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Influences of discharge modes and gas bubbling conditions on \textit{E. coli} sterilization by pulsed underwater discharge treatments

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ABSTRACT
Underwater discharges are considered to be promising solutions to water disinfection problems. In this paper, the sterilization effects of different discharge modes and gas bubbling conditions on \textit{E. coli} are investigated. The experimental results show that spark discharge owns a much higher sterilization efficiency than the streamer discharge. The larger discharge volume and stronger UV emission during spark discharge may play a more important role than the electric field and active species in the sterilization efficiency of discharge modes. To further increase the sterilization efficiency, two kinds of feeding gases, O\textsubscript{2} and Ar, are introduced in underwater discharges, and experimental results show that O\textsubscript{2} bubbling presents a greater promotion than Ar. Higher sterilization efficiency of O\textsubscript{2} bubbling than that of Ar can be explained by the combination of physical and chemical reactions, while in the case of Ar, only physical interactions play a major role.

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I. INTRODUCTION

Water disinfection has been a popular topic in the recent years due to growing attention on water pollution and shortages. Discharge treatment is a promising method for water sterilization due to its advantages of introducing no secondary pollution and high efficiency,\textsuperscript{5,16} compared with the traditional disinfection approaches such as chlorination, ozonation,\textsuperscript{2} UV radiation,\textsuperscript{3} etc. Several plasma–liquid interaction configurations have been adopted to investigate the influence of electric discharge on water sterilization, e.g., plasma jet,\textsuperscript{4,5} dielectric barrier discharge,\textsuperscript{6} and surface discharge.\textsuperscript{7} For these reactors, active species are first produced in the gas phase where plasma is actively generated. Then, these active species immigrate to the liquid surface and penetrate into bulk water to continue further reactions. Although these configurations own the advantages of low energy consumption and high plasma-chemical efficiency, the concentration of active species will decline rapidly with the penetration depth of liquid,\textsuperscript{6} which is not practically suitable for large volume water disinfection. Besides, a few discharge configurations such as discharge over water film\textsuperscript{10} and in water droplet spray\textsuperscript{11} prove highly efficient for organic compound degradation, recently, while the efficiency of these configurations in sterilization requires further investigations. In comparison, underwater discharges can generate plasma in the bulk water to ensure a larger interaction area for active species. The underwater discharge processes also integrate several sterilization factors including active species,\textsuperscript{12} pulsed electric field (PEF),\textsuperscript{13} UV radiation,\textsuperscript{14} and shock waves.\textsuperscript{15} These factors allow synergistic reactions to occur and thereby improve water disinfection efficiency; therefore, underwater discharge has become one of the popular sterilization methods accompanying other traditional approaches. Recently, research results show that the sterilization achieved through underwater discharge depends on various conditions, e.g., voltage parameters,\textsuperscript{16} electrode geometries,\textsuperscript{17} solution conductivity,\textsuperscript{18} and bacteria types.\textsuperscript{19} With the variance of voltage parameters, different discharge modes may appear, e.g., streamer and spark discharge.
discharge, and have a huge influence on sterilization results. Several researchers\cite{22,23} report that underwater spark discharges own a higher sterilization efficiency than streamer discharges. Unfortunately, the differences in working mechanisms of the two discharge modes are not clearly illustrated due to the complexity of chemical and physical reactions in discharge processes. To further increase the disinfection efficiency, several groups introduce bubbling gases into reactors during underwater discharges and find that bubbling gases can improve the sterilization remarkably.\cite{24} However, the mechanisms behind the gas bubbling effects on bacteria inactivation are still a puzzle and need further explorations.

In this paper, we aim at investigating the effects of discharge modes and gas bubbling conditions on Escherichia coli (E. coli) sterilization. Through optical images and H$_2$O$_2$ concentration measurement, the roles of various factors (such as PEF, active species, and UV emission) during disinfection treatment are studied. The variance of sterilization results under different discharge modes and physical–chemical reactions involved in the gas bubbling treatments are discussed as well.

