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*Article*

# Diffusion criteria of $O_3$ gas emitted from non-thermal atmospheric-pressure biocompatible plasma sterilizer for safety environment

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**Abstract:** Medical institutions, where several patients are treated and medical workers engaged, are always exposed to secondary viral and bacterial infections. It is critical to prevent infection transmission by indirect as well as direct contact through air or splash. The infections of most diseases can be transmitted through the air. HEPA filters installed in air conditioning equipment are used to prevent infection transmission through air in medical institutions, but air circulation takes a long time in a large space. Virus and bacteria smaller than 0.3 μm cannot be removed by the HEPA filter; hence, those microbes remain alive throughout the air ventilation. A plasma sterilizer has the capability to provide environmental friendly sterilization by employing reactive oxide species and reactive nitrogen species at a low cost. We developed an excellent plasma sterilizer by using a non-thermal atmospheric-pressure biocompatible plasma (NBP). Ozone concentration in plasma sources has been derived by Kuhn et al. [1]. The diffusion coefficients inside ($D_0$) and outside ($D_1$) the plasma sterilizer have been calculated to be 0.0641 $m^2 s^{-1}$ and 0.717 $m^2 s^{-1}$, respectively. To sustain high $O_3$ concentrations over 121 ppm inside the plasma source and low $O_3$ concentrations below 0.05 ppm outside the sterilizer, it is necessary to keep $O_3$ concentrations at the exit of plasma sterilizer below 0.28 ppm. so that diffusion coefficient $D_1$ has been designed to be as large as 11 times of $D_0$.

**Keywords**: Non-thermal atmospheric-pressure biocompatible plasma; diffusion; ozone species; plasma sterilizer

## 1. Introduction

New antibiotics that are being developed and various antiseptics are expected to reduce the risk of infection in accordance with the developments in medicine. However, nosocomial infections related to medical institutions such as hospitals and senior hospitals are increasing as evidenced by a decrease in the immune function of patients and an increase in antimicrobial resistant strains due to the development of anti-cancer therapies [1,2]. A medical institution is any facility where several people visit a doctor for their diagnosis and treatment as an outpatient or in-hospital patient. Therefore, they are exposed to many risks of infection transmission, and it is very important to protect the patients, visitors, and staff from them. Microbial infections are spread by direct contact or after an indirect contact with air and splashes. Infections such as pneumonia, chickenpox, and measles are transmitted by air, whereas influenza, pertussis, and meningococcal infections are spread through splash. Multidrug-resistant bacteria such as Methicillin-resistant Staphylococcus aureus (MRSA), Vancomycin-resistant Staphylococcus aureus (VRSA), Vancomycin-resistant Enterococci (VRE), and Carbapenem-resistant Enterobacteriaceae (CRE) are representative examples of infections

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caused by contact propagation [1,2]. However, multidrug-resistant bacteria can also be transmitted by air, depending on environmental conditions [3].

Infection through air and droplet transmission can easily occur within a short time in a medical institution. Small particles (5 μm or less) including microorganisms could adhere to dust in the air, float, and then get inhaled to infect patients. In this case, the microorganisms could propagate through air over a long distance. Droplet transmission could occur by spreading to other people's conjunctiva, and nasal or oral mucosa through coughing, sneezing, or talking, when the microorganisms are attached to large particles (larger than 5 μm). The splash generated at this moment can travel for approximately 1 m [4], or even over long distances in some cases [5]. To prevent the spread of infection by air or splash, medical institutions usually rely on air circulation through air conditioning equipment with a high-efficiency particulate air (HEPA) filter that removes 99.97% particles larger than 0.3 μm in diameter. It takes a long time to purify air with an air conditioning equipment in the space of a large medical institution and splashes are difficult to remove because they move a short distance. Bacteria and viruses smaller than 0.3 μm cannot be removed by a HEPA filter; therefore, they may be alive even after air circulation. Moreover, chemicals such as alcohols, aldehydes, and cresols are used periodically for sterilization and disinfection, which are expensive and environmentally damaging materials.

Non-thermal atmospheric-pressure biocompatible plasma (NBP) has been shown to effectively sterilize viruses and bacteria by the reactive oxygen species (ROS) and reactive nitrogen species (RNS) [6,7]. NBP is also applicable to treatment of wounds [8] and cancers [9], making it a growth engine for the 21st century. Recently, permeation models for various reactions of plasma in skin and living cells have been proposed [10]. NBP can be operated continuously for several months simply by turning on the power of a plasma sterilizer at low cost and it can also sterilize microorganisms smaller than 0.3 μm. Additionally, the use of a plasma sterilizer in diverse sizes could sterilize a wide area and spatial volume. A plasma sterilizer is environmental friendly and prevents the transmission of secondary infections effectively.

Many papers on the sterilization of microorganisms using NBP have been published since 1990, but there are few reports on the diffusion coefficient of active species generated from NBP. T. Nagatomo [11] generated ozone gas using dielectric barrier discharge (DBD) and obtained its diffusion coefficient through experiments on soil sterilization. He reported diffusion coefficients of 0.00021-0.00032 $cm^2/s$ in ozone gas when it was diffused into the soil with a concentration of 1.06 $g/cm^3$ naturally. The diffusion studies of reactive species in the sterilization experiments under atmospheric pressure plasma provide important data for the design of plasma sterilizers and information on the diffusion mechanism of the reactive species. We have developed a plasma sterilizer which can be used in medical hospitals, senior hospitals, and ambulances, etc. [6]. The reactive species generated in the plasma source are OH radicals, $O_3$ gas, O radicals, and $H_2O_2$, among others. Because $O_3$ gas has a relatively long life span and harms the human body in high concentrations, its release into the air from the plasma sterilizer should be designed not to exceed 0.05 ppm, according to environmental standards.

In this paper, the developed plasma sterilizer is briefly reviewed and the concentration of $O_3$ gas generated from the DBD plasma source is estimated using a formula derived by S. Kuhn et al. [12]. The concentration of $O_3$ gas is compared with that of OH radical in the plasma source. We also calculate the diffusion coefficient ($D_0$) of the ozone gas travelling from the plasma source toward the exit of the plasma sterilizer, which is located 5 cm away, and the diffusion coefficient ($D_1$) of the ozone gas emitted from the plasma sterilizer exit toward a detection point 50 cm away, using the Fick's first law. These diffusion coefficients are determined by the flow path and structure of the plasma sterilizer. The correlation between $D_0$ and $D_1$ obtained by Fick's first law are examined and optimized

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design criteria for the plasma sterilizer is presented for ensuring a low concentration of $O_3$ gas for safety requirements.

