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Short Communications

Electrostatic Elimination of Fine Smoke Particles by a Newly Devised Air Purification Screen

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Abstract. Our primary concern of air pollution problem was a transboundary movement of air pollutants to Japan from the pollutant generating country because of geographic and meteorological reasons. An electrostatic air purification screen (EAPS) was devised to capture particulate matter (PM) in smoke, which can cause health problems. The EAPS consisted of three layers of insulated conductor wires (ICWs) and two voltage generators that supplied negative charges to the two outer ICW layers and a positive charge to the middle ICW layer. The ICWs generated an attractive force that captured fine particles in the smoke passing through the EAPS. The attractive force was directly proportional to the applied voltage. At ≥4.5 kV, the EAPS exerted sufficient force to capture all fine particles carried in an airflow of 3 m/s. Results showed that the electrostatic barrier that formed inside the EAPS was effective at capturing PM, allowing homes and working environments to remain PM-free and healthy, despite continuous PM exposure.

Keywords: Electric field, fine particle capture, particulate matter.

1. INTRODUCTION

Smoke is made up of a complex mixture of gases and fine particles produced when wood and other organic matter are burned. The biggest health threat from smoke comes from fine particles. These microscopic particles can get into the eyes and respiratory system, where they can cause health problems such as burning eyes, runny nose, and illnesses such as bronchitis. Fine particles can also aggravate chronic heart and lung diseases and are linked to premature death (Kima et al., 2015; Schlesinger et al., 2007). Our primary concern was transboundary air pollution. The pollutants were frequently transmitted to Japan by the prevailing westerlies, because of geographical relation to the air-pollutant generating country. The state and local agencies provide air quality forecasts reporting when particle levels are expected to be unhealthy during regular environmental monitoring of actual levels of common air pollutants (http://www.tenki.jp/particulate_matter/). When an alert is issued, we are advised to stay indoors and close windows and doors to keep indoor air as clean as possible until the alert is cleared. Our goal was to improve the quality of life of those sensitive to air pollutants by eliminating airborne particulate matter (PM) in homes. To this end, we developed an electrostatic air purification screen (EAPS) that prevents fine PM in the air from entering the household. We originally developed similar barriers to trap insect pests for safe crop production and preservation (Kakutani et al., 2012; Matsuda et al., 2012). The apparatus for capturing fine, airborne particles is simple and easy to construct; most importantly, the system is energy-efficient and can operate continuously for long periods of time.

2. MATERIALS AND METHODS

2.1. Devise

A The EAPS consists of insulated conductor wires (ICWs) used as electrodes to form electric fields. Iron wires (diameter: 2 mm; length: 20 cm) were insulated by passing them through a transparent insulator vinyl sleeve (thickness: 1 mm; bulk resistivity: 1 × 109 Ω cm). Three layers of ICWs were configured in parallel arrays. Two electrostatic direct current (DC) voltage generators (DMS-P and DMS-N; Max Electronics, Tokyo, Japan) supplied negative and positive voltages to the ICWs (Fig. 1A). Within each layer, the ICWs were parallel at 5-mm intervals and connected to each other and to the negative or positive voltage generator. The negatively and positively charged ICWs are represented as ICW(–) and ICW(+), respectively. The EAPS consisted of a central ICW(+) layer, with an ICW(–) layer on either side. The layers were parallel and 2-mm apart, and the ICWs in the different layers were offset from each other. The generators were linked to create an electric circuit producing electric fields between the ICW(–) and ICW(+) (Fig. 1B). In this system, free electrons from ICW(+) were pushed towards ICW(–). The opposite surface charges on the ICWs acted as dipoles that formed an electric field between them (Matsuda et al., 2015). A galvanometer (PC7000; Sanwa Electric Instrument, Tokyo, Japan) was integrated into the line between the voltage generators. Both generators were operated with 12-V storage batteries. Power from a 15-W solar panel supplied equal negative and positive voltages to the ICWs. In the EAPS, the voltage generator was the only driving part requiring an electric power supply, and its electric power was 5 W, equivalent to that of a small electric bulb. This enabled the use of a photovoltaic power generation method for supplying the power to the voltage generators.

