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The roles of the various plasma agents in the inactivation of bacteria

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The roles of various plasma agents in the inactivation of bacteria have recently been investigated. However, up to now, the effect of the charged particles on the inactivation of bacteria is not well understood. In this paper, an atmospheric pressure plasma jet device, which generates a cold plasma plume carrying a peak current of 300 mA, is used to investigate the role of the charged particles in the inactivation process. It is found that the charged particles play a minor role in the inactivation process when $He/N_2(3\%)$ is used as working gas. On the other hand, when $He/O_2(3\%)$ is used, the charged particles are expected to play an important role in the inactivation of bacteria. Further analysis shows that the negative ions O_2^- might be the charged particles that are playing the role. Besides, it is found that the active species, including O, O_3, and metastable state O_2^*, can play a crucial role in the inactivation of the bacteria. However, the excited He^*, N_2 $C\ ^3\Pi_u$, and N_2^+ $B\ ^2\Sigma_u^+$ have no significant direct effect on the inactivation of bacteria. It is also concluded that heat and UV play no or minor role in the inactivation process. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2977674]

I. INTRODUCTION

One of the most attractive features of nonequilibrium plasmas is their enhanced plasma chemistry. The plasma chemistry is driven by the electrons, which gain energy from the applied electric field. Due to several orders of difference in mass between the electrons and the heavy particles, the heavy particles can remain at low temperature while undergoing frequent collisions with the energized electrons. The collisions between the energized electrons and the heavy particles result in enhanced levels of excitation, dissociation, and ionization, i.e., enhanced plasma chemistry. It has recently been demonstrated that narrow voltage pulses are favorable for enhanced plasma chemistry.[1–7]

Because of the enhanced plasma chemistry, atmospheric pressure nonequilibrium plasmas (APNPs) have been widely studied for several emerging novel applications such as surface and materials processing, biological and chemical decontaminations of media, absorption and reflection of electromagnetic radiation, and synthesis of nanomaterials.[8–26] Among the novel applications, the use of APNPs in the biomedical field, such as sterilization, is attracting significant attention. Traditionally, the principal methods of inactivation of bacteria are based on thermal treatment (dry or moist heat), chemical treatment (e.g., H_2O_2 and EtO), or radiation (x ray and γ-ray). However, each of the conventional methods has its inherent drawbacks. They either are not suitable for the treatment of temperature sensitive materials or have residue toxic gases or raise significant safety concerns.

For the APNPs used for biomedical applications, their gas temperatures are generally required to stay close to or at room temperature. Therefore, unlike thermal treatment, they can be used for treatment of temperature sensitive materials. Besides, the chemically reactive species generated by the plasmas have relatively short lifetime. When the plasmas are turned off, there is no residue gas as in the case of common chemical treatment. Furthermore, there is no harmful radiation emitted by the plasmas. The APNPs offer very practical and safe sterilization method, where x-ray or γ-ray radiation method does not.

When the APNPs are used for sterilization, the potential active plasma agents are UV radiation, heat, and chemically reactive species and charged particles. The role of UV radiation depends on the wavelength and the power density of UV. The UV doses of several mW s/cm^2 are required to have a significant effect on the inactivation of bacteria, which is not fulfilled for atmospheric pressure air plasma.[27] The effect of heat is normally avoided when the gas temperature of the plasma is at room temperature. Therefore, it is widely accepted that when remote exposure is used, chemically reactive species such as reactive oxygen species (ROS) and reactive nitrogen species (O, O_3, NO, NO_2) play the crucial roles in the inactivation of bacteria.[14] However, the contribution of each type of the reactive species is not well understood. Regarding the role of the charged particles, Mendis *et al.*[28] and Laroussi *et al.*[14] suggest that when direct treatment (bacterial samples are placed inside a discharge gap) is employed, the charged particles may have some effects on the inactivation of bacteria. However, when the bacterial samples are placed inside a dielectric barrier discharge (DBD) discharge gap, as did by Fridman *et al.*,[13] high electric field is also imposed on the bacteria. The high electric field may have a significant effect on the inactivation of bacteria too.