## 2. Materials and Methods

*A. Structure and experiment for measuring emitted $O_3$ gas in the new plasma sterilizer*

A compact-sized new plasma sterilizer with a width of 360 mm, height of 220 mm, and thickness of 84 mm was used with a low power of <20 W. Its concise structure and the detailed explanations are described in [6]. The parts of the plasma sterilizer, such as the fan, plasma source, and UV lamp are shown in Fig. 1. Figure 2 shows the plasma sources of two facing DBD sets with a width of 40 mm, height of 15 mm, and length of 30 mm and a 1 mm discharge gap. The high voltage and drive frequency are 7.5 kV and 30 kHz, respectively. The duty rate is adjusted from 1% to 100% to control the ROS and RNS concentrations. Plasma sterilizers have three diverse operating functions. The second function has been used in this experiment, by using a set of DBD plasma sources with a UV source and adjusting the duty rate of the plasma source to 1% so that the emitted ozone concentration is less than 0.05 ppm. This function can be used to protect patients from secondary infections in a hospital room or during transfer, such as in an ambulance and medical institution. Figure 3 is the experimental schematic showing the measurement of ozone gas released by the air flow of a plasma sterilizer. Water droplets released from the humidifier, situated 5 cm apart, enter the plasma sterilizer via the fan. The amount of water droplets absorbed by the fan into the plasma sterilizer was determined to be 4.3 mg/s in our previous study [6]. The frequency of the ultrasonic generator used in the humidifier was 28 kHz. The humidity and temperature were 30% and 20°, respectively, in the experimental room.

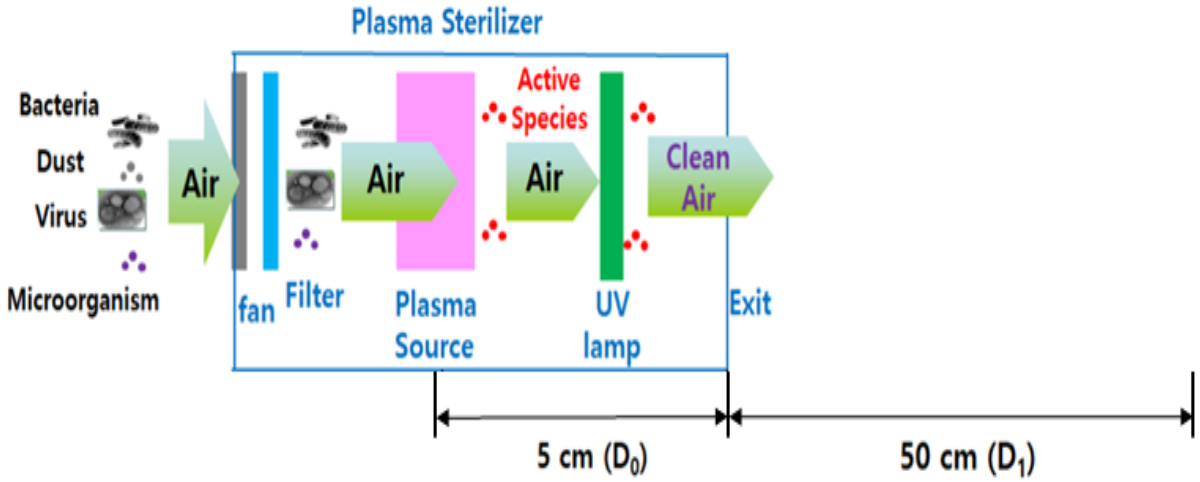


FIG. 1. Path of the absorbed air through the rear fan of the plasma sterilizer. $D_0$ is the diffusion coefficient between the plasma source and the exit of the plasma sterilizer, with a distance of 5 cm. $D_1$ is the diffusion coefficient between the exit and a position 50 cm away from the exit of the sterilizer.

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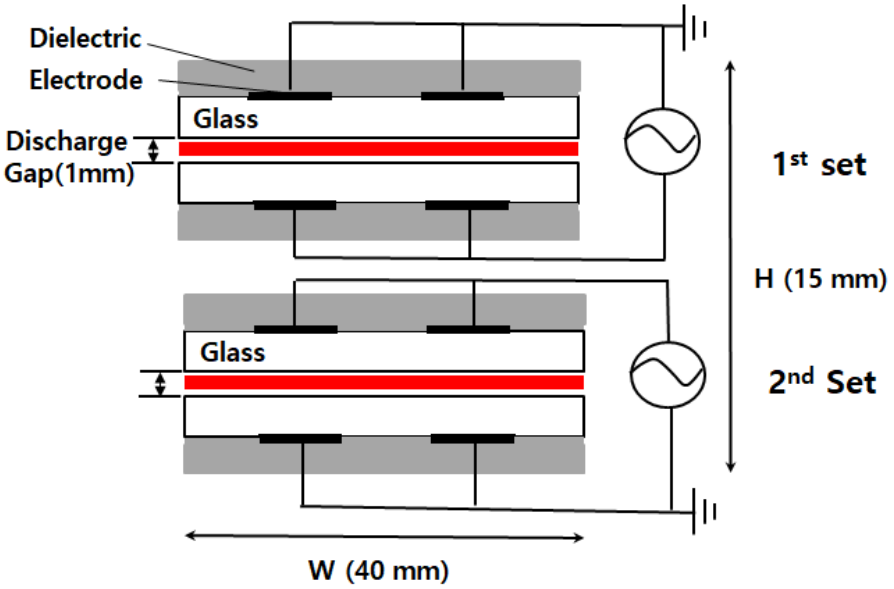


FIG. 2. Structure of the DBD plasma sources (width 40 mm, height 15 mm, length 30 mm, and discharge gap 1 mm) of two sets installed in the plasma sterilizer.

