Inactivation of Bacteria by the Application of Spark Plasma in Produced Water

Hyoungh-Sup Kim^a, Kamau Wright^a, Joshua Piccioni^a, Daniel J. Cho^b, and Young I. Cho^a

^a Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia, PA, 19104 USA

^b A.J. Drexel Plasma Institute, Drexel University, Camden, NJ 08103, USA

ABSTRACT

The objective of the present study was to investigate the effectiveness of spark plasma discharges on the inactivation of acid-producing bacteria (APB) and sulfate-reducing bacteria (SRB) in produced water. Tests were conducted in both static batch mode and once-through flow mode. The residual effect of plasma treatment was assessed by two different protocols: immediate incubation after plasma treatment and incubation after 24-hr storage in a tank post-treatment. In the batch test, 10-min plasma treatment of water showed a total 3-log reduction of APB and 2-log reduction of SRB based on cfu/mL data in the case of clear produced water. In the once-through flow test, 2-log reduction of APB was observed in the case of clear produced water, whereas 1-log to 1.5-log reductions were observed in the case of darkly opaque produced water. The energy efficiency for the once-through flow test with APB for the opaque produced water was 1.7 kJ/L per 1-log reduction. UV radiation together with active plasma species produced by the spark discharge was instrumental in the inactivation of APB and SRB in both clear and dark produced water.

Keywords: MIC, Produced water treatment, APB and SRB, Spark discharge, Coaxial electrode, Bacterial inactivation, and UV radiation

Corresponding Author: Young I. Cho, Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia, Pennsylvania, 19104, USA.

Tel.: +1 215 895 2425, fax: +1 215 895 1478, E-mail address: choyi@drexel.edu

1. Introduction

Microbiologically influenced corrosion (MIC) is common cause of capital equipment depreciation and loss in the oil and gas industry [1]. Pipeline corrosion, reservoir souring, and biofouling caused by microorganisms have been recognized problems for decades and are persistent issues that can also result in higher operating and maintenance costs as well as health risks [2]. This type of corrosion can occur anywhere in the production environment and cause ruptures that seriously impede operations [1]. MIC is mainly caused by two types of bacteria, i.e., sulfate-reducing bacteria (SRB) and acid-producing bacteria (APB). SRB typically reduces the sulfate content in water and produces toxic and flammable hydrogen sulfide (H_2S) using organic acids and hydrogen from decomposing biomass. During these reactions, SRB produces enzymes that remove cathodic hydrogen from steel, which causes rapid pitting of surfaces [3, 4]. On the other hand, APB produces organic acids which can decrease pH to create corrosion on metal surfaces such as pumping components [5].

With the rapid development of shale oil and gas production as an economic driver in the U.S., its extraction through horizontal drilling and hydraulic fracturing is expected to continue to grow [6-9], and the production of produced and flowback water will be significant public and regulatory issues due to the potential risk on the environment, especially the impact of surface water quality [10, 11]. Thus, there is a present need to mitigate MIC and H_2S production in order to enable higher rates of produced water recycling as well as lower costs for beneficial reuse.

Currently, a variety of different physical, chemical, and biological techniques [12, 13] are used to treat produced and flowback water because there are multiple, categorically different treatment targets, including de-oiling, soluble organic removal, disinfection, suspended solid removal, dissolved gas removal, desalination, softening, etc. Since high-voltage (HV) plasma

discharges generate a range of active plasma species such as UV radiation, electric fields and reactive species i.e., ($\cdot\text{OH}$, $\cdot\text{O}$, $^1\text{O}_2$, O_3 , $\cdot\text{HO}_2$, H_2O_2 , NO , NO_2), plasma water treatment has a potential to address multiple treatment targets simultaneously. The present study specifically examined the efficacy of spark plasma discharges on the inactivation of SRB and APB in produced water not only because microbial inactivation is ubiquitous in the treatment of produced water for reuse in fracking but also because bio-decontamination is one of the most promising application areas for plasma in water treatment [14-16]. In general, the inactivation effect has been attributed to the presence of aforementioned active plasma species as well as plasma-generated UV [17-20]. Each of these active species may play a role in the inactivation of microorganisms [18]. Since most of these species, except for ozone (i.e., O_3) and hydrogen peroxide (i.e., H_2O_2) [21-23], have a very short half-life on the order of microseconds or less, the application method of plasma to water should be better understood mechanistically for the best inactivation outcome.

