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Development of compact electrostatic precipitator using EHD gas pump mechanism

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Abstract

In recent years, the removal of airborne particulate matter, such as PM 2.5, pollen, and droplets containing coronavirus, has become an increasingly important issue. Collecting dust closer to its source is considered more effective for removing these particulates. However, most air purifiers are stationary, and electrostatic precipitators (ESPs) that can move freely, such as robotic cleaners, have not yet been developed. In this study, we developed a compact, lightweight ESP capable of moving to the source of dust for collection. To eliminate the need for an electric fan to draw particles into the ESP, we employed the mechanism of an electrohydrodynamic gas pump that uses ionic wind. A wire-to-nonparallel plate electrode configuration was used to generate a unidirectional gas flow containing dust particles. This configuration allows simultaneous corona charging of particles and their precipitation onto the plate electrode. The performance of the single-stage compact ESP was evaluated by visualizing dust particle collection in a transparent acrylic chamber and a mini plastic greenhouse. The proposed compact ESP has no mechanical moving parts and can be integrated into mobile devices or combined with other units.

Keywords: Electrohydrodynamic (EHD), electrostatic precipitator (ESP), ionic wind, gas pump, particulate matter.

1. Introduction

In recent years, interest in air quality has been steadily increasing, particularly concerning the removal of airborne particulate matter (PM 2.5), pollen, and even droplets containing coronavirus. Electrostatic precipitators (ESPs) are a powerful tool for collecting fine particles, and to date, small air purifiers and other related products have been developed [1−8]. However, because the sources of airborne particulates are diverse, conventional air purifiers, which are typically designed for indoor use, may not be efficient in addressing the wide variety of suspended particulate matter present in different environments.

A new concept suggests that it is more effective for an air purifier to be positioned closer to the source of dust, allowing it to collect particles directly at the source. For example, in the event of a fire inside a building, smoke can fill the building. When smoke is captured near its source, visibility for evacuating individuals is improved. Similarly, a more drastic solution to outdoor pollen may involve collecting it in the forests where it originates rather than attempting to capture it indoors using standard air purifiers. The spread of droplets containing coronavirus can also be better controlled if they are captured near the person who has coughed rather than waiting for them to disperse. However, no air purifier capable of collecting dust while moving, such as a robotic vacuum cleaner, has been developed.

In this study, we developed a compact, lightweight ESP that can move toward the source of the dust to be collected. To eliminate the need for a fan, which is a mechanical moving part that can hinder the movement of the ESP, we incorporated a mechanism that applies an electrohydrodynamic (EHD) gas pump [9−12] to the ESP. This study proposes a novel ESP with a compact size and lightweight design and evaluates the effectiveness of EHD gas flow through dust collection experiments.

2. Experimental Methods

2.1 Mechanism of EHD gas pump

Fig. 1 shows a wire-to-nonparallel plate electrode system. A corona discharge occurs when a DC high voltage is applied to the wire electrode. In this configuration, the discharge current density flux is asymmetric between the upstream and downstream regions, resulting in a unidirectional EHD flow. This flow can draw dust-laden air toward the ESP without requiring a mechanical fan. The dust particles are charged by the corona discharge; thus, dust can be collected using a single-stage ESP. One significant advantage of EHD gas pumping is the absence of moving parts, such as fans. Therefore, this mechanism enables the development of a compact ESP.

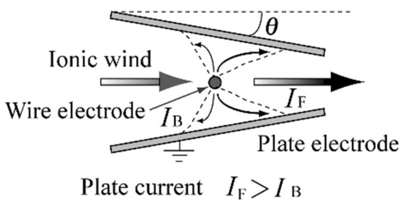

Fig. 1. Mechanism of the EHD gas pump used for the ESP without a fan.