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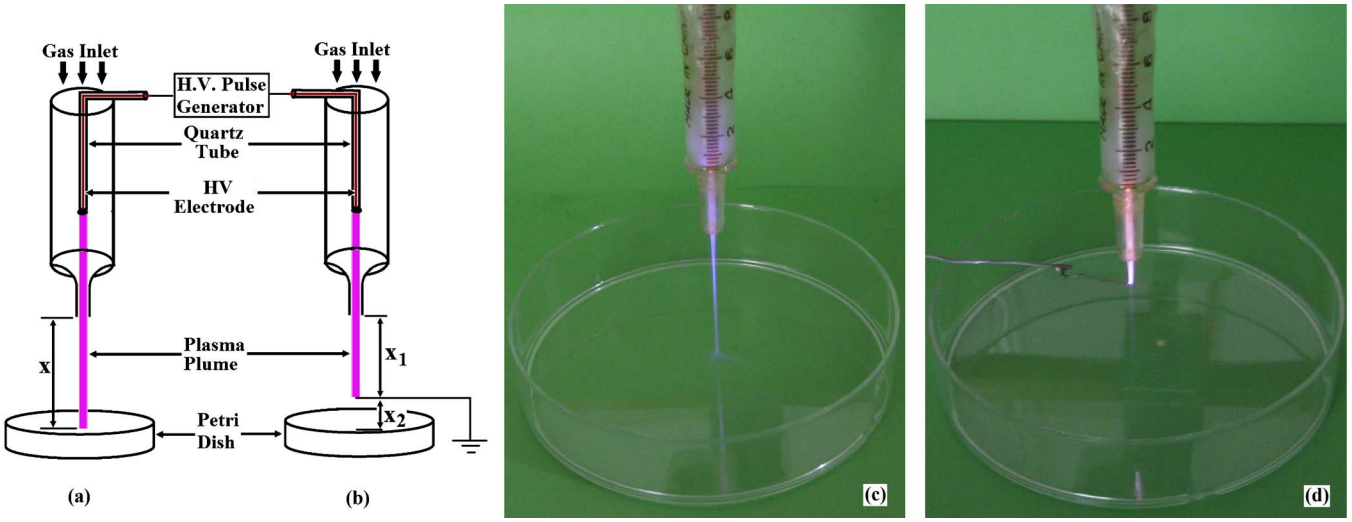

FIG. 1. (Color online) Experimental setup and photographs of the plasma plume. (a) For direct treatment, where x is the distance between the jet nozzle and the bacterial samples. (b) For indirect treatment, where x_1 is the distance between the jet nozzle and the thin ground wire, and x_2 is the distance between the thin ground wire and the bacterial samples. (c) and (d) are the photographs of the plasma plume when it is used for direct and indirect treatments, respectively.

In this paper, a recently developed plasma jet device, which generates a cold plasma plume with high discharge current, is used to investigate the contribution of the charged particles to the inactivation of bacteria. The plasma plume carries a peak current of about 300 mA as reported in Ref. 6. In the mean time, the electric field along the plasma plume is believed to be extremely low since a human finger can touch any part of the plasma plume without any feeling of electrical shock. This remarkable characteristic enables us to distinguish the role of the charged particles from that of the electric field, which should be negligible. Besides, the roles of the active species, heat, and UV in the inactivation process are also investigated in this paper.

