Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Quantitative analysis of droplet deposition produced by an electrostatic sprayer on a classroom table by using fluorescent tracer

Dong-Bin Kwak a, Seong Chan Kim a, Thomas H. Kuehn a, David Y.H. Pui a,b, *

a Particle Technology Laboratory, Mechanical Engineering, University of Minnesota, 111 Church St., S.E., Minneapolis, MN, 55455, USA
b School of Science and Engineering, The Chinese University of Hong Kong, Shenzhen, Guangdong, 518172, China

Abstract

Due to the ongoing COVID-19 pandemic situation, measures to mitigate the risk of transmission of the SARS-CoV-2 virus in indoor settings are urgently needed. Among the various types of disinfectant methods, electrostatic spraying is often applied to decontamination in public places. For quantitatively characterizing electrostatic spraying, we developed the novel evaluation method by using a fluorescent tracer. By applying this method, we performed three different experiment cases (static test on a table, static test on a cylinder, and dynamic test on a table) to figure out its unique characteristics (Coulombic fission and wraparound effect) and measure its performance in various aspects. To be specific, bimodal distribution with peak sizes of ~10 and ~100 μm was found due to Coulombic fission. Otherwise, a unimodal distribution with a peak size of ~100 μm occurred for the uncharged droplets. As a result, the effective contact area increased by 40–80 % due to small progeny droplets. The wraparound effect was examined on two different cylinders: copper (Cu) and polyvinyl chloride (PVC) pipe. When the target surface was not charged (Cu 0 kV and PVC 0 kV), the average normalized concentrations on the backside of the cylinder (θ = 180°) increased by around 67 % for charged droplets. Meanwhile, when the target surface was highly charged (PVC ~19 kV), the average normalized concentrations at θ = 180° were increased more than two times for charged droplets.

1. Introduction

Under the current COVID-19 pandemic situation, it is urgently required to establish general measures to mitigate the risks of SARS-CoV-2 virus transmission in indoor environments. While there is a controversial discussion regarding the dominant transmission path, it is well known that fomite transmissions are considered to be one of the sources of SARS-CoV-2 virus transmission [1–4]. It means that respiratory droplets generated from infected persons settle on shared surfaces such as desks, furniture, door handles, and tools, and those can be transmitted to the next individual who touched the surfaces afterward. In addition to the risk of fomite transmission, the virus within human saliva can survive up to 3 days on plastic, and stainless steel, which makes surface decontamination to be the most practical way to mitigate virus spread [3,5]. For those reasons, currently, surface decontamination of shared surfaces is officially recommended by several authorized organizations, such as WHO [6], ECDC [7], OSHA [8], and CDC [9]. However, most recent studies are solely focused on droplets or aerosols transmission to mitigate the virus transmission [10–17].

As main surface decontamination methods like surface wiping, trigger sprayers, pressure sprayers, and electrostatic sprayers are used with disinfectant solutions for various places from households to public places such as schools, public transportations, and hospitals [18,19]. Among the several types of sprayers, electrostatic sprayers are mainly applied for public place decontaminations due to their time and labor effectiveness over other sprayers. Their characteristics to deliver the droplets to hidden surfaces of the objects, which is called the wraparound effect, result in full even coverage on hardly reaching surfaces [20–22]. The electrostatic nozzle application has been developed in numerous industrial applications including particle synthesis [23], micro-patterning [24], thin-film deposition [25,26], measurement device [27–29], oil burner [30], and agriculture [31–34] due to its unique characteristics. Although the characterization of droplet deposition pattern and droplet size distribution is essential for optimizing the disinfectant sprayer, to our best knowledge, there is no research conducted through quantitatively characterizing the electrostatic sprayer performance.