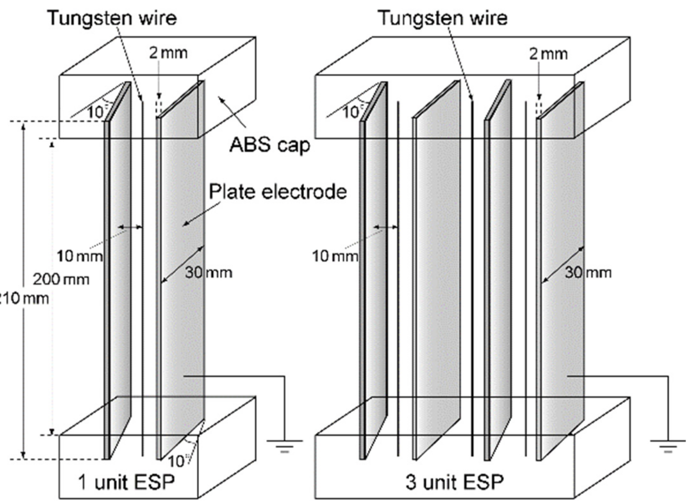

Fig. 2. Experimental setup (a) single-unit ESP and (b) three-unit ESP.

2.2 Design of compact ESP and performance evaluation

Fig. 2 shows a schematic of the proposed compact ESP. The basic structure comprises a wire-to-nonparallel plate electrode, which is set at an angle of 10° (Fig. 2 (a)). To assess its effectiveness as a gas pump, additional plate electrodes with angles of 0° and 5° were also prepared. A tungsten wire with a diameter of 0.25 mm was used as the discharge electrode. The plate electrode was constructed from 2-mm-thick, 210-mm-long balsa wood with grounded aluminum tape. The caps holding the electrodes were made of acrylonitrile butadiene styrene plastic, produced using a three-dimensional (3D) printer (Mutoh Engineering, Value 3D MagiX MF-1000). The wire electrode was positioned at the center of the plate electrode with a distance of 10 mm between the wire and the center of the plate electrode. The weight of the ESP unit is 70 g.

A homemade high voltage DC power supply was used as the power source. In a normal experiment, a high voltage power supply module (15 kV, 1.7 mA) was used. For the mobile dust collection experiments in a plastic greenhouse, a 10-kV high voltage generator powered by a 3-V battery and a two-stage step-up DC–DC converter was used. A DC high voltage of positive polarity was applied to the wire electrode to generate corona discharge. Since the proposed ESP is also intended to be used in buildings and indoors, positive corona discharge was used because it generates less ozone. To further improve the dust collection performance, a device with three units (Fig. 2 (b)) was also developed.

To evaluate the effectiveness of EHD gas pumping in the ESP unit, a hot-wire anemometer (Kanomax, Anemomaster, 6501-A0) was used to measure the air velocity at the position of the wire electrode 3 cm downstream from the unit outlet for both the single- and three-unit ESPs, respectively.

Dust collection experiments were conducted in either a 350 mm × 300 mm × 150 mm acrylic case or a 960 mm × 700 mm × 1,110 mm plastic greenhouse. After filling the acrylic case or greenhouse with a specific amount of incense smoke particles (0.3–1 μm in diameter), a high voltage was applied to the ESP unit to collect the dust. Dust collection performance was evaluated by monitoring changes in the smoke concentration using a video camera (SONY, FDR-AX100). Videography was performed in two ways: under normal room lighting and using laser visualization. For laser visualization, a 1-mm-thick laser sheet, created from a He-Ne laser (NIHON KAGAKU ENG., NEO-30MS, λ = 632.8 nm, Power = 45 mW) using a cylindrical telescope, was introduced into the acrylic case containing the ESP unit.

Particle image velocimetry (PIV) measurements were performed using two video images taken at 1/30-s time intervals. In these measurements, Lycopodium spores (30 µm in diameter), representing pollen, were used as seed tracers instead of incense smoke particles. The captured images were analyzed on a personal computer equipped with Dantec Flow Manager software.

Experiments to measure dust collection efficiency were conducted using incense smoke. Because the experimental conditions were identical to those used for the dust collection observations, conventional particle counters were not used for the measurements. Instead, the particle collection efficiency was evaluated by detecting the light transmittance of a He-Ne laser (NEC, GLG 5000, λ = 632.8 nm, Power = 0.5 mW) with a diameter of 1 mm as it passed through the acrylic case. The transmitted light was detected using a photodiode (THORLABS, DET10A/M), and the time-varying signal was measured using an oscilloscope (Tektronix, DPO 3034). In this experiment, the particle collection efficiency η of the developed ESP was estimated as follows:

$$\eta = \left(1 - \frac{A}{A_0}\right) \times 100\ [\%] \tag{1}$$

where A_0 and A denote the absorbance of the light intensity passing through the acrylic case before and during the collection of the incense smoke particles, respectively. Note that A_0 denotes the absorbance when the laser beam passes through the acrylic case in clean air without particles.