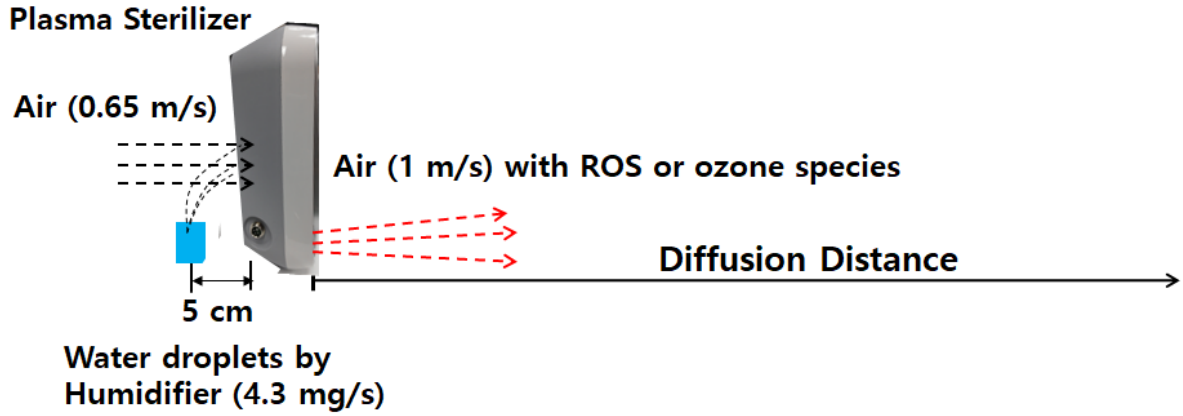


FIG. 3. Schematic of a plasma sterilizer perpendicular to the stage to measure ozone concentration emitted from the plasma sterilizer.

*B. Estimation of $O_3$ gas concentration in the plasma source*

In designing a plasma sterilizer, information about the diffusion coefficients of ozone gas emitted from the source and exit of the plasma sterilizer both are very important because they are related to the sterilization rate and the ozone concentration released to the outside air. The concentration of ozone in the source of the plasma sterilizer can be estimated using the reaction equation derived by S. Kuhn et al. [12]. They estimated the concentration of $O_3$ gas in a steady-state state assuming the dominance of nitrogen atoms in the air environment using Equation (1).

$$[O_3] = \frac{R_{diss}^{O2}}{R_{diss}^{N2}} \cdot [N_2] \cdot [O_2] \cdot \frac{k3k1}{k8k7} \quad (1)$$

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The modified ozone density, Mod[$O_3$], in Equation (2) has been calculated in this study by compensating the ratio (F) of the effective area of DBD discharge and the humidity correction factor (K), which is obtained by calculating the ratio of $O_3$ density with humidity that ranges from 30% to 100%. Moreover, the $O_3$ gas can get converted to OH, O, $O_2$, etc. due to water molecules.

$$Mod[O_3] = F \cdot K \cdot [O_3] \quad (2)$$

$$N_2 + e \rightarrow N + N + e \quad (3)$$

$$R_{diss}^{N_2} = [N_2] \cdot k_{diss}^{N_2} \cdot [e] \quad (4)$$

$$O_2 + e \rightarrow O + O + e \quad (5)$$

$$R_{diss}^{O_2} = [O_2] \cdot k_{diss}^{O_2} \cdot [e] \quad (6)$$

$$N + N + M \rightarrow N_2 + M \qquad k_1 = 4.4 \times 10^{-45}\ m^6s^{-1}\ (300K) \quad (7)$$

$$O + O_2 + N_2 \rightarrow O_3 + N_2 \qquad k_3 = 6.2 \times 10^{-46}\ m^6s^{-1}\ (300K) \quad (8)$$

$$O_3 + N \rightarrow NO + O_2 \qquad k_7 = 5.7 \times 10^{-19}\ m^3s^{-1}\ (300K) \quad (9)$$

$$O + N + M \rightarrow NO + M \qquad k_8 = 5.0 \times 10^{-44}\ m^6s^{-1}\ (300K) \quad (10)$$

The dissociation equation for nitrogen molecules is represented by Eq. (3), where its dissociative rate $R_{diss}^{N_2}$ is represented by Eq. (4), where the dissociation equation for oxygen molecules is represented by Eq. (5), where its dissociative rate $R_{diss}^{O_2}$ in turn is represented by Eq. (6). Here, [$N_2$], [$O_2$], and [e] represent the concentrations of $N_2$, $O_2$, and electron, respectively. The reaction coefficients of $k_1$, $k_3$, $k_7$, and $k_8$ are 4.4 x $10^{-45}$ $m^6s^{-1}$, 6.2 x $10^{-46}$ $m^6s^{-1}$, 5.7 x $10^{-19}$ $m^3s^{-1}$, and 5.0 x $10^{-44}$ $m^6s^{-1}$, as shown in Eqs. (7) to (10), respectively. The reaction coefficients for electron collision on nitrogen and oxygen molecules, $k_{diss}^{N_2}$ and $k_{diss}^{O_2}$, depend on the velocity distribution function and cross-sectional area σ, respectively [13]. $k_{diss}^{N_2}$ and $k_{diss}^{O_2}$ are obtained from the E/N reduced electric field values, where E and N are the electric field and neutral particles in the air, respectively. The E/N value could be expressed by Td, where 1 Td is $10^{-21}$ $Vm^2$. The E/N value of the plasma source used in this experiment is described in detail in [6]. The DBD plasma electrode consists of a patterned Ag electrode with $SiO_2$ material coated on a glass substrate. DBD plasma discharges occur in the 1 mm gap between the two opposing glass surfaces as shown in Fig. 2. The applied voltage difference between the two electrodes was measured to be 7.5 kV, whereas the actual voltage difference between the discharge air gap was estimated to be 3.3 kV as there is a voltage drop of 2.6 kV in the two glass substrates and wall voltage caused by accumulated wall charge on the glass surface from the plasma discharge is 1.6 kV. Therefore, electric field (E) is 3.3 x $10^6$ /V/m so that the reduced electric field (E/N) is estimated to be 120 Td, using the concentration of neutral particles (N) of 2.7 x $10^{25}$ $m^{-3}$ under 1 atmospheric pressure [6]. The reaction coefficients for electron collision on nitrogen $k_{diss}^{N_2}$ and oxygen molecules $k_{diss}^{O_2}$, have been calculated according to Eichwald et al. [14], where $k_{diss}^{N_2}$ = 2.0 x $10^{-11}$ $cm^3s^{-1}$ and $k_{diss}^{O_2}$ = 3.2 x $10^{-11}$ $cm^3$ $s^{-1}$ under a reduced electric field (E/N = 120 Td). Using these values, the Mod [$O_3$] concentration of Eq. (2) can be obtained.