For tracking a large number of droplets, we employed the fluorescent...
tracer method. Due to technological advances in various industries, aerosol transport tracking studies have gained great attention. For example, in the semiconductor industry, it is indispensable to carefully control the particle contamination and figure out the contamination source location to improve the production yields and quality due to reduced minimum pitch size in semiconductor products [35–38]. In order to experimentally verify the particle deposition location, fluorescent particles or droplets have been employed. For example, Lee and
Yook [39] used fluorescent particles to visibly demonstrate the degree of particulate contamination of heated wafers in a front opening unified pod-mimicking plastic chamber according to the position of the wafers. However, Lee and Yook only visualize the degree of particle deposition, not providing the quantitative contamination results through the experiment. Pui et al. [40] obtained particle deposition efficiency on a 90° pipe by using micro-sized fluorescent droplets and comparing the total mass of uranine on the tested part and the outlet part. Even though Pui et al. [40] provided the quantitative results of particle deposition efficiency, their methods cannot demonstrate the particle location and are hard to be applied in large-scale investigations. For investigating the aerosol transport on a bent tube or pipe, Kwak et al. [41] tracked individual particles and showed the particle deposition location and pattern on a sharp-bent tube through a numerical method, but they also did not compare their numerically calculated particle deposition location with experimental results. Also, a fluorescent tracer was used to calibrate the aerosol instrument or sampler. Vaughan [42] utilized a fluorescent tracer to calibrate the Anderson impactor and quantify the wall loss on the impactor during aerosol transport. Those studies [39,40,42] were conducted in a limited space and specific parts of the typical structure such as a wafer, tube interior, and aerosol sampler. Therefore those studies [39,40,42] are not suitable for applying in open spaces.

In this study, we characterized the electrostatic sprayer performance by using a fluorescent tracer. Before characterizing the electrostatic sprayer, we introduce the method to compare the size of aerosol state droplets and deposited droplets on the surface. We used a flow-focusing monodisperse aerosol generator to generate known size aerosol state droplets. For measuring the size of deposited droplets, we made use of the fluorescence microscope. For quantitatively determining the amount of deposited fluorescent droplets, we used a fluorometer. To validate the data, we compared the fluorescent signal with the normalized area of fluorescent droplets. Electrostatic sprayer performance was quantitatively examined in several different conditions: static test on a table, static test on a cylinder, and dynamic test on a table. In a static test on a table section, the overall deposition pattern and droplet size distribution of the electrostatic sprayer were carefully investigated. The wraparound effect was quantitatively described in a static test on a cylinder section. Lastly, we discussed the electrostatic sprayer performance by mimicking two different actual usage situations in a dynamic test on a table section.

2. Materials and methods

2.1. Materials

Electrostatic sprayer (Model VP200ES, Victory Innovation Company, MN, USA) which was easy to control the charging mode was tested for comparing the sprayer performance with and without electrostatic charging. The flow rate of the electrostatic sprayer was set to approximately 92 ml/min. Fluorescein sodium salt (C20H10Na2O5, Cas 518-47-8, Mw = 376.27 g/mol) was purchased from Sigma-Aldrich (St. Louis, MO, USA) for use as a fluorescent tracer. According to the manufacturer’s material data, the fluorescence of peak excitation and the emission wavelength is 460 and 515 nm, respectively. The water solubility of C20H10Na2O5 is 1 g/L. A sample solution was prepared by dissolving 0.1772 g of C20H10Na2O5 in 1.0 L of deionized water. 18 × 18 mm micro cover glasses (Model 48366-045, VWR International, PA, USA) were prepared for collecting droplets on a flat surface and aluminum foil tape (1517CW, 3 M, MN, USA) was prepared using a paper punch with a 6 mm circle for collecting droplets on a curved surface.

2.2. Fluorescence microscope

A fluorescence microscope (Model Eclipse Ti, Nikon, Tokyo, Japan) was employed for characterizing the deposited droplets on cover glasses.

| Table 1 |
| --- |
| Flow focusing monodisperse aerosol generator (FMAG) operational condition for generating monodisperse fluorescent liquid droplets and calculated droplet diameter by using eq. (1). |
| Liquid flow [ml/h] | 2 | 5 | 10 | 19 | 24 |
| Vibration frequency [kHz] | 132 | 100 | 80 | 80 | 60 |
| Droplet diameter [μm] | 20.0 | 29.8 | 40.5 | 50.1 | 59.6 |

Fig. 3. Comparison between generated droplet diameter by FMAG and measured contact diameter by fluorescence microscope. The yellow scale bar in fluorescence microscope images indicates 200 μm. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
exposure time (640 nm). Among the light sources under 10 μm (GFP/FITC filter) with an excitation wavelength range of 465–555 nm was used in this study. The raw images were captured through the fluorescence microscope equipped with a set of light filter cubes mounted in a motorized filter turret. The purposes of light filters were (1) passing a specific wavelength range of white light spectrum to samples to illuminate samples and fluorescent tracer concentration. (2) letting only a specific emission wavelength pass back to the camera. Among the light filters, a green fluorescent protein/fluorescein isothiocyanate filter (GFP/FITC filter) with an excitation wavelength range of 465–495 nm and an emission wavelength range of 515–555 nm was used in this study. The raw images were captured through the fluorescence microscope under 10 × magnification, 4 × 4 binning working mode, and 1 s exposure time (640 × 540 pixels and binned pixel size equal to 2.6 μm).

