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Susceptibility constants of airborne bacteria to dielectric barrier discharge for antibacterial performance evaluation

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HIGHLIGHTS

► We characterized DBD by measuring concentrations of reactive species and ions.
► The inactivation efficiency was deduced using aerosol- and colony-counting methods.
► Susceptibility constant (Z) was introduced for performance evaluation of DBD.
► Modified Z was suggested for evaluation of DBD reactors of different sizes.
► Our methodology will be used for design optimization and performance evaluation.

ABSTRACT

Dielectric barrier discharge (DBD) is a promising method to remove contaminant bioaerosols. The collection efficiency of a DBD reactor is an important factor for determining a reactor's removal efficiency. Without considering collection, simply defining the inactivation efficiency based on colony counting numbers for DBD as on and off may lead to overestimation of the inactivation efficiency of the DBD reactor. One-pass removal tests of bioaerosols were carried out to deduce the inactivation efficiency of the DBD reactor using both aerosol- and colony-counting methods. Our DBD reactor showed good performance for removing test bioaerosols for an applied voltage of 7.5 kV and a residence time of 0.24 s, with \( I_{\text{CFU}}, I_{\text{Number}}, \) and \( I_{\text{activation}} \) values of 94%, 64%, and 83%, respectively. Additionally, we introduce the susceptibility constant of bioaerosols to DBD as a quantitative parameter for the performance evaluation of a DBD reactor. The modified susceptibility constant, which is the ratio of the susceptibility constant to the volume of the plasma reactor, has been successfully demonstrated for the performance evaluation of different sized DBD reactors under different DBD operating conditions. Our methodology will be used for design optimization, performance evaluation, and prediction of power consumption of DBD for industrial applications.

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1. Introduction

Particles of biological origin, such as bacteria, viruses, fungi, and pollen as well as their fragments that are present in air are referred to as bioaerosols. Bioaerosols can cause serious health hazards when they contaminate a human environment. Diseases from pathogenic bacteria are a major cause of death, accounting for nearly 40% of the total 50 million annual estimated deaths worldwide [1,2]. Severe Acute Respiratory Syndrome (SARS) and the threat of avian flu are natural examples illustrating the profound, everyday impacts of bioaerosols on public health [3].

For a long time, researchers have reported that plasma can kill or inhibit the growth of bacteria. Noyce and Hughes [4,5] investigated the bactericidal effect of both negative and positive ions generated by a corona discharge for Escherichia coli and Pseudomonas veronii bacteria. Tests were conducted in a nitrogen atmosphere to prevent production of ozone \( (O_3) \), which is one of the common reactive species generated by an electrical corona in air. After 30 min of exposure to negative and positive ions, the reductions of E. coli bacteria were approximately 91% and 98%, respectively [4], and after 60 min of exposure, the reductions of P. veronii bacteria were approximately 95% and 86%, respectively [5]. Further, it was suggested that cell death could be due to a change in the outer membrane as a result of ionic interactions.
Atmospheric pressure plasmas generate many reactive species, and have substantial merit for sterilization system applications [6]. Reactive species such as O, O3, OH, NO, and NO2, which are common products of electrical coronas in air, can also sterilize cells. The reactive species can oxidize the cell membrane, protein molecules, and DNA [6,7]. Sari and Fadaee [8] used corona discharge for decontamination of both Pseudomonas aeruginosa and E. coli bacteria. They reported that adding H2O2 makes the method faster and more effective, and suggested that HO radicals play an essential role for such behavior.

Compared to other atmospheric pressure plasmas, such as corona discharge reactors, dielectric barrier discharge (DBD) has the advantage of high efficiency for sterilization in a short period of time [9,10]. Choi et al. [9] and Deng et al. [11] reported that bioaerosols are deactivated by physical or chemical processes in a DBD reactor. The physical process proceeds by positive and negative ions in the discharge streamer, while the chemical process is accomplished by reactive species produced in the DBD reactor. Choi et al. [9] obtained a reduction of 99.9% of E. coli within 70 s. Boudam et al. [12] demonstrated the inactivation of spores of Bacillus subtilis by a DBD, which was operated at atmospheric pressure in a N2–N2O mixture. They demonstrated that it is possible to find operating conditions such that spore inactivation with an atmospheric pressure discharge is due to UV radiation and radicals. Fridman et al. [10] reported that Staphylococcus, Streptococcus, and Candida were completely destroyed in less than 15 s when exposed to the DBD.