II. EXPERIMENTAL SETUP AND METHODOLOGY

The overall experimental setup of underwater pulsed discharge is shown in Fig. 1. A pulsed high voltage provided by a Marx generator is applied to the discharge reactor at a frequency of 1 Hz. The rise time of the voltage is 1 $\mu$s, and the full width at half maximum (FWHM) time $t_{FWM}$ is around 12 $\mu$s by choosing a suitable resistance of $R_1$ and $R_2$. The voltage and current waveforms are recorded with an oscilloscope (Tektronix TDS2000C) through a resistor voltage divider (2250:1) and a current monitor (Pearson 6585). The energy of the streamer or spark discharges is calculated by the time integral of the discharge power. The discharge images in experiments are captured by an intensified charge-coupled device (ICCD) camera (Andor iStar DH334T), which is triggered by an output trigger signal of the oscilloscope. A rod-to-cylinder electrode configuration is applied to create large volume discharge in water as presented in Fig. 1(b). The rod electrode is a stainless-steel threaded bolt with a 12 mm diameter. The rod is coated with a silicon rubber layer of 0.1 mm, which is introduced as it contains plenty of micro-cavities inside, hence causing the streamer discharge easier to be initiated.\cite{25,26} A stainless mesh of 108 mm in diameter is chosen as the grounded cylindrical electrode. The discharge reactor is filled with 1 l diluted bacterial solutions with conductivity around 32 $\mu$S/cm. In gas bubbling discharges, high purity Ar and O$_2$ (>99.99%) are, respectively, injected into reactors. We use a flowmeter to control the gas flow within the range of 0–1 l/min.

E. coli (DH5$\alpha$) is used for all the experiments described in this paper. In the cultivation stage, the bacteria are stored in agar media and suspended in 100 ml of a liquid growth medium for 24 h in a shaking incubator at 37 $^\circ$C. Cells are harvested by centrifugation at 3220 $\times$ g for 10 min and washed three times with sterile phosphate-buffered saline (PBS). After the discharge treatment, samples of the bacterial suspension are transferred to sterile tubes stored in the environment of 0 $^\circ$C. After serial dilution, suspension samples are spread onto Petri dishes, which are incubated for 18 h at 37 $^\circ$C. Enumeration of colony-forming units (CFUs) from at least three samples under same treatment conditions is performed, and the number of bacterial colonies is averaged by three measurements. The relative standard deviations of the obtained data are less than 10%. For each time of experiment, the bacterial density in the reactor before treatment is approximately in the order of (1–5) $\times$ 10$^6$ CFU/ml.

The concentration of H$_2$O$_2$ generated by pulsed discharges is measured by a spectrophotometric method.\cite{27} H$_2$O$_2$ solutions are added into potassium titanium (IV) oxalate and form the titanium (IV)-peroxide complex, which possess the maximum absorbance at a wavelength of 400 nm and, thus, can be quantitatively measured by a spectrophotometer.

III. RESULTS AND DISCUSSION

A. Influences of discharge modes on E. coli sterilization

In the experiments, the appearance probability of spark discharge increases with the rise of voltage. To clearly illustrate the transition processes of discharge modes, we choose the parameter of breakdown probability $P_b$ (also indicating the spark appearance probability) as the criterion to distinguish the discharge modes.

![FIG. 1. Schematic diagram of the experimental setup (a) and discharge reactor (b): 1—high voltage electrode, 2—gas inlet, 3—grounded electrode, and 4—gas outlet.](image-url)
We conduct the tests of discharges in bacterial solutions according to the IEC 60243 standard to obtain the breakdown probability curve via a 3-parameter Weibull distribution function, as shown in Fig. 2. Discharges can be divided into three regions under different applied voltage amplitudes $U$, i.e., the streamer discharge region ($P_b = 0$ when $U \leq 27$ kV), the streamer-to-spark discharge region ($0 < P_b < 1$ when $27 < U < 31$ kV), and the spark discharge region ($P_b = 1$ when $U \geq 31$ kV). In Fig. 2, two typical images of streamers and sparks are listed as well. In streamer discharges, several branching channels are observed at the length between 5 mm and 26 mm. While for spark discharge, the main channel owns a much stronger light emission intensity and greater discharge volume, which will generate much more heat, ultraviolet radiation, and shock wave intensities than streamer discharges. Therefore, it can be speculated that streamer and spark discharges might contribute differently to sterilization results.