II. EXPERIMENT SETUP

Figures 1(a) and 1(b) are the schematic of the experiment setup for direct and indirect treatments, respectively. The high voltage (HV) wire electrode, which is made of a copper wire with a diameter of 2 mm, is inserted into a 4 cm long quartz tube with one end closed. The inner and outer diameters of the quartz tube are 2 and 4 mm, respectively. The quartz tube along with the HV electrode is inserted into a hollow barrel of a syringe. The diameter of the hollow barrel is about 6 mm and the diameter of the syringe nozzle is about 1.2 mm. The distance between the tip of the HV electrode and the nozzle is 1 cm. Details on the experiment setup can be found in Ref. 6. When working gas such as helium, argon, oxygen, and nitrogen or its mixtures with a flow rate of a few l/min are injected into the hollow barrel and the HV pulsed dc voltage (amplitudes of up to 10 kV, repetition rate of up to 10 khz, and pulse width variable from 200 ns to dc) is applied to the HV electrodes, a homogeneous plasma is generated in front of the end of the quartz tube, along the nozzle, and in the surrounding air. The length of the plasma plume can reach as long as 6 cm with helium as working gas.

To investigate the role of the charged particles in the inactivation process, the bacterial samples are treated by the plasma plume in two different ways, i.e., direct and indirect treatments. For the direct treatment, the bacterial samples on the agar plates are placed right under the plasma plume at an adjustable distance x from the nozzle. The bacterial samples are directly contacted with the plasma plume. For the indirect treatment, the grounded thin wire with a diameter of 0.1 mm is placed at a distance $x_1=0.5$ cm away from the nozzle while the bacterial samples are placed at an adjustable distance x_2 from the thin wire. Since the diameter of the thin wire is much smaller than that of the nozzle, the influence of the thin wire on the gas flow dynamic is expected to be negligible. This is also confirmed by our following experimental results. Figures 1(c) and 1(d) show the photographs of the plasma plume when it is used for the direct and indirect treatments. Figure 1(d) clearly shows that the plasma plume stops at the thin wire. It should be pointed out that when the thin wire is not directly connected to the ground, such as grounded through a 2 MΩ resistor or even floating, the luminous part of the plasma plume also stops at the thin wire. However, when the thin wire is directly connected to the ground, the plasma is disturbed significantly. Therefore, for all the inactivation experiments of indirect treatment shown in this paper, to minimize the disturbance of the thin wire, the wire is actually connected to the ground through a 2 MΩ resistor.

The bacterial samples that are treated by the plasma plume are prepared as follows: *Staphylococcus aureus*, a gram-positive bacterium, is selected for this experiment. An overnight culture containing approximately 10^8 cfu/ml is prepared. Then the culture is diluted to 10^6 cfu/ml (cfu: colony-forming unit) for the experiments. 200 μl of the diluted suspension containing bacterium concentrations of 10^6 cfu/ml is evenly spread over each agar plate in Petri dish. Afterward, it is treated by the plasma plumes for 2 min immediately. After the plasma treatment, it is incubated for 24 h at 37 °C. For control experiments, the samples are treated by the working gas flowing at the same flow rate with plasma off. It should be pointed out that all the experiments