The present study utilized spark discharges in liquid using a pulsed HV power supply, which had a voltage rise time shorter than the Maxwellian relaxation time of the liquid [24, 25]. High electric field strength can usually be achieved by using a needle-tip electrode, from which a strong electric discharge can be discharged. Although the needle-tip electrode is effective in generating short-pulse spark discharges in water, it is prone to thermal erosion due to high temperatures over 2000 K [26, 27]. Thus, there is a need to have more resilient electrode geometry without a sharp needle-tip so that spark plasma system can be operated over an extended period without thermal erosion.

Historically, a spark plasma switch comprised of two needle-shaped electrodes separated by an air-gap has been used to generate short-pulse sparks in liquid. The main advantages of this

traditional spark-gap switch are simplicity and low cost. However, there are disadvantages of the traditional approach, including unstable discharge frequency and the gradual increase in the spark-gap distance over time due to tip erosion [28, 29], requiring periodic adjustment of the gap distance. Because of these limitations, there is a need for a more robust and reliable pulse generation system whose performance does not degrade with time.

Produced water from shale gas production is relatively clear is therefore an ideal candidate for plasma treatment because this type of wastewater permits UV radiation from plasma discharges to penetrate greater than 10-20 cm in radial depth. However, produced water from hydraulic fracturing for crude oil is opaque and sometimes black, where the penetration depth of the UV radiation is often less than 1 cm. In addition, due to a short half-life of most active plasma species, the diffusion distance of these active species except for ozone and hydrogen peroxide is small. Thus, it is essential to have microorganisms in close proximity to the plasma discharge for effective treatments in the case of opaque water from crude oil fracking.

The present study is based on the hypothesis that the inactivation of bacteria in water is mostly by UV radiation and can be accomplished rapidly with high efficiency[30]. In case of relatively transparent water, UV was reported to be effective and energy-efficient in the inactivation of microorganisms, i.e., 0.36 kJ/L [31]. In contrast, for opaque wastewater from shale-oil production, the penetration depth and treatment efficiency of UV is far less. We hypothesize that in such cases, microbiological inactivation by active plasma species other than UV is by direct contact through diffusion.

In consideration of those hypotheses and aforementioned needs, the objectives of the study were to develop a plasma water treatment system for the reliable generation of spark plasma discharges in high-conductivity water and to investigate the effectiveness of spark plasma

treatment on the inactivation of APB and SRB in both clear and opaque produced waters. In addition, the present study investigated the energy cost of spark plasma treatment of produced water, including the residual effect of plasma treatment on the inactivation of microorganisms.

2. Experimental Methods

2.1 Experimental test setup

The present study two different fluid processing approaches for plasma experiments were employed: static batch tests vs. once-through flow tests. In the former, produced water in a reactor vessel is treated continuously without recirculation over a pre-determined duration. Spark discharges generate shock waves that provide mixing within the reactor vessel, however exposure to plasma species of organic content located away from the electrodes may be limited with static batch testing. For once-through flow tests using a pump, the plasma reactor was configured such that produced water and its organic constituents pass in close proximity with plasma discharges, making contact with active species and at the same time being exposed to UV within a distance less than 1 cm. The drawback of the once-through flow test was the shorter duration of plasma exposure (i.e., approximately 2-5 s).