The typical voltage and current waveforms of streamer (27 kV) and spark (35 kV) discharges are plotted in Fig. 3. The streamer current in the experiment is usually in the range of 10–15 A under 27 kV pulsed voltage [Fig. 3(a)]. In sparks, once a highly ionized channel originated from high voltage electrode reaches the ground, the interelectrode resistance will be instantly decreased and the current increases rapidly to roughly 100 A [Fig. 3(b)].

We present the effects of discharge modes on $E. \ coli$ sterilization in Fig. 4. With the aid of discharge regions shown in Fig. 2, we select three typical voltage amplitudes for $E. \ coli$ sterilization as 27 kV (streamer region), 31 kV (streamer-to-spark region), and 35 kV (spark region). Figure 4(a) shows the varying trend of $\log_{10}(N/N_0)$ value vs treatment time, where $N_0$ denotes the number of $E. \ coli$ colony before treatment and $N$ is the number of surviving bacteria in units of colony-forming units per milliliter (CFU/ml). The experimental results show that discharges in the spark region own a much higher sterilization efficiency than in streamer and streamer-to-spark regions. The $\log_{10}$ reduction of $E. \ coli$ reaches 3.5 after 250 s spark discharge treatment, and this value for the streamer-to-spark region is 1.47, while the number of bacterial colonies nearly makes no change for streamer discharge treatments.

The energy efficiency of treatment under three discharge modes is depicted in Fig. 4(b). Note that the spark region, meanwhile, owns the highest energy efficiency, where the energy injection density is nearly 0.5 J/ml, where $\log_{10}$ reduction reaches 3.6. The energy efficiency is close to that reported in other experimental results.

We attempt to unveil some experimental evidence interpreting the mechanisms behind the discharge mode differences on sterilization results via the instantaneous optical images of the streamer and spark discharges, as shown in Fig. 5. For spark discharges [see Fig. 5(a)], the main discharge channel expands rapidly with strong emission of light and heat when reaching the ground electrode.
(the peak current of sparks climbs to over 100 A; streamers only generate roughly 12 A in Fig. 4). The discharge volume and light emission of streamers are much less compared with sparks [see Fig. 5(b)]. Therefore, much stronger heat emission and UV radiation emission during breakdown processes enable sparks to make a greater contribution to E. coli inactivation than streamers. The role of UV radiation in arc discharge treatment has been verified by the experiments in which the introduction of sunscreen, a UV radiation absorber, into E. coli solutions has accordingly caused the suppression of disinfection.\textsuperscript{14,29}

Previous research\textsuperscript{13} has shown that active species created during the discharge treatments also play a role in sterilization. Most of the free radicals in the reactions are produced through a series of vibrational/rotational excitation and the following relaxing processes, as shown in reactions (1)–(3), due to the limited energy of electrons (0.5–5 eV). After a series of recombination reactions governed by (4)–(6),\textsuperscript{12,35} the radicals will finally transform into long lifetime molecules such as H$_2$O$_2$ and O$_2$. Since H$_2$O$_2$ is one of the major active species generated by the recombination of OH radicals, it is an effective indicator of active species involved in the discharge treatment.\textsuperscript{13} Thus, to some degree, evaluating the roles of H$_2$O$_2$ in the sterilization processes can characterize the sterilization efficiency of active species during discharge treatment,

$$\text{H}_2\text{O} + e \rightarrow \text{H}_2\text{O}^* + e, \quad (1)$$

$$\text{H}_2\text{O}^* + \text{H}_2\rightarrow \text{H}_2\cdot + \cdot \text{OH} + \text{H}_2\text{O}, \quad (2)$$

$$\text{H}_2\text{O}^* + \text{H}_2 \rightarrow \text{H}_2 + \cdot \text{OH}, \quad (3)$$

$$\cdot \text{OH} + \cdot \text{OH} \rightarrow \text{H}_2\text{O}_2, \quad (4)$$

$$\text{H}_2\text{O}_2 + \cdot \text{OH} \rightarrow \text{H}_2\text{O} + \text{HO}_2^*, \quad (5)$$

$$\text{HO}_2^* + \cdot \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{O}_2 + \cdot \text{OH}. \quad (6)$$