Recognizing images and retrieving image information was performed by using commercial software, MATLAB Release 2020a. To extract the fluorescent droplet information and remove the background noise, the color threshold segmentation which is one of the most commonly applied segmentation methods [43,44] was applied to eliminate parts of the image that fall outside a specified color range. Based on 256-color values (0–255), the RGB color threshold range was set from 0 to 255 for red, 75 to 255 for green, and 0 to 50 for blue. The filtered images were analyzed after changing them to binary images.

### 2.3. Fluorometer

In order to perform the quantitative analysis of electrostatic sprayer performance, the fluorometer (Turner digital fluorometer, Model 450, Barnstead-Thermolyne, IA, USA) was utilized. As shown in Fig. 1, excitation energy (340–750 nm) is provided by a quartz-halogen lamp (Model 4SF02-01, Barnstead-Thermolyne, IA, USA), and then it is filtered by a Narrow Band filter (NB440 filter, Model 4SF01-05, Barnstead-Thermolyne, IA, USA) for passing specific wavelength of excitation energy (440–460 nm). For distinguishing the excitation and emission wavelength, Sharp-Cut filter (SC500 filter, Model 4SF01-25, Barnstead-Thermolyne, IA, USA) which allows only emitted light above a specific wavelength (>500 nm) to pass into the light detector. Sample solutions were prepared by putting cover glasses or aluminum foil tapes into containers (Product no. 430828, Corning, NY, USA) with 20 ml deionized water. 12 × 75 mm culture tubes (Product no. 99445-12, Corning, NY, USA) with sample solutions were placed into the fluorometer for measuring the fluorescence signal.

### 2.4. Electrostatic sprayer evaluation methods

In order to quantitatively characterize the electrostatic sprayer performance with or without an electrostatic charge, three different experiment cases were performed, as shown in Fig. 2. For quantitatively determining how far, wide, and evenly the sprayed solution can be delivered, a static test on a table (482.6(W) × 1524(L) mm) was performed, as shown in Fig. 2a. In the static test on a table, the electrostatic sprayer was operated for 5 s. The samples of the static test on a table were collected in 24 locations, as illustrated in Fig. 2b.

Fig. 2c illustrates the static test on a cylinder. The tested cylinders are grounded copper (Cu) and polyvinyl chloride (PVC) pipes with an outer diameter of 25.4 mm. The electrostatic sprayer was operated for 3 s with a height of 400 mm and a distance of 500 mm. The samples of the static test on a cylinder were obtained in 15 locations with different heights (200, 300, and 400 mm), azimuthal angles (0, 45, 90, 135, and 180°). To figure out that the spray deposition pattern changes according to the electrostatic charge on the cylinder surface, the electrostatic voltage of a PVC cylinder was adjusted by using an ionizing air blower (Model 4003767, Simco-Ion, PA, USA) or rubbing it with a dry fabric. The electrostatic voltage of a PVC cylinder was indirectly measured by using an electrostatic field meter (Model 257, Monroe Electronics Inc., NY, USA) with a distance of 100 mm.

For mimicking a daily routine by janitorial staff, experiments with spraying while moving forward of the table (Front) and moving to the side of the table (Side) were carried out to find out the electrostatic sprayer performance in a more practical aspect. The electrostatic sprayer with or without electrostatic charge was continuously and horizontally operated by walking along the front for 10 s (Front) or along the sides for 5 s (Side). In each case, the spray nozzle tip was maintained at a height of 1 m and 0.2 m from the edge of the desk, as shown in Fig. 2e.