Most previous studies have focused on stationary microorganisms captured on surfaces such as an agar plate, except the works of Liang et al. [13], Gallagher et al. [14], and Vaze et al. [15]. In Liang et al. [13], nonthermal plasma generated by a wire-to-plate type DBD reactor was applied to inactivate aerosolized B. subtilis cells and Pseudomonas fluorescens as well as indoor and outdoor bioaerosols. Less than 2% of B. subtilis aerosols survived a plasma treatment of 0.12 s, while none of the P. fluorescens aerosols survived. Exposure of environmental bacterial aerosols to the plasma for 0.06 s also resulted in significant inactivation of more than 95% for bacteria. Gallagher et al. [14] demonstrated a 97% reduction in cultivable E. coli with a millisecond exposure time in a dielectric barrier grating discharge (DBGD) plasma (one pass through discharge), and a subsequent 99.95% reduction in 2 min following treatment. The direct plasma exposure time of 0.73 ms (per pass) allows enough time for bacteria to be attacked by all chemically active components of plasma (charged particles, OH radicals, atomic oxygen, and ozone), which is one explanation for the initial 97% reduction in culturability. Remote exposure to the remaining ozone in the subsequent 2 min direct plasma treatment may account for the additional 99.95% reduction. Vaze et al. [15] suggested that in their DBGD experiment, the main cause of inactivation is the synergetic action of a short-lived plasma agents (charges, radicals) and ozone. This synergy creates a toxic environment for the bacteria, ultimately resulting in inactivation.

Bioaerosols are also a kind of airborne particle, and airborne particles can be physically collected by a DBD reactor [16–19]. Some of the bioaerosols are charged by ions generated from the DBD and are deposited (or collected) on electrode surfaces along the electric field. The collection efficiency was reported to increase with the applied voltage and the flow residence time. In this study, we measured the concentration of bioaerosols at the outlet of the DBD reactor both with and without applied power to determine its collection efficiency, which was not reported in the studies of Liang et al. [13], Gallagher et al. [14], and Vaze et al. [15]. The collection efficiency of a DBD reactor is an important factor in determining the performance of DBD reactors. Since a relatively large amount of bioaerosols can be collected in the DBD reactor and only a small portion of the bioaerosols can exit the reactor under high applied voltage and long flow residence time conditions, simply defining the inactivation efficiency with colony counting numbers for DBD as “on” and “off” may lead to an overestimation of inactivation efficiency of a DBD reactor. In this study, we introduce a methodology to deduce the inactivation efficiency of a DBD reactor using both aerosol- and colony-counting methods.

Since different experimental conditions (such as flow rate, residence time, and power consumption) have been used in previous studies on DBD, direct comparison of inactivation efficiencies of different DBD reactors is not easy. Moreover, for industrial applications, quantitative parameters are needed for design optimization, performance evaluation and prediction of power consumption of DBD systems. As one quantitative parameter, susceptibility has been applied in numerical models to evaluate the antimicrobial effects of an upper-room UVGI (ultraviolet germicidal irradiation) system against bioaerosols [20] and antimicrobial activities of silver and copper nanoparticles against test bacteria [21]. In this study, we introduce for the first time, a susceptibility constant of airborne bacteria to DBD as a quantitative parameter for the performance evaluation of a DBD reactor.

2. Experimental

Staphylococcus epidermidis (ATCC #14990) bacterial cells were obtained from the Korean Culture Center of Microorganisms (Seoul, Korea). S. epidermidis is commonly found in a variety of environments, and is a typical airborne microorganism in bioaerosol research [22–26]. Staphylococci are common parasites in humans and animals, and occasionally cause serious infections. Although there are many species of Staphylococcus, S. epidermidis is the most common isolate recovered from clinical specimens [27]. Moreover, S. epidermidis is commonly found on the skin or mucous membranes of humans [28], and it is recommended by ISO 14698-1 for testing the biological efficiency of air samplers.