We measure the H$_2$O$_2$ concentration vs discharge time, as shown in Fig. 5. Note that the H$_2$O$_2$ concentration is measured every 12 min during 60 min discharge treatment as the H$_2$O$_2$ concentration is too low to be quantitatively measured in short period discharge treatments (<150 s). The H$_2$O$_2$ concentration increases with the rise of applied voltage from 27 kV to 31 kV due to the increase in injected energy in the reactor. It is worth mentioning that the concentration of H$_2$O$_2$ decreases when voltage continuously increases to 35 kV. This is mainly because the average per pulse injected energy under 31 kV is higher than 35 kV as considerable energy has been consumed on the wave front resistance R$_f$ (see Fig. 1) in 35 kV spark discharges, instead of generating radicals. It can be noticed from Fig. 6 that the H$_2$O$_2$ concentration under 31 kV is higher than 35 kV, but the corresponding E. coli sterilization efficiency is much lower (see Fig. 4). This indicates that the generation of active species is not the dominant factor responsible for the variance of sterilization results of streamer and spark discharges.

The effect of the pulsed electric field on bacteria sterilization should also be considered during the discharge process. Estifaee et al.\textsuperscript{34} hold that the pulsed electric field plays a dominant role in the underwater corona discharge treatments where they achieve a 3 log reduction of E. coli at the energy cost of around 130 J/ml for 100 $\mu$/cm E. coli samples. The main mechanism for PEF inactivating bacteria is membrane permeabilization, which usually requires energy density in the range of several tens to hundreds J/ml to gain a remarkable sterilization efficiency. While for the experiments in this paper, the input energy density is less than 1 J/ml, PEF can hardly make a significant influence on the sterilization results.

### B. Influence of gas bubbling on E. coli sterilization

For the purpose of further improving the E. coli inactivation results, we introduce gas bubbling in the sterilization treatment of 35 kV spark discharges. Ar and O$_2$ are chosen as the feeding gases. The experimental results are shown in Fig. 7, and it is found that both Ar bubbling and O$_2$ bubbling make positive contribution to the sterilization results. For Ar bubbling, the maximum log$_{10}$ reduction of E. coli reaches 4.3, when the flow rate is 0.6 l/min compared to 3.4 with no gas bubbling. In contrast, discharges with O$_2$ bubbling gain a higher log$_{10}$ reduction, 5.4, at a flow rate of 0.9 l/min after 300 s discharge treatment.
FIG. 7. Sterilization results of E. coli under different 35 kV gas bubbling conditions.

It is also observed that the log reforms shown in Fig. 7 presents a lower decreasing speed after 60 s treatment. This is closely related to the so-called "shield effect." During each discharge, the total number of bacteria in each experiment is constant. After a period of treatment, the dead cells increase and provide a shield for the alive ones. Therefore, the probability that UV emission or active species directly react with alive cells will decrease, hence lowering the sterilization efficiency. The "shield effect" depends on the initial bacterial density. The initial density in our experiment is in the range of (1–5) × 10^6 CFU/ml, and the concentration is in accordance with the previous experimental results, showing that the "shield effect" starts to work. Besides, it is found that the saturation of sterilization under bubbling conditions is not pronounced as that without gas bubbling. A reasonable explanation is that the agitation effect of the treated liquid caused by the gas flow mitigates the "shield effect" and causes a higher reduction rate of bacteria.

Another contributor for the improvement of sterilization is the increase in discharge volume in the presence of gas bubbles. Figure 8 presents the images of discharge in water with and without bubbling Ar in 35 kV spark. From Fig. 8(a), we can find that discharge occurs in the rising Ar bubbles and bubble clusters at the liquid level, while no such phenomenon is observed without gas injection [Fig. 8(b)].