### 3. Results and discussion

#### 3.1. Calibration

In order to estimate the droplet size in the aerosol state through a fluorescence microscope, we compared the droplet diameter and contact diameter. For generating known-sized droplet, a flow-focusing monodisperse aerosol generator (FMAG, Model 1520, TSI, MN, USA) which can produce highly monodisperse micron-sized aerosol particles with a geometrical standard deviation of 1.05 or less [45] was used by controlling liquid feeding flow rate and vibrating frequency. The generated droplet diameter by FMAG can be directly calculated from the operating conditions by using eq. (1).

---

**Fig. 4.** (a) Comparison between fluorescence signal measured by fluorometer and fluorescent tracer concentration. (b) Comparison between normalized coverage area of fluorescent droplets in fluorescence microscope image and fluorescence signal detected by a fluorometer. The red solid line indicates the fitting curve results. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The light source (Model Sola light engine, Lumencor, OR, USA) provided broad-spectrum white light (380–680 nm) to the illumination port where light filters were located. The fluorescence microscope was equipped with a set of light filter cubes mounted in a motorized filter turret. The purposes of light filters were (1) passing a specific wavelength range of white light spectrum to samples to illuminate samples with a narrow range of excitation wavelengths and (2) letting only a specific emission wavelength pass back to the camera. Among the light filters, a green fluorescent protein/fluorescein isothiocyanate filter (GFP/FITC filter) with an excitation wavelength range of 465–495 nm and an emission wavelength range of 515–555 nm was used in this study. The raw images were captured through the fluorescence microscope under 10 × magnification, 4 × 4 binning working mode, and 1 s exposure time (640 × 540 pixels and binned pixel size equal to 2.6 μm).
Fig. 5. Deposition pattern of static test on a table: (a) image of deposited fluorescent droplets without an electrostatic charge; (b) normalized fluorescent tracer concentration without an electrostatic charge; (c) image of deposited fluorescent droplets with an electrostatic charge; (d) normalized fluorescent tracer concentration with an electrostatic charge. The contour in (b) and (d) indicates the normalized fluorescent concentration. ES OFF and ES ON indicate the sprayer mode without and with an electrostatic charge, respectively.
where $d_p$ is the aerosol state particle (droplet) diameter, $Q$ is the liquid flow rate, and $f$ is the vibrating frequency. The operating condition and of FMAG and calculated droplet diameter were summarized in Table 1.

Generated highly monodisperse aerosol droplets by using fluorescent solution were collected on cover glasses. The collected droplet on cover glasses was investigated by using a fluorescence microscope for determining the contact diameter. Since droplets collected on hydrophilic cover glasses are not spherical, the contact diameter measured by fluorescence microscope is larger than aerosol state droplet diameter. For comparing the contact diameter and the aerosol state droplet diameter, the volume of collected droplet diameter was theoretically calculated as follows [46]:

$$V_{\text{contact}} = \pi \left( \frac{d_{p,\text{contact}}}{2} \right)^2 \left( \frac{2 - 3 \cos \theta + \cos^3 \theta}{3 \sin^2 \theta} \right).$$

where $d_{p,\text{contact}}$ is contact diameter measured by fluorescence microscope.
and θ is the contact angle. If the aerosol state droplet is spherical, the volume of the aerosol state droplet can be calculated as follows:

\[ V_{\text{aerosol}} = \frac{4}{3} \pi d_{i}^{3} \]  

(3)

Through using eqs. (2) and (3), the ratio between the contact diameter and the aerosol state droplet diameter can be obtained as a function of contact angle as follows:

\[ B = \frac{d_{c}}{d_{i}^{\text{contact}}} = \left( \frac{2 - 3 \cos \theta + \cos^{3} \theta}{4 \sin^{3} \theta} \right)^{1/3}. \]  

(4)

Here, it should be noticed that contact angle (θ), as well as a ratio (B), is almost constant for micron-sized droplets [46]. Fig. 3 compared the results between generated droplet diameter by FMAG and measured contact diameter by fluorescence microscope. The measured ratio between the contact diameter and the aerosol state droplet diameter was approximately 0.407, with a corresponding contact angle of 20°. Based on the measured ratio, the generated droplet diameter by electrostatic sprayer was obtained.