3. Results and discussion

3.1 Corona discharge and airflow around the ESP

Fig. 3 shows the current–voltage characteristics of a positive DC corona discharge. The corona discharge occurs at onset voltages of 6.5 and 6.0 kV for the single- and three-unit ESPs, respectively, and the discharge current increases with the applied voltage. In the single-unit ESP, the effect of the tilt angle of the plate electrodes on the current is negligible. Fig. 4 shows the luminescence of the discharge, where a glow-type discharge is generated uniformly along the wire electrode for the single- and three-unit ESPs, respectively.

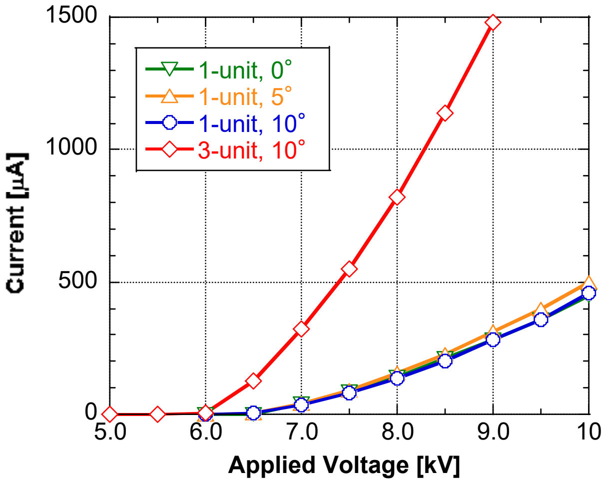

Fig. 3. Current-voltage characteristics for positive DC corona discharge.

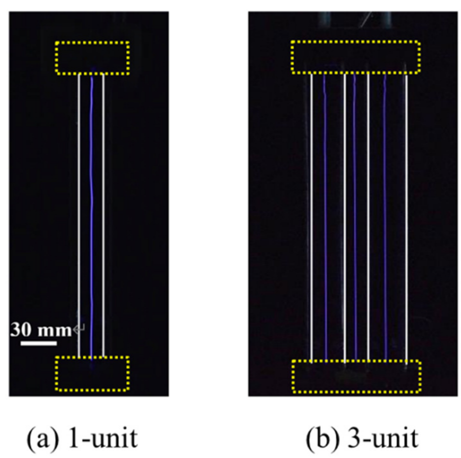

Fig. 4. Luminescence of positive DC corona discharge (Applied voltage: 8 kV).

Fig. 5 shows the airflow velocities of the single- and three-unit ESPs. After the corona onset, as the ionic wind is generated from the wire electrode, an airflow is created around the ESP unit. The airflow velocity tends to increase approximately with the applied voltage. The maximum flow velocity at the ESP outlet section exceeded 1 m/s, which is comparable to that of ionic wind devices using needle electrodes [13]. In the case of the wire-to-nonparallel plate electrode, a unidirectional flow toward the ESP exit occurs. The air velocity measurements were performed at the same location as the wire electrode, 3 cm downstream from the unit; thus, the airflow direction of the wire-to-parallel plate electrode [14] will flow in the opposite direction compared to the wire-to-nonparallel plate electrodes [10, 11]. However, even in parallel plate electrode system, unidirectional flow can be achieved by changing the wire electrode to a plate with spikes [15].

Based on the PIV measurements, a flow velocity vector map at 8 kV is shown in Fig. 6. Lycopodium spores are significantly larger and heavier than incense smoke particles, resulting in significantly lower flow velocity. However, the proposed ESP effectively collects particles without a mechanical fan. The generated flow draws air into the ESP and creates a recirculating flow around the ESP unit (see the peripheral area indicated by arrow "A" in Fig.6).