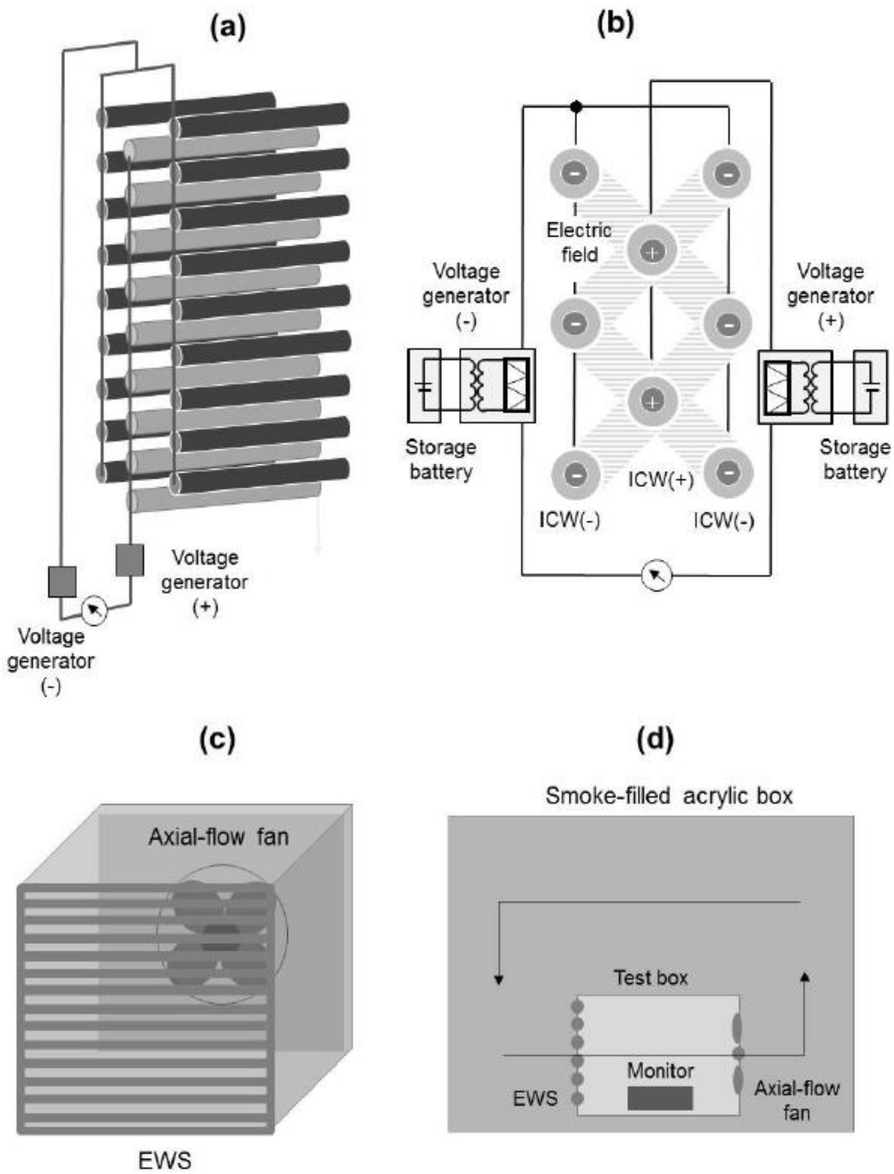

Fig. 1: Structure (A) and cross-sectional view (B) of the three insulated conductor wire (ICW) layers of the electrostatic air purification screen (EAPS). A wooden cubic box (test box) furnished with the EAPS (C). The test box placed in a larger acrylic box for a particle-capturing assay (D). Arrow shows the direction of airflow.

2.2. Set-up experiments

To test the ability of the EAPS to capture fine particles in smoke, mosquito-repelling incense (mosquito coil) (Earth Pharmaceutical, Tokyo, Japan), compressed cherry-wood sawdust for meat smoking (Shinfuji Burner, Toyokawa, Japan), and a cigarette (Japan Tobacco, Tokyo, Japan) were used to generate smoke; the particles emitted ranged in size from 0.5 to 2.5 µm in diameter when burned. In the present assay, a wooden cubic box (side length, 25 cm) was furnished with the test-size EAPS (20 × 20 cm) on one side and an axial-flow fan (blade length, 8 cm) on the opposite side (Fig. 1C). This test box was placed inside a closed larger transparent acrylic box (120 × 90 × 100 cm) (Fig. 1D).