## 3. Results and Discussion

*A. Measurement of ozone concentration using a new plasma sterilizer*

Figure 4 shows the ozone gas concentration over the diffusion distance using a duty ratio 0.01 of the plasma sterilizer with (solid triangle) and without humidifier (solid circle). The diffusion distance was measured from the exit of the plasma sterilizer. The ozone concentration was 0.25 ppm and 0.28

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ppm with and without water droplets at a diffusion distance of 0 cm from the exit, respectively. The difference is due to the conversion of $O_3$ gas to OH, O, and $O_2$ caused by the water molecules. At 50 cm diffusion distance, the ozone concentration decreased drastically and was saturated to almost 0.05–0.08 ppm over 50 cm. The dotted lines are cubic equations obtained using the least squares method. The cubic equations with and without water droplets are $y = -0.2267x^3 + 0.69x^2 - 0.6583 + 0.25$ and $y = -0.2133x^3 + 0.67x^2 - 0.6717x + 0.28$, respectively, and dotted lines fit well with the data. Water droplets of 4.30 mg/s released from the humidifier enter the sterilizer by the rear fan. The humidity in the plasma source with water humidifier of 4.30 mg/s is calculated to be about 100% and the concentration of water molecules in the plasma source is estimated to be about $6 \times 10^{23}\ m^{-3}$ [6] because the water molecule (H2O) concentration can be obtained by Eq. (11):

$$(H2O) = Io \times G \times \Delta T/VO. \quad (11)$$

Here, Io is the number of water molecules absorbed by the rear fan of the plasma sterilizer, G is the fraction of water vapor propagated into the gap of the plasma source, $\Delta T$ is the time required by water molecules to pass through the discharge gap of the plasma source, and VO is volume of the discharge gap. Here, the value $Io = 1.44 \times 10^{20}$ water molecules/s is obtained from $4.30 \times 10^{-3}$ g/s. Using $G = 0.3$, $\Delta T = 0.0167$ s, and $VO = 1.2\ cm^3$, $H_2O$ is calculated to be $6 \times 10^{23}\ m^{-3}$.

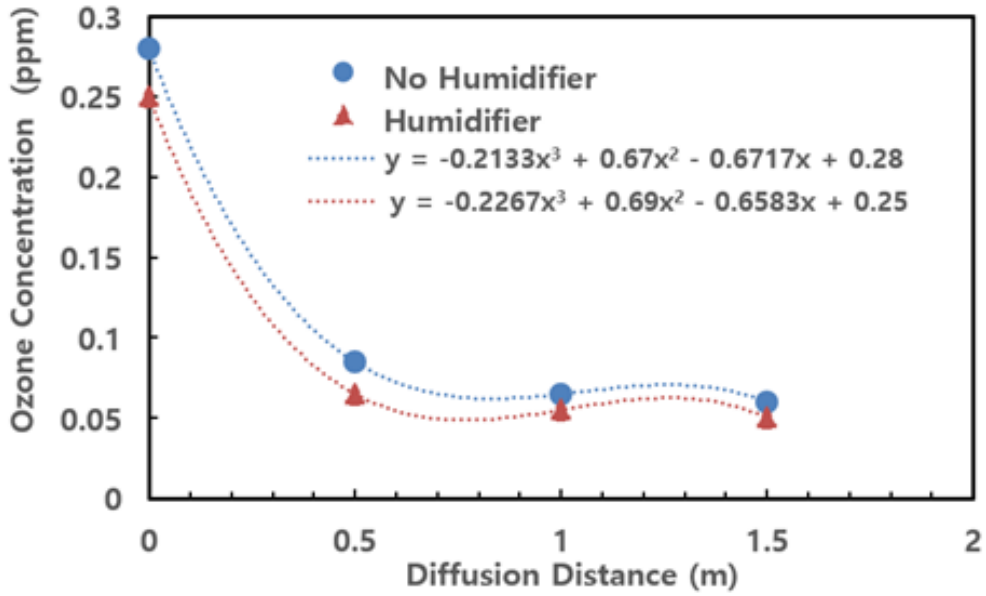


FIG. 4. Ozone concentration for different diffusion distances with or without humidifier. The dotted lines are a cubic equation obtained by using the least squares method and fit well with the data.

*B. Estimation of diffusion coefficient of $O_3$ gas*

In this study, the $O_3$ concentration of the plasma source was obtained using Eq. (2). The ratio of effective discharge area F is taken to be 0.7 and the humidity correction factor K is 1 at a 0% humidity, as shown in Figure 5. The ratio of $O_3$ gas with the humidifier to that without it inside the plasma source would be the same as that at the exit of plasma sterilizer because the half-life of $O_3$ gas is sufficiently long (over 30 min) [15]. The ratio of ozone gas concentration at the exit of the sterilizer (at a diffusion length 0 m) with a humidifier to that without it is approximately 0.89, as shown in Fig. 4. The correction factors (K) for ozone concentration with 100% and 30% humidity are 0.95 and 0.85, respectively. Figure 5 shows the correction factors for ozone concentration versus humidity, which were obtained from the $O_3$ concentrations at 30% and 100% humidity in this experiment [16], where the extrapolation has been used for determining the correction factor 1 at 0% humidity.