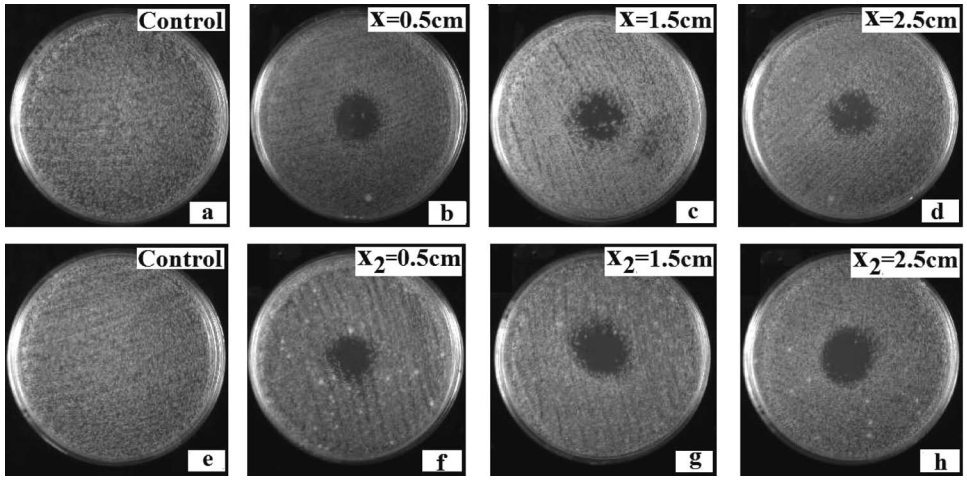

FIG. 2. Photographs of staphylococcus aureus samples on agar in Petri dishes. Working gas $He/N_2(3\%)$ (flow rate of 2 l/min). [(a)–(d)] Direct treatment: (a) control experiment, [(b)–(d)] bacterial samples placed at different distances $x_2=1.5$ from the nozzle. [(e)–(h)] Indirect treatment: (e) control experiment, [(f)–(h)] bacterial samples placed at different distances x_2 from the thin wire, x_1 is fixed at 0.5 cm.

reported in this letter are repeated four times, and the results are consistent with the same experimental conditions.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. The role of the charged particles

The first group of the experiment is done with $He/N_2(3\%)$ at a flow rate of 2 l/min. For the control experiment, the bacterial samples are treated by the $He/N_2(3\%)$ at the same flow rate with plasma off (power off). For all the inactivation experiments reported in this letter, the pulse frequency f of 4 kHz, pulse width t_{pw} of 1.6 μs, and applied voltage V of 9 kV are fixed. Figures 2(a)–2(h) show the experimental results. Areas, where bacteria are killed, look like uncontaminated agar (black) while areas that were not affected change color (gray) and appearance significantly as the bacteria grow there. According to these photographs, it can be concluded that with plasma off, the flowing of $He/N_2(3\%)$ gas has no effect on the growth of the bacteria.

Since the plasma plume stops at the thin wire, it is reasonable to assume that there are no significant charged particles reaching the bacterial samples for the indirect treatment. Figures 2(f)–2(h) show that the affected areas do not reduce at all for the indirect treatment results. Therefore, it can be concluded that the charged particles play a minor role in the inactivation process for the He plasma plume, and the ground wire has negligible effect on the gas flow dynamic. As was reported in Ref. 6, the peak current carried by the plasma plume reaches more than 300 mA. So, the peak electron density of the plasma plume can be estimated according to the diameter of the nozzle and electron drift velocity. It is in the order of $10^{13}/cm^3$. Hence, it is suspected that the concentration of the charged particles is much lower than that of the active free radicals.

The second group of the experiment is conducted with $He/O_2(3\%)$ as working gas at a flow rate of 2 l/min. Figures 3(a)–3(d) show the test results for the direct and indirect treatments (To save space, the control experiment results are not shown here, which indicate that the gas flow has no effect on the inactivation of bacteria). It clearly shows that the affected areas for both the direct and indirect treatments are much larger than those in Fig. 2. This will be discussed in Sec. III C. It should be stressed that according to Fig. 3, the affected areas of the direct treatment are much larger than those of the indirect treatment. As has been demonstrated that the ground wire for the indirect treatment should mainly affect the contribution of the charged particles to the inactivation process; therefore, the charged particles should play a significant role in this case. This observation is opposite to that obtained with He/N_2 as working gas. As we know that when He/N_2 is used as working gas, the dominant ions are He^+, He_2^+, or N_2^+ ions. Their densities should be close to those of electrons, i.e., in the order of 10^{13} cm^{-3}. On the other hand, when He/O_2 mixture is used as working gas, besides He^+, He_2^+, O_2^+, and electrons, high concentration of negative ion O_2^- may be present in the plasma. The O_2^- is formed mainly through the following reaction:

$$e + O_2 + M \rightarrow O_2^- + M, \tag{1}$$

where M is the third body, which is O_2 or He for this experiment. For simplicity, we assume that the reaction rates of Eq. (1) for the third body O_2 and He are the same. The reaction rate of Eq. (1) can be expressed as $k_1=1.4\times10^{-29}(300/T_e)\exp(-600/T)\exp[700\times(T_e-T)/T_eT]$ cm^6 s^{-1}.[29] Assuming $T=300$ K and $T_e=1$ eV, the characteristic time of the process described by Eq. (1) is estimated to be about 8 ns. In other words, it takes about 8 ns for an electron to form an O_2^- ion. This is much shorter than