Burning mosquito coils or sawdust lumps and cigarettes were put inside the acrylic box. The internal air was circulated at 3 m/s to prepare a constant smoke by operating the axial-flow fan of the test box. The airflow speed was measured at the surface of the ICW using a sensitive anemometer (Climomaster 6533; Kanomax, Tokyo, Japan). Particle density in the circulated air was measured by the air quality monitor DC1100 PRO (Sato Shouji Inc., Kawasaki, Japan; detectable particle range: 0.5–2.5 µm in diameter) placed inside the test box. When the particle density reached a certain level (1.5 × 108 particles/m3), we removed the smoke source and then charged the ICWs for 120 s with the same negative and positive voltages (0.5–4.5 kV) to determine the voltage range for capturing all of the particles passing through the EAPS. The non-charged box was used as a negative control. For the non-charged control box, we assumed that 100% of the particles passed through the EAPS; the number of particles in the charged box was expressed as a percentage relative to that of the non-charged control. Experiments were repeated five times; data are presented as the mean ± standard deviation (SD). Significant differences among data were analyzed using Tukey's method (see the caption of Fig. 2); a p-value < 0.05 was considered to be statistically significant. Smoke attraction was also recorded using a digital electro-optical system (EOS) camera (Canon, Tokyo, Japan).

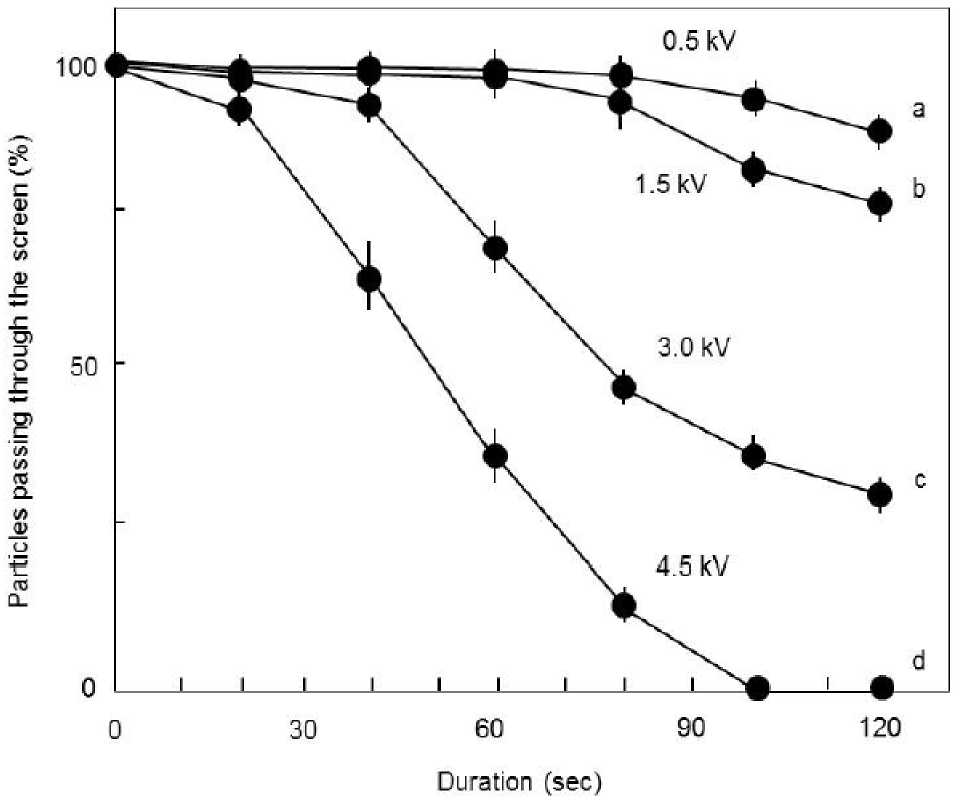

Fig. 2: Purification of fine particles of mosquito-coil smoke by the EAPS charged with different voltages. The smoke was circulated at 3 m/s. The mean and standard deviation were calculated from five replicates. The different letters on the plots at 4.5 kV indicate significant differences ($p < 0.05$) according to Tukey's method.