For discharge with Ar bubbling, we measure the H_2O_2 concentration after the discharge and find that the H_2O_2 concentration has little variance compared with no gas bubbling. Thus, the promotion of E. coli inactivation efficiency in discharges with Ar bubbling is more closely linked with physical reactions including agitation of gas and larger volume discharge in bubbles instead of the chemical reactions, which can improve the generation of active species.

However, O_2 could promote the generation of high oxidation potential species (e.g., O, OH, O_3) during discharge processes, as shown in the following reactions:

\[ e^+ + O_2 \rightarrow O(^3P) + O(^1D) + e^- \],
\[ O(^1D) + H_2O \rightarrow 2 \cdot OH \],
\[ O(^3P) + O_2 + M \rightarrow O_3 + M \].

Electron impact dissociation of oxygen molecules can form metastable oxygen atoms as in reaction (7), which are subsequently involved in a series of reactions to create more hydroxyl radicals [reaction (8)] and ozone [reaction (9)]. The increase in these active species will conquer natural defense of bacteria and inactivate DNA, protein, and membrane, which can explain the improvement of sterilization efficiency.

The concentration of H_2O_2 is measured after the discharge treatment with O_2 bubbling, as shown in Fig. 9. The H_2O_2 concentration increases up to 0.19 mmol/l after 60 min discharge treatments compared with 0.13 mmol/l when no gas is injected. The increase in concentration indicates that the bubbling of O_2 effectively promote the generation of other stronger active species to benefit the sterilization results.

FIG. 8. Discharge images in water with/without Ar bubbling conditions: (a) 35 kV spark discharge with Ar bubbling and (b) 35 kV spark discharge without gas flow. The gate width is set as 3 ns and the delay of the ICCD trigger 3 μs for (a) and (b) to avoid overexposure of ICCD.

FIG. 9. H_2O_2 concentration vs treatment time under 35 kV with O_2 bubbling.
IV. CONCLUSION

We investigate the effects of discharge modes on E. coli sterilization. It is found that spark discharges cause a 3.5 log reduction of bacteria after 250 s treatment, and the discharges of the streamer-to-spark reach 1.5 under the same conditions, while streamer discharges can hardly inactivate the E. coli. The experimental results suggest that sparks are of highest sterilization efficiency among the mentioned discharge modes. By means of discharge images and H2O2 concentration measurement during the treatments, larger discharge volume, stronger heat emission, and UV emission during the spark discharges may contribute more to the distinguished sterilization efficiency enhancement compared with streamer discharges.

The results of spark discharges with gas bubbling show that Ar bubbling gains a higher inactivation efficiency (1.7 log) by integration of not only physical interactions, but also chemical reactions, which can jointly increase the production rate of active species.