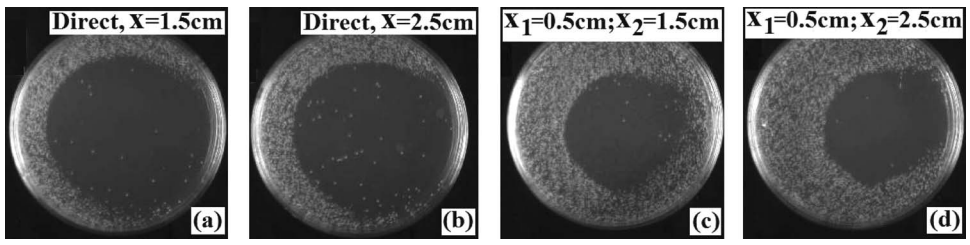

FIG. 3. Photographs of staphylococcus aureus samples on agar in Petri dishes. Working gas $He/O_2(3\%)$ (flow rate of 2 l/min). (a) and (b) are for direct treatments with $x=1.5$ and 2.5 cm, respectively. (c) and (d) are for indirect treatments with $x_2=1.5$ and 2.5 cm, respectively, x_1 is fixed at 0.5 cm.

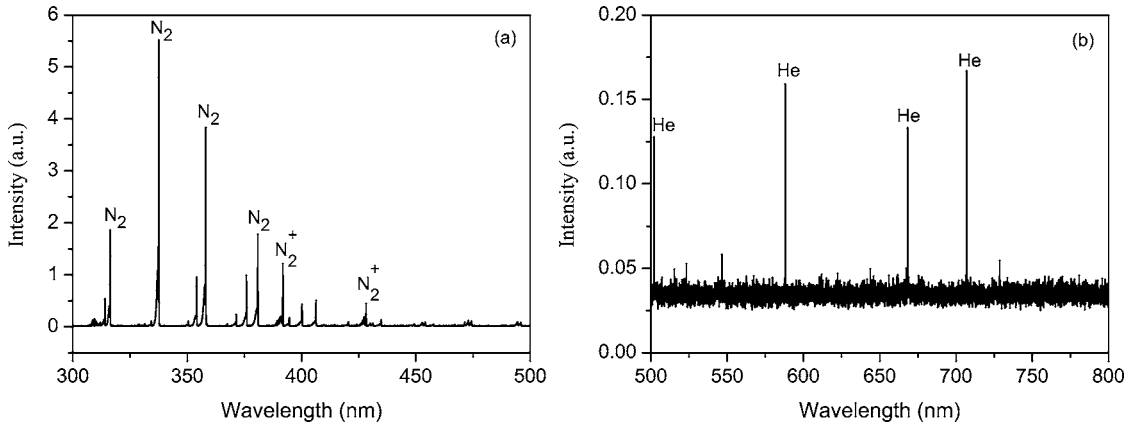

FIG. 4. Typical emission spectra of the plasma plume for $He/N_2(3\%)$ (flow rate of 2 l/min).

the pulse width of the discharge current, which is about 100 ns.[6] Therefore, during the discharge current pulses, the concentration of O_2^- ions might reach a value much higher than that of electrons. Simulation of a low temperature air plasma actually shows that the O_2^- ion concentration can reach a few orders higher than that of the electrons under certain conditions.[30] However, further studies, including simulation and experiment work, are still needed to confirm this conclusion.