A suspension of S. epidermidis was prepared by culturing it overnight, and then inoculating 15 mL of nutrient broth with 0.1 mL of the initial overnight culture followed by incubation for an additional 18 h. The nutrient broth was prepared by dissolving 5 g of peptone and 3 g of meat extract in 1000 mL of sterilized deionized water and then sterilizing the mixture in an autoclave. The tubes containing the suspension were then spun at 6000 rpm for 15 min using a centrifuge (VS-15000N, Vision Scientific Co., Ltd., Korea), and the supernatant was carefully removed. The remaining pellets were then resuspended in sterilized deionized water and vortexed for a few seconds using a vortex mixer (KMC-1300V, Vision Scientific Co., Ltd., Korea). This washing process was repeated three times, after which the pellets were resuspended in sterilized deionized water to obtain a base suspension with a bacterial density of 10⁶ cells/mL.

The DBD reactor was installed in an acryl duct (5 cm × 5 cm) and consisted of nine parallel plate electrodes that were configured in an alternating fashion, with one electrode being grounded and the next one receiving high AC voltage. The gap spacing between any two electrodes was 5 mm. Each electrode was made from a 0.03-mm thick copper foil (5-mm stream-wise length and 40-mm span-wise length) sandwiched between two 0.25-mm thick dielectric plates (alumina plates, 20-mm stream-wise length and 50-mm span-wise length). Voltage and current were measured using an oscilloscope (WaveRunner 6050A, Lecroy, USA), and their root-mean-square (RMS) amplitude values are indicated in Fig. 1(a). RMS discharge currents were 0.44–1.59 mA for RMS voltages of 0.5–7.5 kV (power consumption: 0.22–11.93 W). The transition to sparking occurred at voltages slightly higher than 8 kV. Fig. 1(b) shows the temporal voltage and current profiles when the RMS voltage and frequency were 7.5 kV and 60 Hz, respectively.
DBD reactor operated stably without thermal cracking of the electrodes.

The experimental schematic is shown in Fig. 2. *S. epidermidis* bioaerosols were dispersed into air using a nebulizer (1 jet, BGI Inc., USA) at a flow rate of 2 L/min. In the nebulizer, a gas is used to aspirate liquid into a sonic velocity gas jet, and this jet is impacted against a barrier (the inside of the jar) to remove a large fraction of the droplets. After passing through a diffusion dryer to remove the residual moisture, the flow enters an aerosol neutralizer (Soft X-ray charger 4530, HCT Co. Ltd., Korea) to eliminate charges induced during the aerosolization process. The neutralizer neutralizes charges present in aerosol particles using soft X-ray photoionization. Some of the air flow including bioaerosols enters the test duct through an inlet port located 12 cm in front of the inlet of the DBD reactor and is then diluted with particle-free air delivered through a clean air supply system. There was a one-to-one ratio between the air flow including bioaerosols and the particle-free air flow. Next, the diluted mixture is treated by passing it through the plasma region formed by the DBD reactor. The residence time of bioaerosols in the DBD reactor was controlled by changing the total flow rate (flow rate: 2, 3, 4 L/min). The temperature and relative humidity of the test duct were 22.5 °C and 10%, respectively.

Radical species generated from the DBD reactor were analyzed by optical emission spectroscopy (OES) using a spectrometer (USB4000, Ocean Optics, USA). The detection position was 3 cm behind the exit of the DBD reactor. The emission spectrum can be used to determine the composition of a material, since it is different for each element of the periodic table. Emission spectra are collected by a focusing mirror and are converted into a digital signal by a detector. Each digital signal on the detector corresponds to a wavelength, which is monitored by the Spectra Suite application system. Gases produced by the DBD reactor were delivered through a sampling port located 7 cm behind the exit of the DBD reactor. For NO and NO$_2$ concentration measurement, a gas analyzer (GreenLine MK2, Eurotron Instruments s.r.l., Italy) was used, while O$_3$ concentration was measured using an O$_3$ monitor (PortaSensII, Ati Inc., USA).