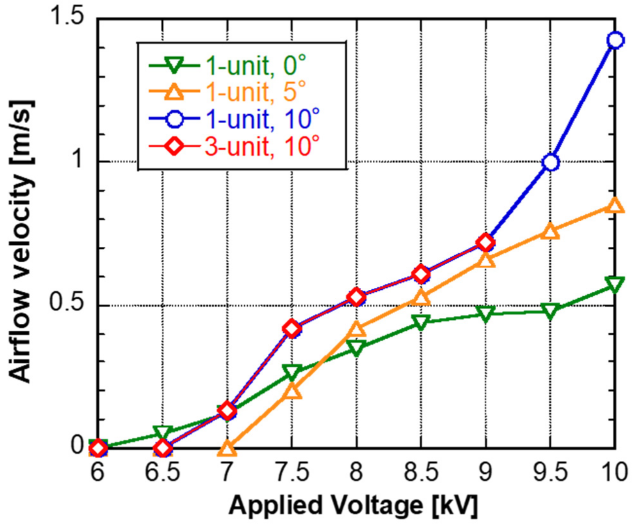

Fig. 5. Airflow velocities for single-unit ESP and three-unit ESP.

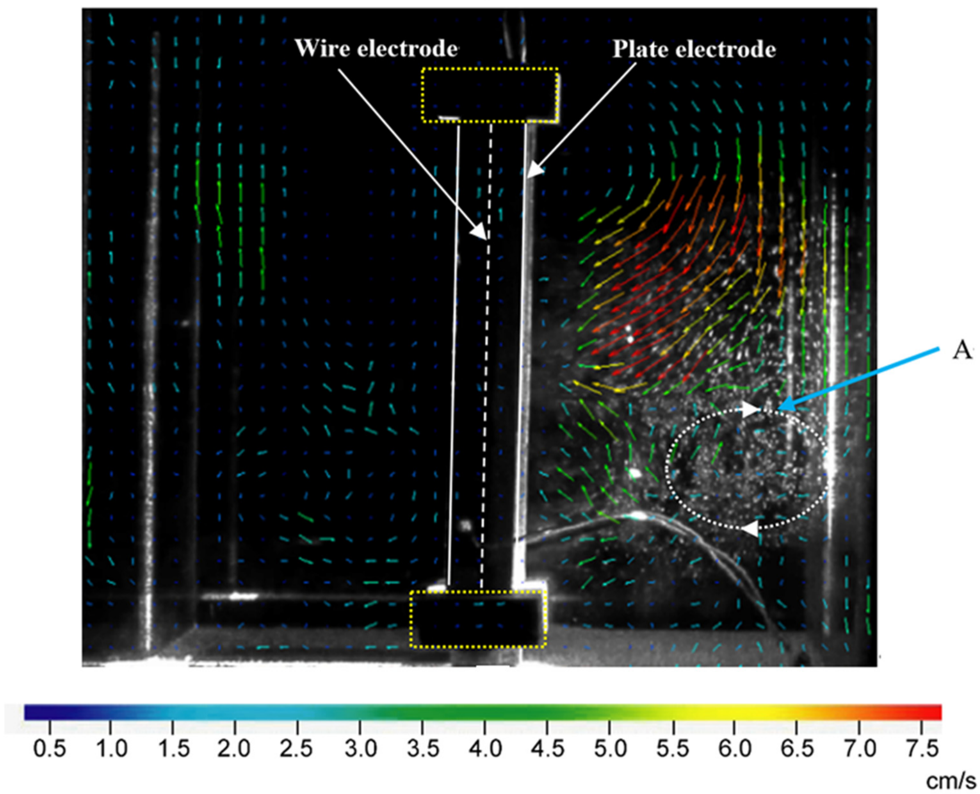

Fig. 6. Air velocity map of single-unit ESP placed inside the acrylic case (Applied voltage: 8 kV).