B. The role of excited N_2^*, N_2^{+*}, and He^*

A half meter spectroscopy (Princeton Instruments Acton SpectraHub 2500i) is used to measure the optical emission of the plasma plume. Figure 4 shows the typical emission spectra of the plasma plume for working gas of $He/N_2(3\%)$ at a flow rate of 2 l/min. It can be seen that the emission spectra are dominated by the excited N_2^*, N_2^{+*}, and He^*. The experiment on the spatial resolved emission spectra shows that the N_2 ($C\ ^3\Pi_u \rightarrow B\ ^3\Pi_g$), N_2^+ ($B\ ^2\Sigma_u^+ \rightarrow X\ ^2\Sigma_g^+$), and He^* emission intensities from the plasma plume of 1.5 cm away from the jet nozzle are about 5–10 times higher than those of 2.5 cm away from the jet nozzle. However, Figs. 2(b)–2(d) show that the inactivation efficacy does not depend on the distance where the samples are placed. So, the excited N_2 $C\ ^3\Pi_u$, N_2^+ $B\ ^2\Sigma_u^+$, and He^* are not expected to play a significant direct role in the inactivation process.

C. The roles of reactive oxygen species

It is widely agreed that the ROSs play a crucial role in the inactivation process. This is also confirmed by our experimental results. When the working gas of $He/N_2(3\%)$ is replaced by $He/O_2(3\%)$, Figs. 3(c) and 3(d) show that the affected areas are significantly enlarged. Since the charged particles are collected by the thin wire, the improved inactivation efficacy can only be attributed to the ROS. The potential ROSs include atoms O, O_3, and metastable state O_2.

Figures 3(c) and 3(d) show that when the bacterial samples are indirectly treated by the plasma plume at different distances away from the ground wire electrode, the affected areas are similar. Therefore, the agents that have significant contribution to the inactivation process should have lifetimes of milliseconds or longer so that their concentrations will not decrease significantly at a few centimeters away from the ground wire electrode where the samples are placed. As we know, O_3 and some metastable state O_2^*, such as O_2 (a $^1\Delta_g$), have lifetimes of millisecond range or longer. Regarding O, the main reaction pathways that lead to the consumption of O for He/O_2 plasma are

$$O + O + M \xrightarrow{k_2} O_2 + M, \tag{2}$$

$$O + O_2 + M \xrightarrow{k_3} O_3 + M, \tag{3}$$

$$O + O_3 \xrightarrow{k_4} O_2 + O_2. \tag{4}$$

At room temperature, the reaction rates $k_2 = 3.6 \times 10^{-33}$ cm^6 s^{-1}, $k_3 = 6.4 \times 10^{-34}$ cm^6 s^{-1}, and $k_4 = 8.3 \times 10^{-15}$ cm^3 s^{-1}.[31] The concentrations of O and O_3 are estimated to be less than 0.1%.[32] The lifetime of O can be estimated by Eqs. (2)–(4). It is in millisecond range. So, O atom can play a role under this condition.

D. The role of heat

To evaluate the inactivation role of heat, the gas temperature of the plasma plume is determined by comparing experimentally measured emission spectrum of the second position system of nitrogen with simulated spectra at different temperatures. The gas temperature is obtained when the best fit of the simulated spectra and the measured spectrum are achieved.[33] Figure 5 shows that the simulated spectrum of rotational temperature of 300 K gives a good fit to the measured spectrum. Therefore, the gas temperature of the plasma plume is at room temperature.

E. The role of UV

The UV emission from the plasma plume is measured by an UV photometer (International Light Technology, model IL1400A). When we are measuring the UV intensity, the Petri dish is removed and the detector of the UV photometer is placed at the location. For all the tested working gases, the measured UV emission intensity is around 0.05–0.1 mW/cm^2. Therefore, the UV emission plays a minor role in the inactivation of the bacteria.