For quantitatively determining the amount of deposited fluorescent droplets, the fluorometer was calibrated by diluting solution, as shown in Fig. 4a. The integrated fluorescent signal and fluorescent tracer concentration can be represented as a log-log linear relation [47]. The best-fitted results are as follows:

\[ \log C_{f} = 4.314 + 1.064 \times \text{FS}. \]  

(5)

Here, \( C_{f} \) is fluorescent tracer concentration in ng/L (ppt), and FS is the integrated fluorescent signal measured by fluorimeter in digital number (DN). To determine whether or not the fluorescent signal method could well represent the area covered by deposited droplets, the measured fluorescent signal and the normalized area covered by deposited droplets observed with a fluorescence microscope were compared, as shown in Fig. 4b. Two cover glasses were placed side by side on the table in 15 different locations, and the fluorescent solution was sprayed with an electrostatic sprayer, by changing the spraying method. Of the 180 samples obtained by repeating six times, 90 samples were used to obtain a fluorescent signal, and the remaining 90 samples were used to obtain a normalized area of fluorescent solution with the fluorescence microscope. The value of the normalized area of the fluorescent solution was averaged by using 3 pictures of each sample. The linearly fitted relation was as follows:

\[ FS = 2.441 \times (A_{f} / A_{i}). \]  

(6)

Here, \( A_{f} \) is the area covered by deposited fluorescent droplets in the sample picture, and \( A_{i} \) is the sample picture area.

The electrostatic field meter was calibrated by directly applying the voltage on a copper cylinder through the voltage supplier (Model 230, Bertain, NY, USA), and strong linear relation was found between the applied voltage on a copper cylinder and electric field strength with a slope of 38.77 m⁻¹. The electric field strengths of a PVC cylinder were measured as 0, −450, and −750 kV/m, corresponding electrostatic voltage of 0, −11.6, and −19.3 kV.

### 3.2. Static test on a table

A static test on a table was conducted as shown in Fig. 2a. Fig. 5 showed the deposition pattern of static test on a table by varying the sprayer mode without (a and b) or with (c and d) an electrostatic charge. For quantitatively comparing the deposition pattern in terms of how far, wide, and evenly the sprayed solution is spread, normalized fluorescent tracer concentration is defined as the measured concentration at each point divided by the maximum value. One of the common features in both sprayer modes is that maximum normalized fluorescent tracer concentration occurs at the distance of 0.25L (~380 mm) from the spray nozzle. In the absence of an electrostatic charge, the deposition pattern was formed in an elongated elliptical shape along the spraying direction, whereas in the condition of an electrostatic charge, the deposition pattern was created in a triangular shape which gradually narrowing the sprayed area from the sprayed place.

To be specific, based on the criteria value of the normalized fluorescent tracer concentration of 0.2, when sprayed without an electrostatic charge, it reached 0.76L (~1160 mm) in the direction parallel to the spraying direction but reached 0.49W (~240 mm) in the direction perpendicular to the spraying direction. On the other hand, when the sprayer was operated in the presence of an electrostatic charge, it reached 0.67L (~1020 mm) in the direction parallel to the spraying direction and spread with a width of 0.79W (~380 mm) in the direction perpendicular to the spraying direction. Thus, when the spraying in the presence of an electrostatic charge, the deposition pattern was shorter by approximately 0.09L, spread as wide as 0.30W. Furthermore, in the absence of an electrostatic charge, the maximum concentration occurred at 0.27L, and the maximum concentration appeared at 0.26L in the presence of an electrostatic charge, as shown in Fig. 5b and d. In particular, what we want to emphasize here is that it can be used in various industrial fields such as semiconductors, where it is essential to determine the cause of particle contamination by predicting the motion trajectory of particles using fluorescent technology.

Fig. 6 showed fluorescence microscope images and contact diameter histograms of the deposited droplets obtained from the sprayer with and without an electrostatic charge at different three distances from the spray nozzle: 410 mm (0.27L), 760 mm (0.50L), and 1120 mm (0.73L). One of the biggest features in the difference between the presence or absence of an electrostatic charge on droplets is that the number of peak points (modes) in the distribution of the contact diameter is measured by a fluorescence microscope. If there is no electrostatic charge on the droplets, a unimodal distribution with a peak size of ~100 μm occurred, but if there is an electrostatic charge on the droplets, a bimodal distribution with peak sizes of ~10 and ~100 μm was shown. Small contact diameters (<10 μm) were not found in the case without an electrostatic charge but in the case with an electrostatic charge. However, in both cases, most of the droplets were deposited on the cover glasses with a distance of 0.27L, and as the distance from the spray nozzle increased (such as 0.50L and 0.73L), the number of droplets shown in the fluorescence microscope images gradually decreased. It should be noted that the results of fluorescence microscope images strongly supported the results of the deposition pattern of static test on a table in Fig. 5.