Bioaerosols passing through the DBD reactor were sampled through the same port used in gas analysis for measurements of size distribution and total number concentration using an APS (Aerodynamic Particle Sizer, Model 3321, TSI Inc., USA). The APS measures particles from 0.5 to 20 μm in aerodynamic diameter using a double-crest optical system, and the rates of aerosol sample flow and sheath air flow were 1 L/min and 41 L/min, respectively. When the diffusional wall loss of the bioaerosols is neglected, the removal efficiency based on the number concentration ($\eta_{\text{Number}}$) is defined by

$$\eta_{\text{Number}} = 1 - \frac{N_D}{N_0}$$

where $N$ is the number concentration of bioaerosols measured by APS.

The bioaerosols passing through the DBD reactor were sampled using the sixth stage of an Anderson impactor (TE-10-800, Tisch Environmental Inc., USA) with a cutoff diameter of 0.65 μm for the culture-based colony counting method. A nutrient agar plate was used as the impaction plate. For 1.5 min, 1 L/min was sampled through a sampling port located 7 cm behind the exit of the DBD reactor, and 27.3 L/min particle-free air was delivered through the clean air supply system. The bioaerosols sampled on the nutrient agar plate were incubated for 5 days at 37 °C. After incubation, the colony forming units (CFU) were estimated by visual inspection. The removal efficiency based on the number of CFU ($\eta_{\text{CFU}}$) is defined as follows:

$$\eta_{\text{CFU}} = 1 - \frac{\text{CFU}_0}{\text{CFU}_d}$$

Subscripts D and 0 correspond to conditions of on and off of the DBD power, respectively.

Before experimenting with the DBD reactor, we evaluated the sampling efficiency of the impactor used in this study, as low sampling efficiency for bioaerosols can undermine confidence in the reliability of experimental results. Polystyrene latex (PSL) particles were used for evaluating the sampling efficiency of the impactor. Fig. 3 shows the size distribution of *S. epidermidis* bioaerosols (inset) and sampling efficiency of the impactor, which were measured using APS. The geometric mean diameter of *S. epidermidis* was 1.08 μm, and the cutoff diameter of the impactor was 0.7 μm, which was in good agreement with the cutoff diameter of 0.65 μm reported by the company. The sampling efficiency of *S. epidermidis* bioaerosols is also plotted in Fig. 3, and the efficiency was approximately 90%.

3. Inactivation efficiency

When bioaerosols enter the DBD reactor, some of the bioaerosols are inactivated under the influence of the DBD plasma. In addition, these or other bioaerosols can be precipitated onto the electrode surface of the reactor, also owing to the DBD plasma. Therefore, non-precipitated bioaerosols exiting the reactor can be both active and inactive. In this study, the number concentration
Fig. 2. Schematic diagram of experimental setup.

of the non-precipitated bioaerosols is measured by the aerosol number-counting method, while the number concentration of the non-precipitated, inactivated, and culturable bioaerosols is measured by the colony-counting method. Assuming that the inactivation and precipitation of the bioaerosols can be de-coupled into two independent and series processes, the inactivation efficiency of bioaerosols in a DBD reactor ($\eta_{\text{Inactivation}}$) is calculated by

$$\eta_{\text{CFU}} = 1 - (1 - \eta_{\text{Inactivation}})(1 - \eta_{\text{Number}})$$  \hspace{1cm} (3)

Vaze et al. [15] reported that the main cause of inactivation under DBD treatment is the synergetic action of short-lived plasma agents (charges and radicals such as OH) that disturb the membrane and ozone.