3.2 Particle collection performance

Fig. 7 shows the time-dependent particle collection efficiency of the single- and three-unit ESPs. As initial conditions, two incense sticks (6 g) were burned in an acrylic case to fill it with smoke. The particle collection efficiency, η, was evaluated using Eq. (1). Compared to a wire-to-parallel plate-type ESP (inverted triangular symbol in Fig. 7), the wire-to-nonparallel plate-type ESP (circle and triangular symbols in Fig. 7) demonstrates rapid collection performance. Furthermore, the three-unit ESP exhibited significantly faster dust collection characteristics than the single-unit ESP, as shown in Fig. 7.

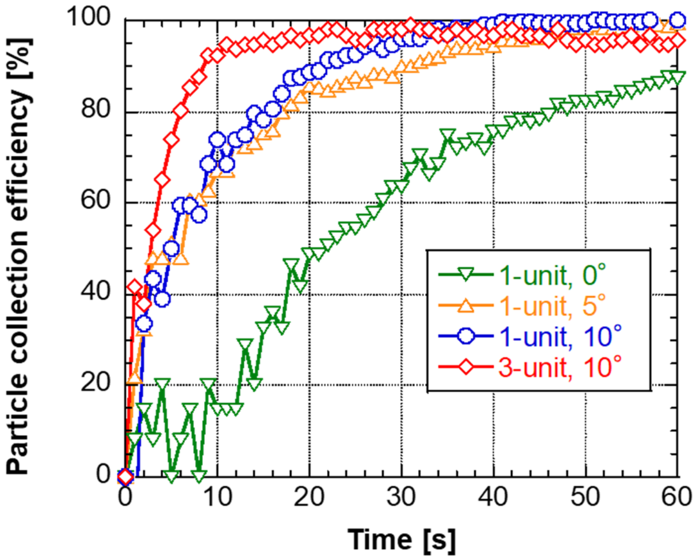

Fig. 7. Time dependence of particle collection efficiency (Applied voltage: 8 kV).

The particle collection performance was visually observed as the interior of the acrylic case or plastic greenhouse gradually became transparent from the initially cloudy white state caused by smoke. Fig. 8 shows typical images of the time-dependent particle collection performance of the single- and three-unit ESPs. For both units, a DC high voltage of 8 kV with positive polarity was applied to a 10° tilt nonparallel plate unit, and the ESP was moved back and forth inside the acrylic case during a 20-s round trip. Over time, particle collection improves, and the interior of the acrylic case becomes clearer. Some particles sneak through the unit because the dust collection plate area is small, approximately 30 mm in width. A trade-off exists between the compact size and collection efficiency. However, particle leakage is reduced when using the three-unit ESP device. In the three-unit ESP, some uncollected particles that have passed through the central unit are collected by the airflow effect of the units on either side. Similarly, particles that have passed through the units on the sides are partially collected by the central unit. Integrating the units allows us to collect a larger volume of particles.

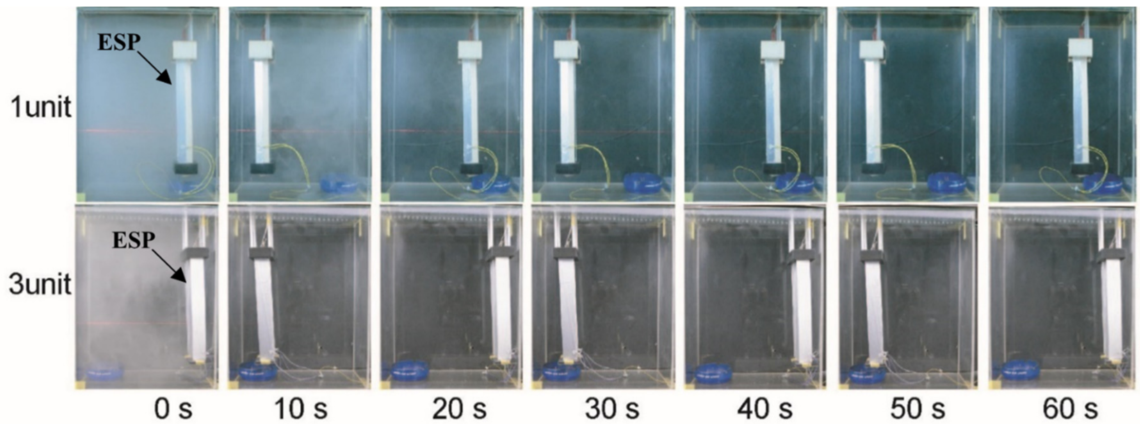

Fig. 8. Comparison of single-unit ESP and three-unit ESP. Change in smoke concentration in acrylic case (Applied voltage: 8 kV).