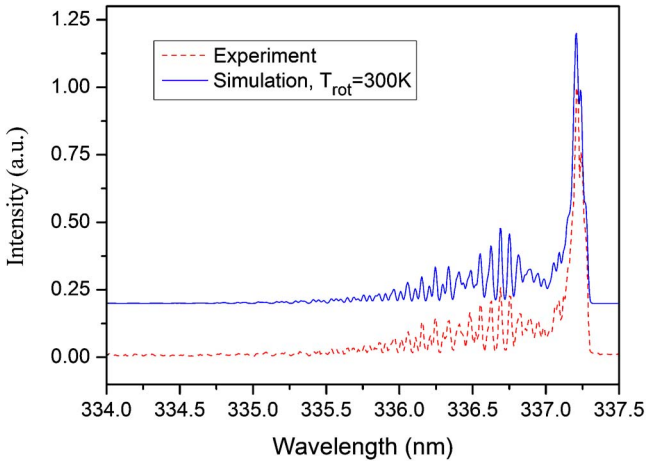

FIG. 5. (Color online) Simulated and measured rotational bands of the 0–0 transition of the second positive system of nitrogen. The spectra are intentionally shifted vertically for better comparison.

Finally, for curiosity, about 50–100 ml of alcohol is evenly spread on the center part of the bacterial sample with an area of about 1.5 cm in diameter in the Petri dish. Figures 6(a) and 6(b) show the tested results for the control and alcohol treated samples after incubation for 24 h at 37 °C. It clearly shows that the growth of the bacteria within the alcohol treated area is not significantly affected.

IV. CONCLUSION

In this paper, a specially designed plasma jet device, which generates a room temperature plasma plume with a peak discharge current of about 300 mA, is used to study the role of the various plasma agents in the inactivation process. By using a thin wire to collect the charged particles, the role of the charged particles in the inactivation process is studied. When $He/N_2(3\%)$ is used as the working gas, it is found that the charged particles do not play a significant role in the inactivation process. On the other hand, when $He/O_2(3\%)$ is used, the charged particles are expected to play a crucial role in the inactivation of bacteria. Because of the fast attachment rate of electron and O_2, it is concluded that the O_2^- might be the charged particles playing the role. This behavior is similar to common effects in a dusty plasma, where negative ions can take part in the charging of dusty particles.[34] Begum *et al.*[35] recently confirmed that the plasma plume is actually negatively charged.

In addition, by placing the bacterial samples at different distances away from the jet nozzle, according to the spatial resolved emission spectra of the plasma plume, it is concluded that the excited N_2^*, N_2^{+*}, and He^* have no significant direct effect on the inactivation of bacteria. Furthermore, by comparing the inactivation experiment results of $He/N_2(3\%)$ plasma with those of $He/O_2(3\%)$ plasma, it is concluded that the ROSs, including the O_3, metastable state O_2, and atom O, which is estimated to have a lifetime in the millisecond range, are playing the main role in the inactivation process. Finally, the measurements of the UV intensity show that the UV emission is too weak to play a crucial direct role in the inactivation process.

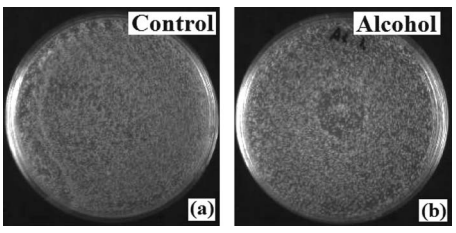

FIG. 6. Photographs of staphylococcus aureus samples on agar in Petri dishes. (a) Control and (b) treated by a drop of alcohol (50–100 ml) on the center part of the bacterial sample with a diameter of 1.5 cm in the Petri dish.