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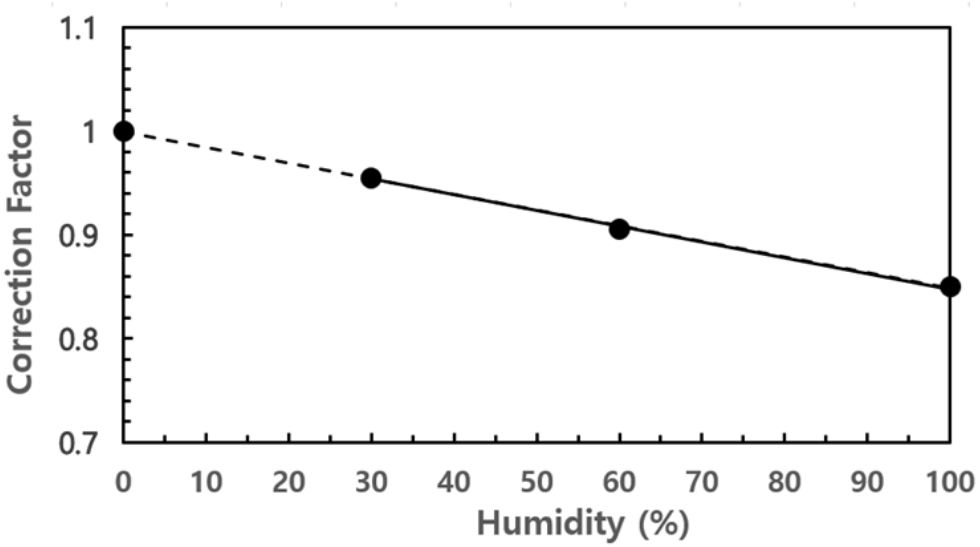


FIG. 5 . Correction factor for humidity in the estimation of ozone concentration. Correction factors are 1, 0.95, and 0.85 for humidity values of 0%, 30%, and 100%, respectively.

$R_{diss}^{N_2}$ in Eq. (4) is estimated to be 4.19 x $10^{26}$ $m^{-3}$ $s^{-1}$ from $k_{diss}^{N_2}$ = 2.0 x $10^{-17}$ $m^3$ $s^{-1}$, [$n_e$] = 1 x $10^{18}$ $m^{-3}$, and [$N_2$] = 2.09 x $10^{25}$ $m^{-3}$. Similarly, $R_{diss}^{O_2}$ in Eq. (6) is estimated to be 1.81 x $10^{26}$ $m^{-3}$ $s^{-1}$ from $k_{diss}^{O_2}$ = 3.20 x $10^{-17}$ $m^3$ $s^{-1}$ and [$O_2$] = 5.64 x $10^{24}$ $m^{-3}$. The discharge effective area, F, is 0.7 and the correction factors K are 0.95 and 0.85 for 30% and 100%, respectively. Therefore, the ozone concentration Mod[$O_3$] in Eq. (2) under 30% and 100% humidity are estimated to be 3.24 x $10^{21}$ $m^{-3}$ (121 ppm) and 2.91 x $10^{21}$ $m^{-3}$ (108 ppm), respectively, in Eq. (2). In the previous paper [6], the concentration of OH radical in plasma source with 100% humidity has been shown as 9.79 x $10^{21}$ $m^{-3}$. The number of OH radicals is shown to be over three times than that of $O_3$ gas in plasma source, where the oxidation potential of OH radical and $O_3$ are 2.8 and 2.1 V, respectively. Therefore, sterilization inside the plasma source would be done mainly by the OH radical and that outside the plasma source by $O_3$, because OH density is high inside the plasma source and these OH radicals may transform into $H_2O_2$, whose oxidation potential is 1.7 eV outside the plasma source with an unchanged $O_3$ density due to their longer half-life [17].

Figure 6 shows a schematic illustration of the air flow released from the plasma source and the exit, which is 5 cm away from it. $S_0$, $S_1$, and $S_2$ are the cross-sections in the plasma source, the sterilizer exit, and a random area 50 cm away from the sterilizer, respectively. Diffusion coefficients (D) for ozone gas in the plasma source and the exit of the sterilizer can be obtained, respectively, from Eq. (11) using Fick's first law of diffusion by assuming a steady flow of ozone,

$$J = D\, dC/dx \fallingdotseq D\,(C_o - C_x)/x \qquad (12)$$

Here, J is the diffusion flux, $C_o$ and $C_x$ represent ozone concentrations at the plasma source and a position x, respectively, from the source. The ozone concentration $C_0$ at the plasma source with 30% humidity is estimated to be 3.24 x $10^{21}$ $m^{-3}$ (121 ppm) from Eq. (2). Therefore, the diffusion flux ($J_0$) for ozone at the plasma source, $J_0 = nvS_0$, is estimated to be 4.15 x $10^{21}$ $m^{-2}$ $s^{-1}$, where air velocity v and cross-section area $S_0$ in the plasma source are 1.28 m $s^{-1}$ and 4.0 x $10^{-5}$ $m^2$, respectively, in this experiment. The $O_3$ concentration ($C_x$) at the sterilizer exit is measured to be 7.53 x $10^{18}$ $m^{-3}$ (0.28 ppm) and x is 0.05 m; accordingly, the diffusion coefficient ($D_o$) at the plasma source is estimated to be 0.0415 $m^2$ $s^{-1}$. The diffusion coefficient at 100% humidity is the same as that at 30% humidity because of not being dependent on humidity. The diffusion flux ($J_1$) of ozone gas between the exit and 50 cm outside the region of the plasma sterilizer is estimated to be 7.53 x $10^{18}$ $m^{-2}$ $s^{-1}$ using the cross-sectional area ($S_1$ = 1.2x$10^{-3}$ $m^2$) at the exit of the plasma sterilizer and air velocity ($v_1$ = 1.0 m $s^{-1}$). Using the ozone

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concentration of 2.28 x $10^{18}$ $m^{-3}$ (0.085 ppm) at 50 cm distance from the plasma sterilizer, the ozone diffusion coefficient ($D_1$) is 0.717 $m^2 s^{-1}$. Table 1 shows the components used to obtain the diffusion coefficients $D_0$ at the plasma source ($S_0$) and $D_1$ at the exit of plasma sterilizer ($S_1$), as shown in Fig. 6. Figure 7 shows the ozone concentration versus diffusion distance for variation of duty ratio of a plasma source. The duty ratios (DR) are adjusted by 0.005, 0.01, 0.02, and 0.03 in driving voltage waveforms of the plasma sterilizer. The exit position of the plasma sterilizer is set to be 0 m in the x axis of diffusion distance, whereas the position of the plasma source is adjusted by -5 cm. The ozone concentrations for duty ratios of 0.005, 0.01, 0.02, and 0.03 are obtained from this study, and are represented in Fig. 7. Table 2 shows these values according to the given duty ratios. The duty ratio of the plasma sterilizer was set to 0.01 in our experiment, whereas the diffusion distance is required to be located more than 1.6 m away from the exit of the plasma sterilizer for ozone concentrations lower than 0.05 ppm, as shown in Fig. 7. It is necessary for ozone concentrations released from the plasma sterilizer to be below 0.05 ppm at a distance shorter than 1.6 m for acquiring wide area of human life.