3. RESULTS AND DISCUSSIONS

We constructed the EAPS with multiple gap-free electric fields because successful particle capture depends on the formation of an electrostatic barrier with no spaces through which the particle can pass. An essential step in forming the electric fields was charging the insulated electrodes. High voltages produced through the Cockcroft circuit (Wegner 2002) of two voltage generators were used to electrify both electrodes by adding electrons to ICW(–) and pushing electrons away from ICW(+).

The prospective use of the EAPS is to install actual room windows to prevent fine particle air pollutants from entering a room with good air penetration. Good air flow is vital for efficient ventilation in healthy housing. However, active air circulation also has a downside because the air flow can carry airborne pollutants throughout the house. Our primary concern was to eliminate fine particles from the airflow passing through the EAPS.

Figure 2 shows the percentage of fine particles of the mosquito-coil smoke trapped by ICWs charged at different voltages for airflow of 3 m/s (maximum wind speed of the present apparatus). The number of detector-recorded fine particles decreased with the applied voltage. In the electric field, a particle was subjected to an electrostatic attractive force and a force produced by the airflow; the direction of the particle's motion was determined by the combined vector of these two forces. The ICWs trapped all of the fine smoke particles in the electric field created when the voltage applied to the electrodes exceeded 4.5 kV; however, at lower voltages, particles passed through the EAPS. Under these conditions, the force produced by the electric field was weaker than the airflow force. These findings indicate that the reduction in the trapping force increased as the voltage decreased. To demonstrate this visually, Video Supplement 1 shows that the EAPS can capture fine particles in smoke blown toward the screen. In the video, the electrostatic barrier completely prevents the smoke from passing through the EAPS with a sufficient charge. In the assay using other smoke sources (sawdust smoke and cigarette smoke), we obtained similar results for capturing the smoke (data not shown).

In our previous research, we developed an electric field between ICWs and a grounded net by placing a grounded metal net on each side of the ICW layer to trap insect pests. In that system, ICW(–) pushed free electrons from the surface cuticle layers (conductor) of insects released near ICW(–) to give insects a net positive charge (Kakutani et al., 2012; Nonomura et al., 2014), whereas insects near ICW(+) gained a net negative charge with the addition of free electrons to the cuticle layer (Matsuda et al., 2012); ultimately, the negatively and positively electrified insects were attracted to oppositely charged electrodes. In the current study, however, we present an additional explanation of the fine particle attraction in the electric field due to the dielectrophoretic movement of the particle subjected to a non-uniform electric field. Dielectrophoresis is a phenomenon in which a force is exerted on a dielectric particle (oppositely polarized particle) in a non-uniform electric field (Cross, 1987). This force does not require the particle to be charged because all particles exhibit dielectrophoretic activity in the presence of a non-uniform electric field. Obviously, the round electrodes used in this study produced a non-uniform electric field, such that the particle becomes polarized dielectrically. According to the dielectrophoresis theory, the polarization of the particle relative to the surrounding electric field changes along the gradient of the electric field strength. This changeable polarization enables the particle to move toward the electrodes. In fact, the particle moved toward the nearest electrode, that is, in the direction of increasing electric field intensity produced by the electrode. In this study, the electrodes were oppositely charged with equal voltages; thus, both electrodes created the same gradient of field strength. These oppositely charged electrodes exerted the same attractive force on particles. The gradient of the field intensity increased with the voltage applied to the electrodes, and eventually both electrodes created a force sufficiently strong to capture the particle.

4. CONCLUSION

The primary contribution of this work was the use of basic electrostatics for improving the human environment. The EAPS is a unique product developed for this purpose. The structure of the EAPS is simple; no special technique is required for its construction. The EAPS can operate normally at low electric power consumption to capture fine particles involved in smoke in a dielectrophoretic manner. This work demonstrated that the proposed EAPS can easily eliminate fine PM from living spaces to improve the comfort of occupants and minimize the likelihood of air quality-related health problems.