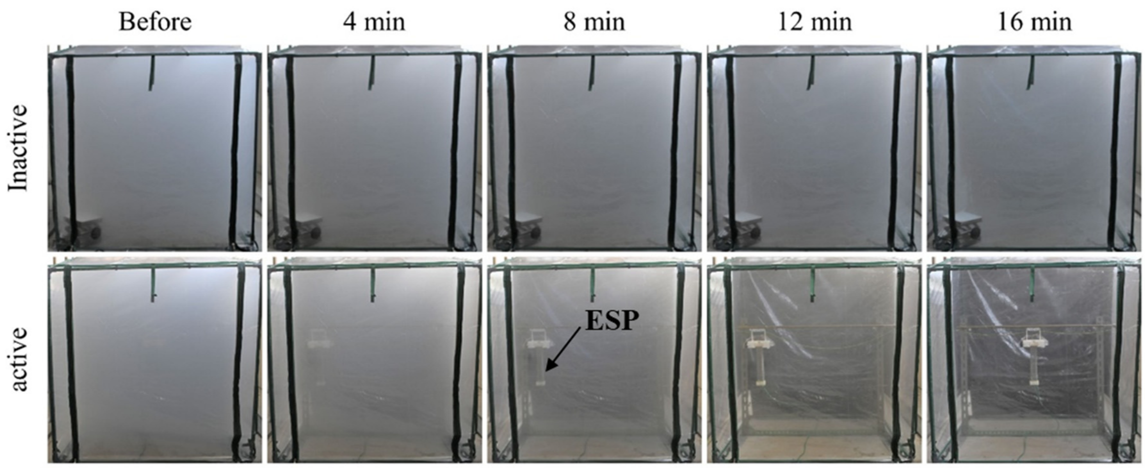

Fig. 9. Comparison of ESP non-operation (top) and ESP operation (low). Change in smoke concentration in plastic greenhouse (Single-unit operation at 10 kV).

Fig. 9 shows the change in the smoke concentration in the plastic greenhouse at 4-min intervals after the start of dust collection. The figure compares the case in which a DC high voltage of 10 kV is applied to the dust collection unit with a 10° tilt nonparallel plate unit to the case in which no voltage is applied. The ESP was moved back and forth inside the plastic greenhouse at 60 s intervals. The single-unit ESP was operated with a battery-driven 10-kV voltage; thus, the current was not as high as the discharge current shown in Fig. 3. When the high voltage was applied, the smoke faded with time, and after 16 min, the smoke was sufficiently dissipated to make the interior of the mini-greenhouse visible. In addition, after collecting the incense smoke, tar-like brown deposits were observed on the plate electrodes. This type of deposit can be cleaned by wiping it off with tissue paper.

4. Conclusion

In this study, we have proposed a novel ESP that uses an EHD gas pump mechanism. The proposed ESP offers several advantages, including being very small and lightweight and having no mechanical fan. Consequently, with further refinement, the ESP unit can be mounted on electric vehicles and drones to collect particles and other materials while approaching dust sources. The main results are as follows:

1) A wire-to-nonparallel plate electrode system, measuring 30 mm wide, 210 mm long, and weighing 70 g, was fabricated as a single-unit ESP. The EHD pump effectively draws particles into the ESP device without requiring a fan. In terms of dust collection performance, nonparallel plates with an inclination angle of 10° were effective for the plate electrode geometry.
2) Even in small spaces such as an acrylic case or a plastic greenhouse, dust collection is faster when the ESP unit is moved than when it is fixed and stationary. Particle leakage is unavoidable with a single-stage ESP with a short plate width. However, we proposed a three-unit ESP with an alternating arrangement on a flat surface, which improved dust collection performance.