4. Results and discussion

Before the study of bioaerosol removal, we measured concentrations of various gaseous species generated from our DBD reactor. Fig. 4 shows the optical emission spectra of the DBD plasma produced at a voltage and residence time of 7.5 kV and 0.24 s, respectively. The spectra in the presence of bioaerosols in the DBD reactor were similar to those in the absence of the bioaerosols. Several peaks were observed, including NO (301 and 339 nm), OH (317 and 320 nm), O$_3$ (319 nm), N$_2$O$^+$ (356 nm), N$_2$ (354, 360, 371, 400, 434 nm), NO$_2$ (378 nm), O$_2$ (381 nm), O (395 and 533 nm), H$_2$ (407 nm), and N$_2$ (428 nm) [29–31]. The reactive species O, O$_3$, OH, NO, and NO$_2$ have been reported to oxidize cell membranes, protein molecules, and DNA [6,32]. Our results were similar to those of Mahoney et al. [33], who reported the results of electrical and spectral characterization of air plasma generated by a capillary dielectric barrier discharge (Cap-DBD), consisting of metal wire electrodes inside quartz capillary tubes powered with a high-voltage AC power supply. The plasma reactor was operated in atmospheric-pressure air. In their study, optical emission spectroscopy (OES) was also

![Fig. 3. Size distribution of S. epidermidis bioaerosols (inset) and sampling efficiency of the impactor used in this study.](image-url)
employed to evaluate the reactive species generated in the plasma source.

In addition to OES measurements, we measured NOx and O3 concentrations produced by our DBD reactor using a real-time gas analyzer and an O3 monitor, respectively. Fig. 5 shows the results for various applied voltages. The NO2 and O3 concentrations were 60.6–74.7 and 25.8–38.1 ppm, respectively. Higher applied voltages led to higher concentrations of NO2 and O3 because it became statistically more likely that N2 and O2 would be attacked by electrons. According to Pekárek [34], the initial steps in the formation of NO2 and O3 are the dissociation of N2 and O2 by electrons. The number of generated electrons is proportional to the applied current, which is also proportional to the applied voltage. Therefore, NO2 and O3 concentrations are proportional to the applied voltage. In this study, NO was observed using a spectrometer, however it was not detected by the gas analyzer (the detection limit for NO concentration is about 1 ppm). The spectrometer detects light emitted by NO molecules during their transition from an excited state to a lower energy state, while the final products of molecules from chemical kinetics are measured downstream by the gas analyzer. Hackam and Akiyama [35], Ruan et al. [36], and Wang et al. [37] presented that NO produced by plasma can be removed via the following reactions:

$$O + NO + M \rightarrow NO_2 + M$$

(4)

$$N + NO \rightarrow N_2 + O$$

(5)

where M is a third body, which can be N2 or O2. Therefore, from our results obtained using the spectrometer and the gas analyzer, we expect that NO produced by plasma was changed to NO2 or N2 before entering the gas analyzer.

The ion concentration \(N_{\text{ion}}\) generated from the DBD reactor was estimated using the following equation [18]:

$$N_{\text{ion}} = \frac{I}{e \mu_{\text{ion}} L A}$$

(6)

$$E = \frac{V}{d}$$

(7)

where \(I\) is the current, \(e\) is the elementary charge of an electron \((1.6 \times 10^{-19} \text{ C})\), \(\mu_{\text{ion}}\) is the mobility of air ions, \(E\) is the electric field strength, \(A\) is the inner surface of the ground-electrode, \(V\) is the voltage, and \(d\) is the gap spacing between electrodes. To calculate Eq. (6), we assumed that the mobilities \(\mu_{\text{ion}}\) were 1.1 and 1.9 cm²/V s for positive and negative air ions, respectively [38]. We inserted the maximum absolute current values \(I_{\text{max}}\) as \(I\) in Eq. (6) for obtaining the maximum air ion concentrations. The maximum concentrations of positive and negative air ions for 7.5 kV were 4.09 \(\times 10^{14}\) and 2.08 \(\times 10^{15}\) ions/cm³, respectively. The reason that the concentration of positive air ions was higher than that of negative air ions is the higher mobility of positive air ions. Our results were similar to those of Byeon et al. [39]. When the units of concentration were converted to ppm, the range of the maximum air ion concentration was 0.0083–0.0164 ppm, which was approximately 1/3100–1/2300 the value of the ozone concentration (25.8–38.1 ppm). However, according to Vaze et al. [15], the bacterial inactivation efficiency is not high if only ozone exists without other reactive species. They reported that the reduction of E. coli bioaerosols exposed to DBD was 97% for 10 s of exposure time, but the reduction of E. coli bioaerosols exposed to ozone (concentration: 28 ppm; exposure time: 10 s) was only 10%.