SUPPLEMENTARY MATERIAL

See supplementary material for trapping of mosquito-coil smoke by the EAPS.
https://www.dropbox.com/s/n5jx5mzg338tni8/Video%20supplement%201.mp4?dl=0

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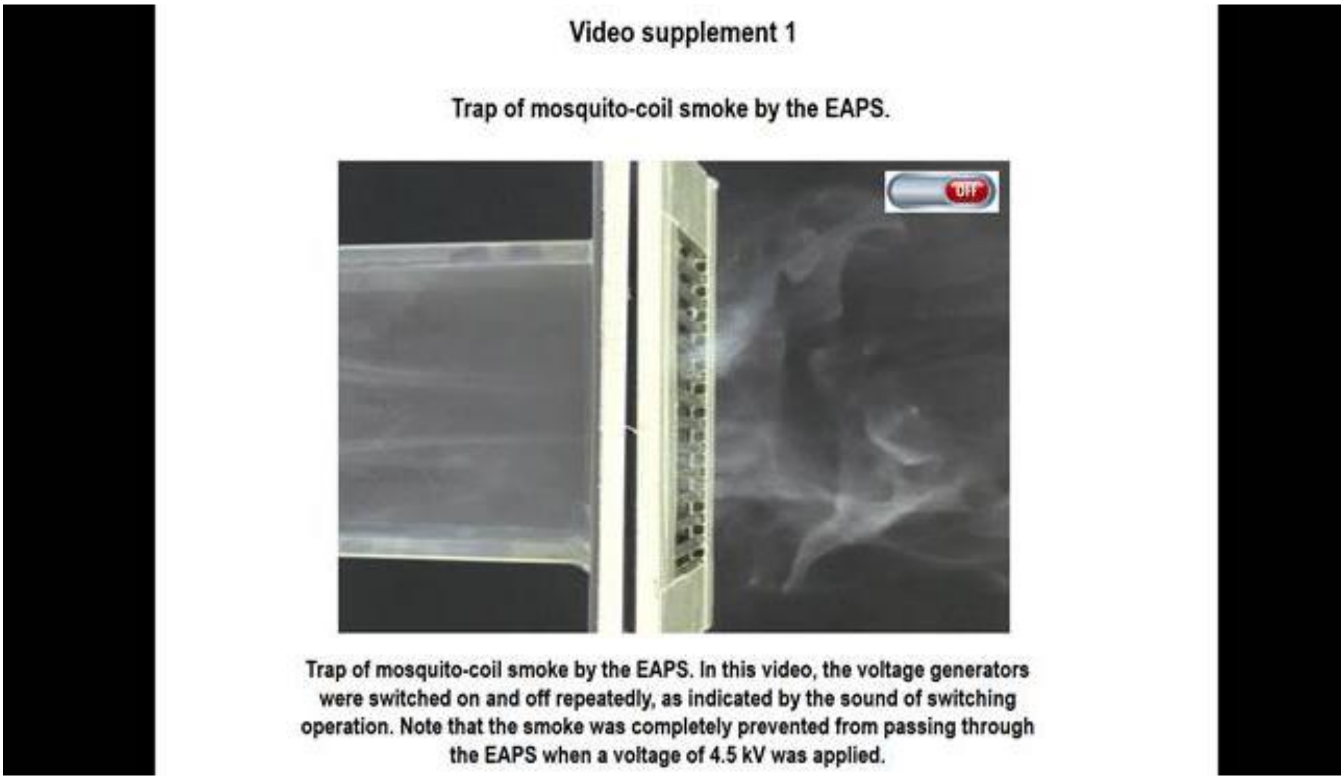
Appendix



Video supplement 1: Trap of mosquito-coil smoke by the EAPS. In this video, the voltage generators were switched on and off repeatedly, as indicated by the sound of switching operation. Note that the smoke was completely prevented from passing through the EAPS when a voltage of 4.5 kV was applied.

See supplementary material for trapping of mosquito-coil smoke by the EAPS.

https://www.dropbox.com/s/n5jx5mzg338tni8/Video%20supplement%201.mp4?dl=0

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