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REFERENCES

1. C. Wang, Y. Wu, and G. Li, J. Electrost. 66, 71 (2008).
2. T. A. Ternes, J. Stuber, N. Herrmann, D. McDowell, A. Ried, M. Kampmann, and B. Teiser, Water Res. 37, 1976 (2003).
3. J. Kosunen and H. Heinonen-Tanski, Water Res. 39, 1519 (2005).
4. A. Sarani, A. Yu. Nikiforov, and C. Leys, Phys. Plasmas 17, 063504 (2010).
5. H. Xu, D. Liu, W. Xia, C. Chen, W. Wang, Z. Liu, X. Wang, and M. G. Kong, Phys. Plasmas 25, 013520 (2018).
6. W. Tian and M. J. Kushner, J. Phys. D: Appl. Phys. 47, 165201 (2014).
7. C. Winters, V. Petrischek, Z. Yin, W. R. Lempert, and I. V. Adamovich, J. Phys. D: Appl. Phys. 48, 424002 (2015).
8. C. Zheng, Y. Xu, H. Huang, Z. Zhang, Z. Liu, K. Yan, and A. Zhu, Aiche J. 59, 1458 (2013).
9. C. Chen, D. X. Liu, Z. C. Liu, A. J. Yang, H. L. Chen, G. Shama, and M. G. Kong, Plasma Chem. Plasma Process. 34, 403 (2014).
10. M. A. Malik, Plasma Chem. Plasma Process. 30, 21 (2010).
11. Y. Minamitani, S. Shoji, Y. Ohba, and Y. Higashiyama, IEEE Trans. Plasma Sci. 36, 2586 (2008).
12. R. P. Joshi and S. M. Thagard, Plasma Chem. Plasma Process. 33, 17 (2013).
13. J. Wan, J. Coventry, P. Swiergon, P. Sanguansri, and C. Versteeg, Trends Food Sci. Technol. 20, 414 (2009).
14. W. K. Ching, A. J. Colussi, and M. R. Hoffmann, Environ. Sci. Technol. 37, 4901 (2003).
15. Q. Hu, S. Hossain, and R. P. Joshi, J. Phys. D: Appl. Phys. 51, 285403 (2018).
16. R. Xiong, A. Yu. Nikiforov, P. Vanraes, and C. Leys, Phys. Plasmas 19, 023501 (2012).
17. N. M. Efremov, B. Y. Adamiak, V. L. Blochin, S. J. Dadashiev, K. I. Dmitriev, V. N. Semjonov, V. F. Levashov, and V. F. Jusbashev, IEEE Trans. Plasma Sci. 28, 224 (2000).
18. Y. Li, C. Yi, J. Li, R. Yi, and H. Wang, Plasma Sci. Technol. 18, 173 (2016).
19. N. D. Vaze, K. P. Arjunan, M. J. Gallagher, V. N. Vasilets, A. Gutsol, A. Fridman, and S. Anandan, in Proceedings of the 16th IEEE International Pulsed Power Conference (IEEE, 2007), pp. 1231–1235.
20. T. Izedehski, M. Dors, and J. Mizeraczyk, IEEE Trans. Plasma Sci. 39, 953 (2011).
21. L. Marsali, S. Espie, J. G. Anderson, and S. J. Macgregor, Radiat. Phys. Chem. 65, 507 (2002).
22. T. Zhu, Q. Zhang, X. Shi, Z. Li, and L. Yang, IEEE Trans. Plasma Sci. 36, 237 (2008).
23. X. Q. Wen, G. S. Liu, and Z. F. Ding, IEEE Trans. Plasma Sci. 38, 3330 (2010).
24. R. M. Sellers, Analyst 105, 950 (1980).
25. P. Roega, IET Sci. Meas. Technol. 10, 665 (2016).
26. R. Locke, M. Sato, P. Sunka, M. R. Hoffmann, and J. S. Chang, Ind. Eng. Chem. Res. 45, 882 (2006).
27. Y. C. Hong, H. J. Park, B. J. Lee, W. S. Kang, and H. S. Uhm, Phys. Plasmas 17, 053502 (2010).
28. P. G. Rutberg, V. A. Kolikov, V. E. Kurochkin, L. K. Panina, and A. P. Rutberg, IEEE Trans. Plasma Sci. 35, 1111 (2007).
29. W. K. Ching, A. J. Colussi, H. J. Sun, K. H. Nealson, and M. R. Hoffmann, Environ. Sci. Technol. 35, 4139 (2001).
30. P. Estafae, X. Su, S. K. Yannam, S. Rogers, and S. M. Thagard, Sci. Rep. 9, 2326 (2019).
31. Q. Xin, X. Zhang, and L. Lei, Plasma Chem. Plasma Process. 28, 689 (2008).
32. B. Sun, S. Kunitomo, and C. Igashii, J. Phys. D: Appl. Phys. 39, 3814 (2006).
33. B. R. Locke and K. Y. Shih, Plasma Sour. Sci. Technol. 20, 034006 (2011).
34. P. C. Wouters, A. P. Bos, and J. Ueckert, Appl. Environ. Microbiol. 67, 3092 (2001).
35. P. Rossi, O. Kylil, and M. Hasina, Plasma Sour. Poly. 3, 431 (2006).
36. Q. Xin, Z. Li, L. Lei, and B. Yang, Plasma Sci. Technol. 18, 943 (2016).