After characterization of our plasma reactor, one-pass removal tests of bioaerosols were then carried out for various residence times and applied voltages. Applying high air flow rates, three different residence times of 0.12, 0.16, and 0.24 s, were selected. These plasma treatments were much shorter than 1 s, as in Liang et al. [13] and Gallagher et al. [14].

Figs. 6 and 7 show the efficiency of bioaerosols as functions of voltage and residence time, respectively. These efficiencies increased as the applied voltage or residence time increased. Because the amplitude of oscillation of bioaerosols in a DBD reactor and the particle charging increased as the applied voltage increased, a higher applied voltage led to higher collection efficiencies. With a particle mobility, \(b_p\), electric field strength, \(E\), and excitation frequency, \(\omega\), the maximum particle displacement, \(l_{\text{max}}\), is \((2b_pE)/\omega\) [40] and the electric field strength, \(E\), is proportional to the applied voltage. Longer residence times and higher applied voltages increased the chance of bioaerosols being attacked by ions, ozone, or atomic oxygen, which resulted in higher inactivation efficiencies. Efficiencies \(\eta_{\text{CFU}}, \eta_{\text{Number}},\) and \(\eta_{\text{Inactivation}}\) of up to 94%, 64%, and 83%, respectively, were obtained for an applied voltage of 7.5 kV and a residence time of 0.24 s. Liang et al. [13] and Gallagher et al. [14] also obtained more than 90% efficiency based on CFUs for removing bioaerosols for plasma treatment times under 1 s. Fig. 8 shows the scanning electron microscopy (SEM) images of S. epidermidis precipitated on the DBD plate with and without plasma treatment. It is apparent that S. epidermidis suffered severe membrane rupture during the plasma treatment.
The performance of a DBD reactor can also be evaluated using specific input energy (SIE). SIE was calculated with the following relation [41]:

\[
\text{SIE (specific input energy)} = \frac{\text{discharge power (W)}}{\text{gas flow rate (L/min)}} \times 60 \text{ (J/L)}
\]  \hspace{1cm} (8)

**Fig. 6.** Removal efficiencies of bioaerosols as a function of voltage.

**Fig. 7.** Removal efficiencies of bioaerosols as a function of residence time for 7 kV of applied voltage.

Discharge power (W) = applied voltage (V) \times \text{applied current (A)}  \hspace{1cm} (9)

**Fig. 9** shows the survival fraction behavior of bioaerosols with SIE. While the UV susceptibility constant has been widely used to quantify the effect of UV light on microorganisms in the study of UV systems [42,43], in this study the SIE susceptibility constant is suggested as a quantitative parameter for the estimation of the ability to remove bioaerosols by collection and inactivation processes in the DBD reactor. The SIE susceptibility constants of collection and inactivation processes, \( Z_{\text{Number}} \) and \( Z_{\text{Inactivation}} \), respectively, are defined by the following equations:

\[
Z_{\text{Number}} = -\ln(1 - \eta_{\text{Number}}) \left(\frac{\text{L}}{\text{J}}\right)_{\text{SIE}}
\]  \hspace{1cm} (10)

\[
Z_{\text{Inactivation}} = -\ln(1 - \eta_{\text{Inactivation}}) \left(\frac{\text{L}}{\text{J}}\right)_{\text{SIE}}
\]  \hspace{1cm} (11)

The SIE susceptibility constant for the combined effect of collection and inactivation processes, \( Z_{\text{CFU}} \), is defined by the following equation:

\[
Z_{\text{CFU}} = -\ln(1 - \eta_{\text{CFU}}) \left(\frac{\text{L}}{\text{J}}\right)_{\text{SIE}}
\]  \hspace{1cm} (12)