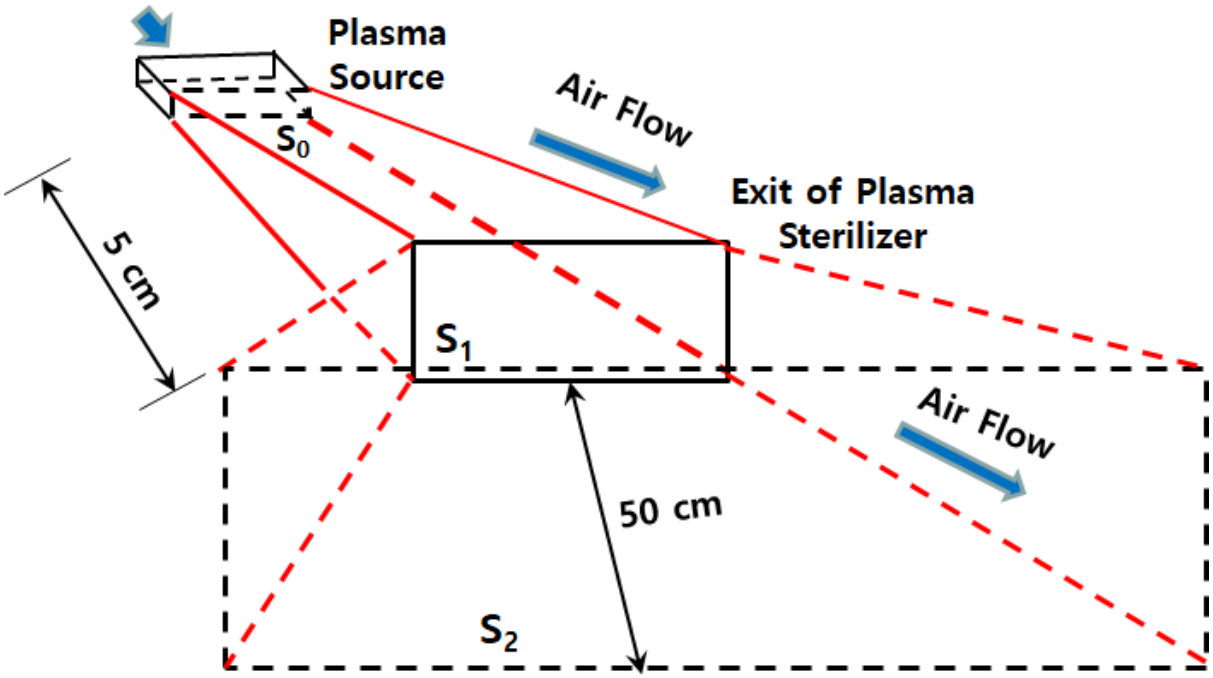


Figure 6. Schematic drawing of the air flow of plasma source, the exit of the plasma sterilizer, and a 50 cm area away from the exit of the plasma sterilizer. $S_0$, $S_1$, and $S_2$ are cross-sections in the plasma source, exit, and 50 cm area from the exit of plasma sterilizer, respectively. $S_2$ is described as a random area of air flow outside the exit. The distances between $S_0$ and $S_1$, and $S_1$ and $S_2$ are 5 cm and 50 cm, respectively. Components to calculate the diffusion coefficient in $S_0$ and $S_1$ are described concisely in Table 1.

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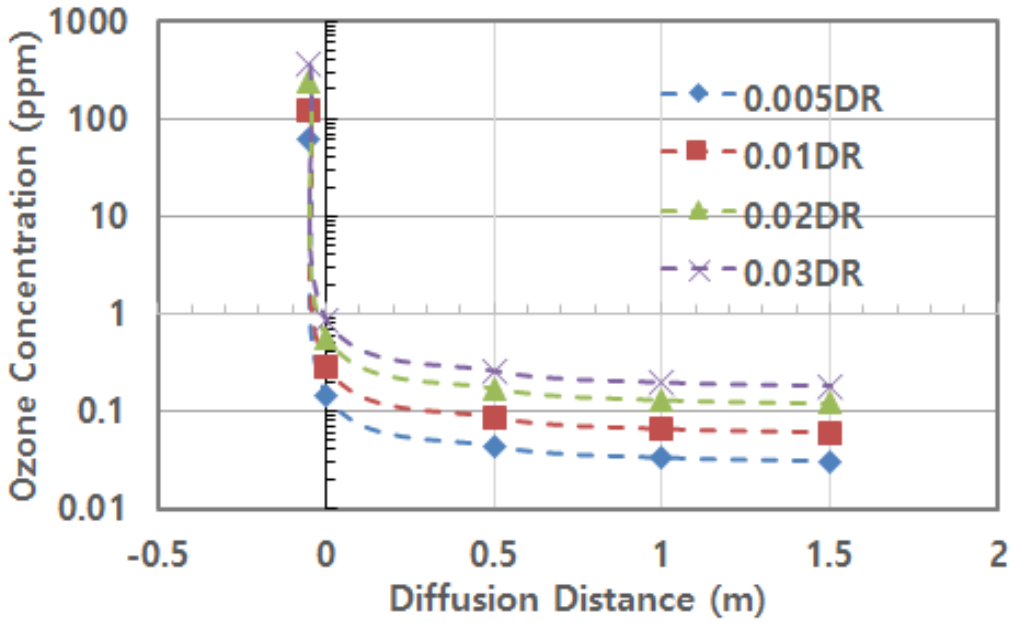


FIG 7. Ozone concentration for different diffusion distances with variation in the duty ratio of the plasma source. Diffusion distance of -5 cm indicates the position of plasma source.

