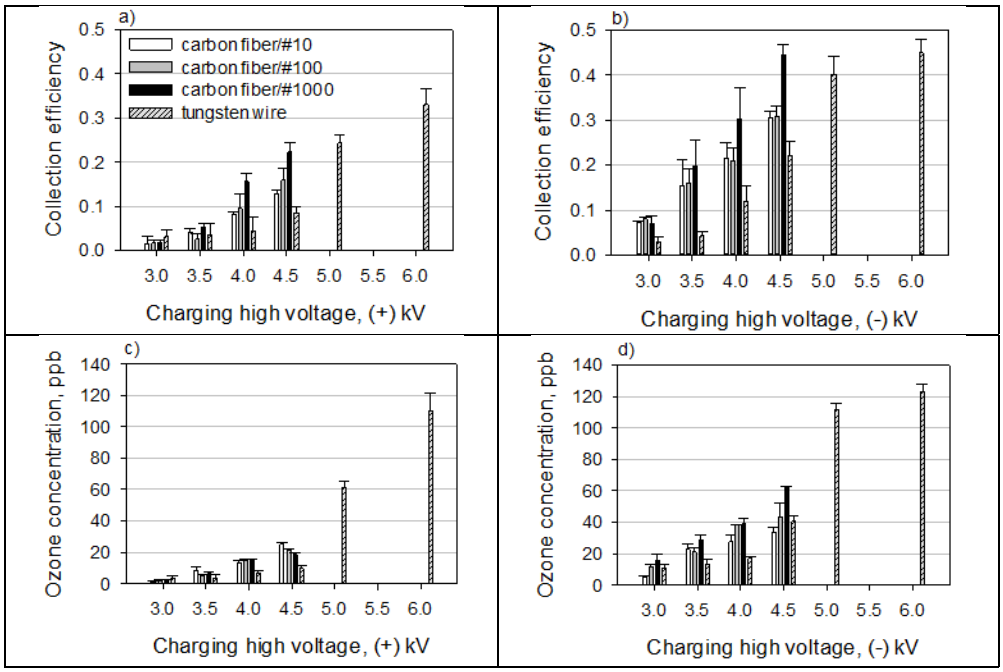

Figure-3. Particle collection efficiency and ozone concentration of the single-stage electrostatic collector as a function of charging high voltage (positive or negative 3.0-6.0 kV) at 1.1 m/s face velocity: a) versus. b) (i.e., positive vs. negative)for collection efficiency and c) vs. d) for ozone concentration. The error bars represent the standard deviation from three repeats.

33.1±3.5% vs. 2.9±1.3%-44.9±2.9% (i.e., positive vs. negative) and average ozone concentration was 3.5±1.3 ppb-110.2±11.3 ppb vs. 10.6±2.5 ppb-124.7±6.9 ppb, respectively.

At the low operating conditions (3-4.5 kV) the performance with the tungsten needle showed much lower than that with the carbon fiber brush, but it then sharply increased at 5 kV (24.3±1.8% vs. 40.2±3.9%) and 6 kV (33.1±3.5% vs. 44.9±2.9%) of both polarities, respectively. Based on t-test results, the difference of overall average efficiency between positive and negative polarities among the four groups was not statistically significant except the carbon fiber brush (~10 fibers) ($P>0.05$), while the difference of ozone concentration between two polarities) was statistically significant with the carbon fiber (~1000 fibers) ($P < 0.05$).

Figure-4 shows collection efficiency with applied collection voltage (power-off and −3 to −5 kV) at different charging voltages (+3.5, +4.0, and +4.5 kV) for particle size of 0.5 µm PSL particles. As shown in Figure-4a, the average collection efficiency of the single-stage collector (collection high voltage=0 kV) at +3.5, +4.0, and +4.5 kV charging voltages was 3.3±1.5%, 12.2±3.1%, and 21.2±2.7%, respectively. As the applied collection voltage increased, the collection efficiency gradually increased across the whole range of charging voltages: 4.8±1.6%-7.5±2.4% (at +3.5 kV), 13.2±3.7%-16.3±5.0% (at +4.0 kV), and 24.4±3.0%-28.4±4.7% (at +4.5 kV), respectively. However, the difference is not statistically significant ($P>0.05$). Average collection performance of the two-stage collector for voltage levels of −3 to −5 kV was enhanced by 52.6%

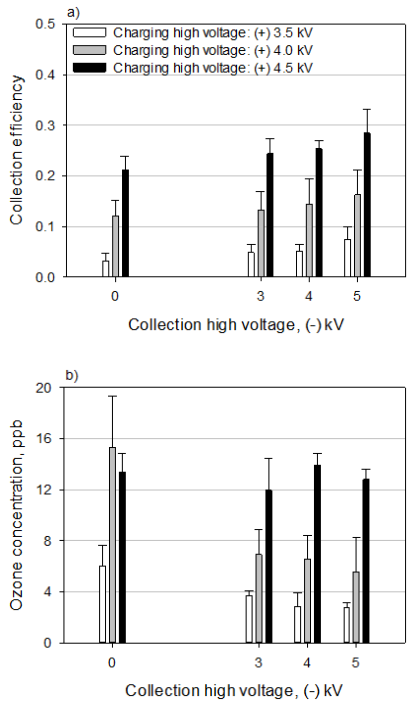

Figure-4. Particle collection efficiency and ozone concentration of the two-stage electrostatic collector as a function of collection high voltage (negative 3.0-5.0 kV) at three different charging condition (+3.5, +4.0, and +4.5 kV) and at 1.1 m/s face velocity. The error bars represent the standard deviation from three repeats.

(at +3.5 kV), 13.5% (at +4.0 kV), and 17.5% (at +4.5 kV), respectively, when compared to that for power-off (i.e., single-stage collector). Figure-4b shows the variation in the concentration of ozone emitted from the charger (carbon fiber (~1000) brush) as a function of high voltage applied to the collector at a face velocity of 1.1 m/s.

In the single-stage collector, the ozone concentration at +3.5, +4.0, and +4.5 kV was 6.0±1.6 ppb, 15.3±4.0 ppb, and 13.4±1.5 ppb, while in the two-stage collector the average ozone concentration in the whole range (-3 to -5 kV) of collection voltage was 3.1±0.5 ppb (at +3.5 kV), 6.3±0.7 ppb (at +4.0 kV), and 12.9±1.0 ppb (at +4.5 kV), respectively. Based on ANOVA, the difference in ozone concentrations at each high voltage(-3, -4, and -5 kV) was not statistically significant ($P>0.05$). However, the difference between the two different collectors (single- versus two-stage collectors) was statistically significant ($P < 0.05$) except the +4.5 kV charging voltage condition.

Thus, the CESP prototype was successfully tested as a function of ionizer material (carbon fiber vs. tungsten wire) and configuration (single-stage vs. two-stage system) at a face velocity of 1.1 m/s. These tests, integrated with a carbon fiber brush in the two-stage system, show a potential of the proposed design and operating condition to remove particles with low ozone production.

CONCLUSIONS

In this study, the Cell-type Electrostatic Precipitator (CESP) has been designed and tested with 0.5μm PSL particles. This electrostatic collector with a carbon brush and two-stage configuration achieved around 28% collection efficiency without a significant ozone production (around less than 15 ppb).

These results were obtained with a single cell electrostatic collector and evaluated with a single pass air. For the application and testing of this concept in a multi-cell type ESP (e.g., a 5 × 5 channel), it must be fabricated and tested at various wind speed (e.g., up to 2 m/s) with a wide range of particle sizes (e.g., 0.1 to 3 μm) in the next step of this study.

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