One of the most striking features of charged droplets generated by the electrostatic sprayers is Coulombic fission. In the case of droplets without electrostatic charge, as shown in Fig. 7a, the effect of simply reducing the size of the droplets occurred. However, in the case of charged droplets, as shown in Fig. 7b, not only evaporation but also
Fig. 8. Deposition pattern of static test on a cylinder according to different spray modes and surface charges of the cylinder. The results of spraying without an electrostatic charge are illustrated in (a), (c), (e), and (g). The results of spraying with an electrostatic charge are illustrated in (b), (d), (f), and (h). Contour indicates the normalized fluorescent concentration. ES OFF and ES ON indicate the sprayer mode without and with an electrostatic charge, respectively.
charged liquid jets in addition to droplets generated by Coulombic fission. Here, we assumed that the volume of sprayed solution was the same on both progeny droplets and parent droplets with an electrostatic charge for the 'single droplet diameter according to the distance from the sprayer nozzle. The peak droplet diameters gradually decreased regardless of the presence of an electrostatic charge on the droplet. It is worthwhile to mention that smaller droplets may include droplets generated by a breakup in highly charged liquid jets in addition to droplets generated by Coulombic fission.

In order to quantitatively describe the benefits of progeny droplets which were originated from the breakup of charged droplets in terms of electrostatic sprayer performance, the increment of effective contact area based on the same volume of droplets was introduced. Here, we defined the effective contact area by using the electrostatic force and gives backside deposition. Although it is a well-known fact that an electrostatic sprayer has a wraparound effect on a curved or hidden surface, there is little data to quantify the sprayer performance. The wraparound effect occurs when sprayed droplets that passed through the object are drawn back to the object’s surface by the electrostatic force and gives backside deposition. In addition, there are a lot of electrostatic charges that accumulate on the target surface to be sprayed on due to dry air in winter. For figuring out the performance and characteristics of the electrostatic sprayer on the charged surface, the static test on a cylinder was carried out as shown in Fig. 2c, Fig. 8 illustrates the deposition pattern of static test on a cylinder according to different spray modes and surface charges of the cylinder. It should be noted that samples were only collected on one side (0°–180°) for the experiment of static test on a cylinder since the deposition pattern was almost the same on both sides based on the mainstream of the spray as shown in Fig. 5.

Regardless of whether droplets were charged or not, most of the droplets were deposited on the targeted surface facing the sprayer nozzle (0°) for all experimental cases. Without electrostatic charges on grounded Cu cylinder, i.e., Cu 0 kV, few uncharged droplets were deposited on the backside of the Cu cylinder (90°–180°), however, in the case of charged droplets, approximately 0.01–0.03 normalized fluorescent concentration was deposited on the backside of the cylinder. Therefore, it was confirmed that the difference between the charged droplets and the uncharged droplet of the wraparound effect for the grounded Cu cylinder was clearly visible.

Furthermore, looking at the wraparound effect when there is an electrostatic charge on the target surface in the PVC cylinder, it can be seen that the more the electrostatic charge on the surface, the more droplets are attached. The peculiar thing here is that even if the droplet is not charged, the wraparound effect can be seen. Although, the solution droplets start off neutral, with the same amount of positive and negative charges, when the neutral droplets approach to the charged cylinder, the droplets push electrons away, and leaving a positively charged area which is attracted to the charged target surface. For this reason, even if the droplet is not charged, we can observe the wraparound effect.