Table 1. $O_3$ concentration, cross-section of plasma source, air velocity, and the diffusion flux to calculate the diffusion coefficient of ozone gas. $S_0$, $S_1$, and $S_2$ are explained in Fig. 6. "Imaginary" word means the imaginary cross-section 50 cm away from the sterilizer.

| Items | Plasma source ($S_0$) | Exit of sterilizer ($S_1$) | 50 cm from sterilizer ($S_2$) |
|---|---|---|---|
| $O_3$ density ($m^{-3}$) | $3.24 \times 10^{21}$ (121 ppm) | $7.53 \times 10^{18}$ (0.28 ppm) | $2.28 \times 10^{18}$ (0.085 ppm) |
| Cross-section ($m^2$) | $4 \times 10^{-5}$ | $1.2 \times 10^{-3}$ | imaginary |
| Air velocity ($ms^{-1}$) | 1.28 | 1.0 | |
| Diffusion flux ($m^{-2} s^{-1}$) | $4.15 \times 10^{21}$ | $7.53 \times 10^{15}$ | |
| Diffusion coefficient ($m^2 s^{-1}$) | 0.0641 | 0.717 | |

Table 2. Ozone concentration for different diffusion distances with variation in duty ratio of plasma source (value of FIG. 7.) Diffusion distance of −0.05 m indicates the position of plasma source.

| Diffusion distance (m) | 0.005 DR | 0.01 DR | 0.02 DR | 0.03 DR |
|---|---|---|---|---|
| -0.05 | 60.5 | 121 | 242 | 363 |
| 0 | 0.141 | 0.28 | 0.562 | 0.843 |
| 0.5 | 0.043 | 0.085 | 0.171 | 0.256 |
| 1.0 | 0.033 | 0.065 | 0.130 | 0.196 |
| 1.5 | 0.030 | 0.06 | 0.120 | 0.181 |

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Figure 8 shows the ozone concentration versus diffusion distances for the different cross-sectional areas corresponding to cross-section area $S_1$, which are 1.5 (1.5 $S_1$) and 2 (2.0 $S_1$) times bigger than $S_1$ under the same air velocity (1 m $s^{-1}$) at the exit of plasma sterilizer. It is necessary to keep a fan near the exit of a sterilizer to sustain the same air velocity as $S_1$ in cross-sectional areas 1.5 $S_1$ and 2.0 $S_1$. When the exit cross-sections of the sterilizer are 1.5 $S_1$ and 2.0 $S_1$, the ozone concentrations at the exit point, where the diffusion distance is 0 m, are 0.19 ppm and 0.14 ppm, respectively. Ozone concentrations at diffusion distances over 0.6 m and 0.5 m for cross-sections 1.5 $S_1$ and 2.0 $S_1$ are shown to be below 0.05 ppm, respectively; however, it was 1.6 m for $S_1$. The diffusion coefficient $D_1$ is the same in the cross-sections $S_1$, 1.5 $S_1$, and 2.0 $S_1$ by Eq. (12). The diffusion coefficients $D_0$ and $D_1$ of this plasma sterilizer were calculated to be 0.0641 $m^2 s^{-1}$ and 0.717 $m^2 s^{-1}$, respectively. To sustain the $O_3$ concentrations over 121 ppm inside the plasma source located at the diffusion distance of -5 cm and those below 0.05 ppm outside the exit of plasma sterilizer, it is necessary and desirable to keep $O_3$ concentration below 0.28 ppm at the exit of plasma sterilizer (diffusion distance of 0 m). As one can observe, the diffusion coefficient $D_1$ has been designed to be as large as 11 times of $D_0$.

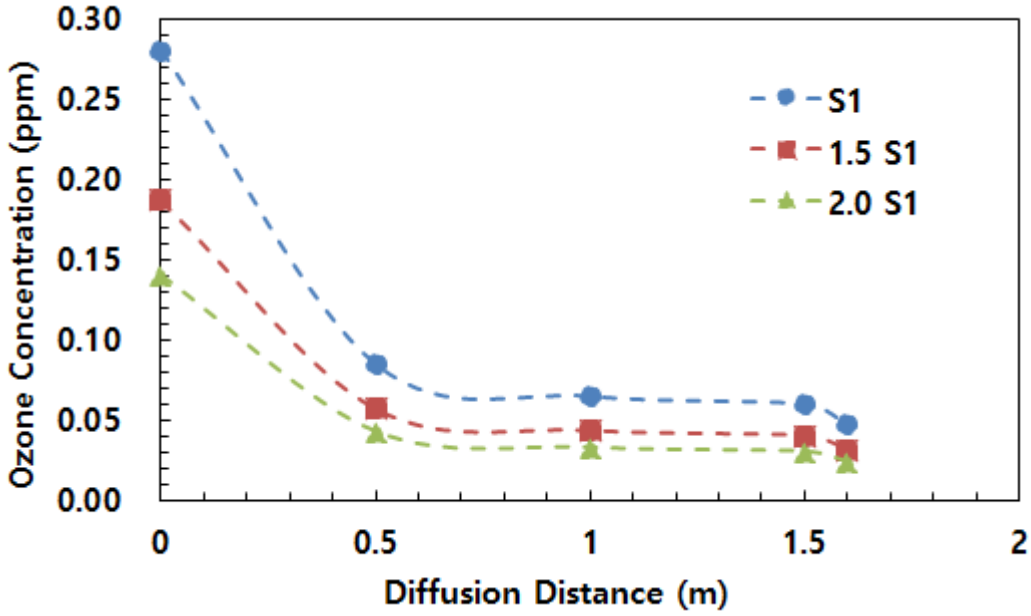


FIG 8. Ozone concentration for diffusion distances in case of 1.5 (1.5 $S_1$) and 2.0 times (2.0 $S_1$) for conventional area ($S_1$) with same air velocities at the exit of plasma sterilizer.