In the future, further integration of the proposed ESP unit will enable large-volume processing and allow its incorporation into mobile systems. Combined with a particle sensor, this integration will facilitate a more effective dust collection while in motion. Furthermore, a comprehensive evaluation that takes into account power consumption and ozone production is necessary. These issues are consistent with ongoing research.

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References

[1] Turner J.H., Lawless P.A., Yamamoto T., Coy D.W., Greiner G.P., McKenna J.D., and Vatavuk W.M., Sizing and costing of electrostatic precipitators, *J. Air Pollut. Control Assoc.,* Vol. 38, pp. 458−471, 1988.
[2] Huang S.H., and Chen. C.C, Filtration characteristics of a miniature electrostatic precipitator, *Aerosol Sci. Technol.,* Vol. 35, pp.792−804, 2001.
[3] Shaughnessy R.J., and Sextro G.R., What is an effective portable air cleaning device? A review, *J. Occup. Environ. Hyg.,* Vol. 3, pp.169−181, 2006.
[4] Botvinnik I., Taylor C. E., and Snyder G., High-efficiency portable electrostatic air cleaner with insulated electrodes (January 2007), *IEEE Trans. Ind. Applicat.,* Vol. 44, pp. 512−516, 2008.
[5] Ongwandee M., and Kruewan A., Evaluation of portable household and in-car air cleaners for air cleaning potential and ozone-initiated pollutants, *Indoor Built Environ.* Vol. 22, pp. 659−668, 2013.
[6] Kim M., Kim G.T., Kim Y.J., K, Han B., Woo C. G., and Kim H.J., A novel electrostatic precipitator-type small air purifier with a carbon fiber ionizer and an activated carbon fiber filter, *J. Aerosol Sci.,* Vol. 117, pp. 63−73, 2018.
[7] Zeng Y., Xie R., Cao J., Chen Z., Fan Q., Liu B., Lian X., and Huang H., Simultaneous removal of multiple indoor-air pollutants using a combined process of electrostatic precipitation and catalytic decomposition, *Chem. Eng. J.,* Vol. 388, 124219, 2020.
[8] Kähler C. J., Hain R., and Fuchs T., Assessment of mobile air cleaners to reduce the concentration of infectious aerosol particles indoors, *Atmosphere,* Vol. 14, 698, 2023.
[9] Tsubone H., Ueno J., Komeili B., Minami S., Harvel G.D., Urashima K, Chang C.Y., and Chang J.S., Flow characteristics of dc wire-non-parallel plate electrohydrodynamic gas pumps, *J. Electrostat*., Vol. 66, pp. 115−121, 2008.
[10] Kocik M., Podliński J., Mizeraczyk J., and Chang J.S., Particle image velocimetry measurements of wire-nonparallel plates type electrohydrodynamic gas pump, *IEEE Trans. Dielectr. Electr. Insul.,* Vol. 16, pp. 313−319, 2009.
[11] Kocik M., Podliński J., Mizeraczyk J., Urashima K., and Chang J.S., Flow distribution measurement in wire-nonparallel plate type electrohydrodynamic gas pump by a particle image velocimetry, *IEEE Trans. Dielectr. Electr. Insul.,* Vol. 16, pp. 601−607, 2009.
[12] Chang J.S, Tsubone H., Chun Y.N., Berezin A.A., and Urashima K., Mechanism of electrodynamically induced flow in a wire-non-parallel plate electrode type gas pump, *J. Electrostat*., Vol. 67, pp. 335−339, 2009.
[13] Kanazawa S., Imagawa W., Matsunari S., Akamine S., Ichiki R., and Kanazawa K., Ionic wind devices prepared by a 3D printer, *Int. J. Plasma Environ. Sci. Technol.*, Vol. 11, pp. 38−42, 2017.
[14] Zhao L., and Adamiak K., Numerical simulation of the electrohydrodynamic flow in a single wire-plate electrostatic precipitator, *IEEE Trans. Ind. Appl*., Vol. 44 (3), pp. 683−691, 2008.
[15] Katatani A., and Mizuno A., Generation of ionic wind by using parallel located flat plates, *J. Inst. Electrostat. Jpn.*, Vol. 34 (4), pp. 187−192, 2010. (in Japanese)