The values of \( Z_{\text{CFU}} \), \( Z_{\text{Number}} \), and \( Z_{\text{Inactivation}} \) were 0.00781, 0.00325, and 0.00456 L/J, respectively (Fig. 9). In Fig. 9, the curve fits to experimental results are represented by \( R^2 \) values of 0.8580, 0.7468, and 0.8212 for \( 1 - \eta_{\text{CFU}}, 1 - \eta_{\text{Number}}, \) and \( 1 - \eta_{\text{Inactivation}} \), respectively. The \( Z_{\text{Inactivation}} \) value was larger than the \( Z_{\text{Number}} \) value, indicating

**Fig. 8.** Scanning electron microscopy (SEM) images of *S. epidermidis* precipitated on the DBD plate (a) without plasma treatment and (b) with plasma treatment.
that the effect of inactivation is larger than the effect of physical collection for removing bioaerosols with our DBD reactor.

In Liang et al. [13] and Gallagher et al. [14], the efficiencies based on the number of CFUs for removing B. subtilis bioaerosols and E. coli bioaerosols were 98 and 97% under 115.2 and 102.94 J/L, respectively. If these efficiencies are converted to susceptibility constants suggested in this paper, the susceptibility constants become 0.0340 and 0.0341 L/J, respectively, for Liang et al. [13] and Gallagher et al. [14], which are four-fold higher than the CFU-based susceptibility constant of our DBD reactor, 0.0078 L/J. Therefore, it should be noted that the susceptibility constants introduced so far cannot be directly used for comparing the performance of DBD reactors whose dimensions are different from each other. The removal efficiency increases as plasma treatment time increases, and plasma treatment time increases with the volume of the plasma reactor. For example, the volumes of the reactor used in Liang et al. [13] and Gallagher et al. [14] were 0.026 and 0.025 L, respectively, while our reactor volume was 0.008 L. Therefore, if the same flow rate were used, the removal efficiency using a larger DBD reactor will be higher than that of a smaller DBD reactor, resulting in a higher susceptibility constant for the bigger DBD reactor. For comparing the performance of DBD reactors of different sizes, the modified susceptibility constant is introduced as follows:

$$Z' = \frac{Z}{\text{volume of plasma reactor (J/L)}}$$  \hspace{1cm} (13)

Using Eq. (13), $Z'$ of our DBD reactor was 0.9763 J^{-1}, which is similar to 1.3061 J^{-1} for Liang et al. [13] and 1.3639 J^{-1} for Gallagher et al. [14]. So far, the modified susceptibility constant has been successfully demonstrated for performance evaluation of DBD reactors of different sizes under different DBD operating conditions. Our methodology will be used for design optimization, performance evaluation, and prediction of power consumption of DBD systems for industrial applications.

5. Conclusions

We characterized our lab-made DBD reactor by measuring current–voltage profiles and concentrations of reactive gaseous species and ions using an oscilloscope, a gas analyzer, optical emission spectroscopy, and an ozone monitor. After characterization of our plasma reactor, one-pass removal tests of S. epidermidis bioaerosols were carried out for various residence times and applied voltages to deduce the inactivation efficiency of the DBD reactor using both aerosol- and colony-counting methods. Our DBD reactor showed good performance for removing these test bioaerosols for an applied voltage of 7.5 kV and a residence time of 0.245. % CFU, %Number, and %Inactivation were 94%, 64%, and 83%, respectively. Suggesting the SIE susceptibility constant (Z-value) as a quantitative parameter for performance evaluation of a DBD reactor, we found that the Z_inactivation value was larger than the Z_Number value, indicating that the effect of inactivation was higher than the effect of physical collection for removing bioaerosols in our DBD reactor. Moreover, after suggesting the ratio of the SIE susceptibility constant to the volume of a plasma reactor for comparing performances of DBD reactors whose dimensions are different, we demonstrated that the performance of our plasma reactor was similar to those of previous works.

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