In order to quantitatively compare the wraparound effect for each case, Fig. 9 shows that the normalized concentration at the back of the cylinder (θ = 180°) at different heights of 200 mm, 300 mm, and 400 mm according to different surface charges of the Cu or PVC cylinder. The more the electrostatic charge on the target surface, whether the droplet was charged or not, the more obvious the wraparound effect is. To be specific, when the target surface was not charged (Cu 0 kV and PVC 0 kV), the average normalized concentrations on the backside of the cylinder (θ = 180°) were 0.009 for uncharged droplets, and 0.015 for charged droplets. However, when the target surface was highly charged (PVC 19 kV), the average normalized concentrations at θ = 180° were 0.068 for uncharged droplets, and 0.139 for charged droplets. Also, the point that can be seen in Fig. 9 is that the wraparound effect according to the height is different. The spray was sprayed at a height of 400 mm. As shown in Fig. 8, in the targeted surface facing the sprayer nozzle (0°), droplets were deposited mostly at 400 mm, but on the back of the target surface (180°), more particles were deposited at 200 mm than at 400 mm.

3.3. Static test on a cylinder

where $A_{eff}$ is effective contact area, $\pi(d/2)^2$. The calculated increment of effective contact area by using the electrostatic sprayer were $\eta_{0.27L} = 42.1\%$, $\eta_{0.50L} = 76.6\%$, and $\eta_{0.72L} = 61.4\%$. From this analysis, we can conclude that spraying the charged droplets can drastically improve the contact area between the solution and surface due to small progeny droplets.
Fig. 10. Deposition pattern of dynamic test on a cylinder according to different spray modes and moving directions. The sprayer was continuously applied by walking along the front of the table for 10 s in (a) and (b) or along the side of the table for 5 s in (c) and (d). The results of spraying without an electrostatic charge are illustrated in (a) and (c). The results of spraying with an electrostatic charge are illustrated in (b) and (d). Contour indicates the normalized fluorescent concentration. ES OFF and ES ON indicate the sprayer mode without and with an electrostatic charge, respectively. Front and Side indicate the different moving directions.
mm.

3.4. Dynamic test on a table

For evaluating the electrostatic sprayer in a real application situation, the electrostatic sprayer was continuously applied by walking along the front of the table for 10 s (Front) or along the side of the table for 5 s (Side). Fig. 10 shows the normalized deposition pattern results of the dynamic test on a table. For the front moving direction case, the overall averaged normalized concentration is approximately 0.475 for uncharged droplets, and 0.660 for charged droplets. In terms of covered areas based on the criteria value of the normalized fluorescent tracer concentration of 0.6, the percentage of covered areas for the front moving direction cases showed a significant difference between uncharged droplets (11.5 %) and charged droplets (50.9 %). As shown in the previous static tests on a table or cylinder, it continuously showed better performance in the charged droplets, but a very interesting result came out in the side moving direction case of the dynamic test experiment. The overall averaged normalized concentrations were measured as 0.384 for uncharged droplets, and 0.310 for charged droplets. In the side moving direction case, the covered areas of uncharged (14.8 %) and charged droplets (18.5 %) did not show a significant difference compared with the front moving direction case. These results might be due to the fact that the deposition pattern for uncharged droplets was formed in an elongated elliptical shape along the spraying direction, however, the deposition pattern for charged droplets was created in a triangular shape which gradually narrowing the sprayed area from the sprayed place, which is illustrated in Fig. 5. In the overall dynamic test, it was confirmed throughout all the results that the hotspot was biased to one side. This is probably because when the spray is first sprayed, it is not sprayed consistently, and when the spray is activated, a large amount is produced at the beginning. It is worthwhile to mention that since we quantitatively investigated these features, these differences depending on the spraying method can be found. Here, from a macro perspective, electrostatic sprayers are recommended to cover large areas with short spray distances. In addition, it is expected that more detailed and precise user guidelines can be presented if additional investigations are carried out.

4. Conclusions

In the present study, we reported the quantitative analysis and its method of electrostatic sprayer performance by using fluorescent tracer. For estimating the sprayer droplet size in the aerosol state by using the fluorescence microscope, we generated monodisperse droplets by using FMAG and obtained the ratio between the contact diameter and the aerosol state droplet diameter of 0.407, with a corresponding contact angle of 20° between droplets and micro cover glasses. In addition, we calibrated the fluorometer for quantitatively estimating the amount of deposited fluorescent droplets. We also compared the normalized areas obtained by the fluorescence microscope with the signal values measured by the fluorometer and as a result, the relationship between the two data was linear. Therefore, we believe that the introduced fluorescent tracer method in this study can be widely employed to quantitatively characterize the deposited droplets even in complex conditions and geometries. In addition, the fluorescent tracer method might be very useful in various applications such as analyzing semiconductor yield degradation due to particle contamination.