## 4. Conclusion

Most infections can be transmitted through the air. The HEPA filter of an air conditioning equipment is used to prevent infection transmission through air in medical institutions. However, viruses and bacteria smaller than 0.3 μm cannot be removed by the HEPA filter; therefore, those microbes remain alive throughout the air ventilation. A plasma sterilizer has the capability to provide environmental friendly sterilization by ROS and RNS at low cost. We developed a new DBD plasma sterilizer. Ozone concentrations of 3.24 x $10^{21}$ $m^{-3}$ (121 ppm) and 2.91 x $10^{21}$ $m^{-3}$ (108 ppm) were estimated inside the DBD plasma source under 30% and 100% humidity conditions, respectively, using a formula derived by S. Kuhn et al. The concentration of OH radicals was noted to be three times higher than that of $O_3$ in 100% humidity inside the plasma source. Therefore, sterilization inside the plasma source will be mainly provided by the OH radicals and by $O_3$ and H2O2 outside the

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plasma source. The diffusion coefficients $D_0$ and $D_1$ of this plasma sterilizer are calculated as 0.0641 $m^2 s^{-1}$ and 0.717 $m^2 s^{-1}$, respectively. To sustain high $O_3$ concentrations (over 121 ppm) inside the plasma source and low $O_3$ concentration (below 0.05 ppm) outside the plasma sterilizer, it is necessary to keep $O_3$ concentration at the exit of plasma sterilizer below 0.28 ppm. Therefore, the diffusion coefficient $D_1$ between $S_1$ and $S_2$ has been designed to be as large as 11 times of $D_0$ between $S_0$ and $S_1$. When the conventional cross-section at the exit of a sterilizer are 1.5 $S_1$ and 2.0 $S_1$ and with the same air velocity, ozone concentrations for diffusion distances over 0.6 m and 0.5 m are below 0.05 ppm, respectively, and these are relatively shorter diffusion distances than 1.6 m found in conventional cross-section $S_1$.

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**Conflicts of Interest:**

## REFERENCES


1. Kritsotakis, E. I.; Kontopidou, F.; Astrinaki, E.; Roumbelaki, M.; Ioannidou, E.; Gikas, A. Prevalence, incidence burden, and clinical impact of healthcare-associated infections and antimicrobial resistance: a national prevalent cohort study in acute care hospitals in Greece. *Infect Drug Resist*. **2017**, *10*, 317–328.
2. Zimlichman, E.; Henderson, D.; Tamir, O. Health care-associated infections: a meta-analysis of costs and financial impact on the US health care system. *JAMA Intern Med*. **2013**, *173*, 2039–2046.
3. Wilson, R. D.; Huang, S. J.; McLean, A. S. The correlation between airborne methicillin-resistant Staphylococcus aureus with the presence of MRSA colonized patients in a general intensive care unit. *Anaesth Intensive Care*. **2004**, *32*, 202-209 .
4. Chen, S. Y.; Anderson, S.; Kutty, P. K.; Lugo, F.; McDonald, M.; Rota, P. A. Ortega-Sanchez I.R.; Komatsu K.; Armstrong G.L.; Sunenshine R.; Seward J.F.; Health care-associated measles outbreak in the United States after an importation: challenges and economic impact. *J. Infect. Dis*. **2011**, *203*, 1517–1525.
5. Hall, C. B. The Spread of Influenza and Other Respiratory Viruses: Complexities and Conjectures .*Clin Infect Dis*. 2007, *45*, 353–359.
6. Park, J. S.; Han, I.; Choi, E. H. Properties of plasma sterilizer using non-thermal atmospheric-pressure biocompatible plasma. *AIP Advances*. **2019**, *9*, 075125.
7. Han, I.; Choi, E. H. The role of non-thermal atmospheric pressure biocompatible plasma in the differentiation of osteoblastic precursor cells, MC3T3-E1. *Oncotarget*. **2017**, *8*, 36399-36409.
8. Kang, S. U.; Choi, J. W.; Chang, J. W.; Kim, K. I.; Kim, Y. S.; Park, J. K.; Kim, Y. E.; Lee, Y. S.; Yang, S. S.; Kim, C. H. $N_2$ non-thermal atmospheric pressure plasma promotes wound healing in vitro and in vivo: Potential modulation of adhesion molecules and matrix metalloproteinase-9. *Experimental Dermatology*. 2017, *26*, 163-170.
9. Ishaq, M.; Evans, M. M.; Ostrikov, K. Effect of atmospheric gas plasmas on cancer cell signaling. *Int. J. Cancer*. 2014, *134*, 1517-1528.
10. Lu, X.; Keidar, M.; Laroussi, M.; Choi, E.; Szili, E. J.; Ostrikov, K. Transcutaneous plasma stress: From soft-matter models to living tissues. *Mater. Sci. Eng*. R. 2019, *138*, 36-59.
11. Nagatomo, T.; Abiru, T.; Mitsugi, F.; Ebihara, K.; Nagahama, K. Study on ozone treatment of soil for agricultural application of surface dielectric barrier discharge. *Jpn. J. Appl. Phys.* **2016**, *55*, 01AB06 .
12. Kuhn, S.; Bibinov, N.; Gesche, R.; Awakowicz, P. Non-thermal atmospheric pressure HF plasma source: generation of nitric oxide and ozone for bio-medical applications. *Plasma Sources Sci. Technol*. 2010, *19*, 015013.
13. Rajasekaran, P.; Bibinov, N.; Awakowicz, P. Quantitative characterization of a dielectric barrier discharge in air applying non-calibrated spectrometer, current measurement and numerical simulation. *Meas. Sci. Technol*. 2012, *23*, 085605.
14. Eichwald, O.; Yousfi, M.; Hennad, A.; Benabdessadok, M. D. Coupling of chemical kinetics, gas dynamics, and charged particle kinetics models for the analysis of NO reduction from flue gases *J. Appl. Phys*. 1997, *82*, 4781.
15. McClurkin, J. D.; Maier, D. E.; IIeIeji, K. E. Half-life time of ozone as a function of air movement and conditions in a sealed container. *J. Stored Products Research*. 2013, *55*, 41–47.
16. Ki, S. H.; Masur, K.; Baik, K. Y.; Choi, E. H. Effects of humidity on room disinfection by dielectric barrier discharge plasma. *J. Phys. D*. 2019, *52*, 425204.
17. Tang, S.; Lu, N.; Shang, K.; Li, J.; Wu, Y. Detection of hydroxyl radicals during regeneration of granular activated carbon in dielectric barrier discharge plasma system. *J. of Physics: Conference Series*. 2013, *418*, 012104.