ACKNOWLEDGMENTS

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[1] S. Liu and M. Neiger, J. Phys. D **34**, 1632 (2001).
[2] M. Laroussi, X. Lu, V. Kolobov, and R. Arslanbekov, J. Appl. Phys. **96**, 3028 (2004).
[3] X. Lu and M. Laroussi, J. Phys. D **39**, 1127 (2006).
[4] X. Lu and M. Laroussi, J. Appl. Phys. **100**, 063302 (2006).
[5] X. Lu and M. Laroussi, Appl. Phys. Lett. **92**, 051501 (2008).
[6] X. Lu, Z. Jiang, Q. Xiong, Z. Tang, and Y. Pan, Appl. Phys. Lett. **92**, 151504 (2008).
[7] J. L. Walsh and M. G. Kong, Appl. Phys. Lett. **91**, 221502 (2007).
[8] R. Dorai and M. J. Kushner, J. Phys. D **36**, 666 (2003).
[9] Z. Machala, E. Marode, M. Morvova, and P. Lukac, Plasma Processes Polym. **2**, 152 (2005).
[10] K. Ostrikov, Rev. Mod. Phys. **77**, 489 (2005).
[11] F. Leipold, R. H. Stark, A. EI-Habachi, and K. H. Schoenbach, J. Phys. D **33**, 2268 (2000).
[12] C. Jiang, A. A. Mohamed, R. H. Stark, J. H. Yuan, and K. H. Schoenbach, IEEE Trans. Plasma Sci. **33**, 1416 (2005).
[13] G. Fridman, A. Brooks, M. Balasubramanian, A. Fridman, A. Gutsol, V. Vasilets, H. Ayan, and G. Friedman, Plasma Processes Polym. **4**, 370 (2007).
[14] M. Laroussi, Plasma Processes Polym. **2**, 391 (2005).
[15] M. Laroussi, IEEE Trans. Plasma Sci. **30**, 1409 (2002).
[16] M. Laroussi, J. P. Richardson, and F. C. Dobbs, Appl. Phys. Lett. **81**, 772 (2002).
[17] J. J. Shi and M. G. Kong, IEEE Trans. Plasma Sci. **33**, 276 (2005).
[18] K. H. Becker, K. H. Schoenbach, and J. G. Eden, J. Phys. D **39**, R55 (2006).
[19] E. Stoffels, I. E. Kieft, and R. E. J. Sladek, J. Phys. D **36**, 2908 (2003).
[20] I. Levchenko, K. Ostrikov, and E. Tam, Appl. Phys. Lett. **89**, 223108 (2006).
[21] R. Vidmar, IEEE Trans. Plasma Sci. **18**, 733 (1990).
[22] M. Lee, S. Han, H. Baik, and K. Song, J. Appl. Phys. **101**, 103305 (2007).
[23] I. Levchenko, K. Ostrikov, M. Keidar, and S. Xu, J. Appl. Phys. **98**, 064304 (2005).
[24] D. Kim, J. Rhee, S. Moon, and W. Choe, Appl. Phys. Lett. **89**, 061502 (2006).
[25] D. Kim, J. Rhee, B. Gweon, S. Moon, and W. Choe, Appl. Phys. Lett. **91**, 151502 (2007).
[26] X. Lu and M. Laroussi, J. Appl. Phys. **98**, 023301 (2005).
[27] M. Laroussi and F. Leipold, Int. J. Mass. Spectrom. **233**, 81 (2004).
[28] D. A. Mendis, M. Rosenberg, and F. Azam, IEEE Trans. Plasma Sci. **28**, 1304 (2000).
[29] I. Kossyi, A. Kostinsky, A. Matveyev, and V. Silakov, Plasma Sources Sci. Technol. **1**, 207 (1992).
[30] X. Lu, J. Appl. Phys. **102**, 033302 (2007).
[31] K. H. Becker, U. Kogelschatz, and K. H. Schoenbach, *Non-Equilibrium Air Plasmas at Atmospheric Pressure* (IOP, London, 2005), p. 133.
[32] J. Jeong, J. Park, I. Henins, S. Babayan, V. Tu, G. Selwyn, G. Ding, and R. Hicks, J. Phys. Chem. A **104**, 8027 (2000).
[33] G. Faure and S. M. Shkol'nik, J. Phys. D **31**, 1212 (1998).
[34] K. Ostrikov, S. Kumar, and H. Sugai, Phys. Plasmas **8**, 3490 (2001).
[35] A. Begum, S. Dhali, and M. Laroussi, Proceedings of the 35th IEEE International Conference on Plasma Science, Karlsruhe, Germany, 15–19 June, 2008 (unpublished), p. 146.