For the static test on a table, we presented the deposition pattern by changing the sprayer mode without or with an electrostatic charge and found out that the deposition pattern was formed as an elongated elliptical shape along the spraying direction for the sprayer mode in absence of an electrostatic charge, however, the triangular shape-deposition pattern was created for the electrostatic charge mode. In a fluorescence microscope investigation, we found that small droplets were created when there is an electrostatic charge on the droplets due to Coulombic fission of the parent droplet. The increment of effective contact area due to Coulombic fission was determined as 40–80 % for the same sprayed amount of solution.

Static test on a cylinder showed the quantitative results of wraparound effect for the electrostatic sprayer. We found that most of the droplets were attached on the front surface which facing the sprayer nozzle and more charged droplets were deposited on the backside of neutralized or grounded cylinder. We also quantitatively demonstrated that the higher the electrostatic charge on the cylinder surface, the more droplets are attached to the back of the target surface. In a dynamic test, we tested two different spraying conditions for simulating the actual usage environment and found that electrostatic sprayers are suitable to cover large areas with short spray distances. Particularly, we expect that the electrostatic sprayer with wraparound effect and large coverage area can be utilized in places where an unspecified number of people share a space, such as airplane cabins, public transportation, and classrooms.

CRediT authorship contribution statement

Dong-Bin Kwak: Writing - original draft, Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Validation, Data curation. Seong Chan Kim: Methodology, Investigation, Writing - review & editing, Supervision. Thomas H. Kuehn: Conceptualization, Writing - review & editing. David Y.H. Pui: Conceptualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank the support from members of the Center for Filtration Research: 3 M Corporation, Applied Materials, Inc., BASF Corporation, Boeing Company, Corning Co., China Yancheng Environmental Protection Science and Technology City, Cummins Filtration Inc., Donaldson Company, Inc., Entegris, Inc., Ford Motor Company, Guangxi Wat Yuan Filtration System Co., Ltd, LG Electronics Inc., MSP Corporation, Parker Hannifin, Samsung Electronics Co., Ltd, Xinjiang Shengda Filtration Technology Co., Ltd., Shigematsu Works Co., Ltd., TSI Inc., W. L. Gore & Associates, Inc., and the affiliate member National Institute for Occupational Safety and Health (NIOSH). URL: http://www.me.umn.edu/cfr/. Portions of this work were conducted in the Minnesota Nano Center, which is supported by the National Science Foundation through the National Nano Coordinated Infrastructure Network (NNCI) under Award Number ECCS-1542202.

References

[1] C.-C. Lai, T.-P. Shih, W.-C. Ko, H.-J. Tang, P.-R. Hsueh, Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and coronavirus disease-2019 (COVID-19): the epidemic and the challenges, Int. J. Antimicrob. Agents 55 (2020) 105924, https://doi.org/10.1016/j.ijantimicag.2020.105924.
[2] E. Goldman, Exaggerated risk of transmission of COVID-19 by fomites, Lancet Infect. Dis. 20 (2020) 892–893, https://doi.org/10.1016/S1473-3099(20)30561-2.
[3] B. Feng, K. Xu, S. Gu, S. Zheng, Q. Zou, X. Xu, L. Yu, F. Lou, F. Yu, T. Jin, Y. Li, J. Sheng, H.-L. Yen, Z. Zhong, Y. Wei, Y. Chen, Multi-route transmission potential of SARS-CoV-2 in healthcare facilities, J. Hazard Mater. 402 (2021) 123771, https://doi.org/10.1016/j.jhazmat.2020.123771.
[4] L. von Seidlein, G. Alabaster, J. Deen, J. Knudsen, Crowding has consequences: prevention and management of COVID-19 in informal urban settlements, Build. Environ. 188 (2021) 107472, https://doi.org/10.1016/j.buildenv.2020.107472.
[5] N. van Doremalen, T. Bushmaker, D.H. Morris, M.G. Holbrook, A. Gamble, B. N. Williamson, A. Tamin, J.L. Harcourt, N.J. Thornburg, S.I. Gerber, J.O. Lloyd-Smith, E. de Wit, V.J. Munster, Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1, N. Engl. J. Med. 382 (2020) 1564–1567, https://doi.org/10.1056/NEJMoa2004973.