Figure 1 shows the present test setup which was composed of a plasma reactor with coaxial electrode connected to a HV power supply, two water reservoirs (each 56.7 liter), water pump (3/4 hp), flow meter, two flow-control valves, two water sampling ports, and connecting PVC piping (1/2 in. STD pipe). One reservoir (#1 in Fig. 1) was used to store untreated produced water, whereas the other reservoir (#13 in Fig. 1) was to store the water post-treatment. In the case of the once-through dynamic flow test, the water flow rate into the plasma reactor was controlled by adjusting two valves located in the main flow line and bypass line. In case of batch

tests, the plasma reactor was pre-filled with produced water using the pump, which was turned off during the test.

2.2 Coaxial electrode system for the generation of spark plasma discharge in water

Figure 2 shows the plasma reactor and coaxial electrode system used in this study. The plasma reactor was made of transparent PVC pipe (4 in Schedule 80, inside diameter = 97 mm, length = 250 mm), which held 1.8 L of produced water. **Figure 3** shows a schematic drawing of the coaxial electrode system. The coaxial cylindrical electrode consisted of the following components: (1) a negative HV electrode made of a 316 stainless steel acorn nut (Part No. 92994A031, McMaster-Carr) connected to a HV power supply via a long stainless steel extension tube with an inner diameter of 5.3 mm, and (2) an outer cylindrical ground electrode made of 316 stainless steel with an inner diameter of 26.6 mm (1 in STD stainless steel pipe). The two cylindrical electrodes formed a coaxial configuration and were electrically separated by an insulating material (i.e., glass-filled Teflon, Part No. 85275K48, McMaster-Carr) except for the acorn-nut tip having 15-mm length at the end of the HV electrode. The radial gap distance between the tip of the HV electrode and the surrounding ground electrode was 5.5 mm, the distance that provided an optimum electrical resistance for the ignition of spark discharges.

Compressed air was introduced through the inner channel of the HV stainless steel extension tube to the gap space between the tip of the HV electrode and surrounding ground electrode. After experimentally varying the flow rate, airflow of 0.08 L/s was found to be an optimum value for the present study. The airflow rate was controlled and monitored using a flow meter with a control valve.

2.3 Power supply and the characterization of spark discharge

Considering the shortcomings of an air-gap switch employed for spark plasma, an electronic pulse generation system using a thyristor (silicon-controlled rectifier, SCR) was developed to provide the main discharge switch for the generation of spark pulses in high-conductivity water for the present study. **Figure 4** shows the schematic circuit diagram of HV DC power supply, which was designed to produce short-pulse spark discharges in produced water. The power supply consisted of a capacitor-charging HV DC power supply (5 kW, Magna-Power Electronics, Inc., Flemington, NJ), silicon-controlled rectifier (SCR), pulse-forming network (PFN) capacitor and inductor, as well as a current-limiting resistor.

Figure 5 shows voltage and current profiles, which were measured and recorded by a digital phosphor oscilloscope (TDS3014C, Tektronix, Inc., Beaverton, OR). For the measurement of current profiles, a magnetic core current probe was utilized (CM-10-L, Ion Physics Corporation, Fremont, NH), whereas the voltage profile was measured using a HV probe (P6015A, HV Probe 1000X 75 MHz, Tektronix, Inc., Beaverton, OR). Peak-to-peak voltage (U) and current (I) were determined to be 1.7 kV (based on settings of 1.6 V per division $\times$ 1000 for the voltage probe) and 1.2 kA (based on settings of 2.5 A per division $\times$ 10 A/V for the current probe), respectively. The frequency of spark pulses was 8 Hz, a value that was determined from the time period of each pulse of 125 ms measured with the oscilloscope, i.e., $f = 1/T$. The energy of the spark discharge in one pulse was calculated by two different methods:

$$\text{Energy (J per pulse)} = 0.5 CV^2 = 0.5 (16 \mu\text{F}) (4 \text{ kV})^2 = 128 \text{ J/pulse} \quad (1)$$

$$\text{Energy (J per pulse)} = \int U(t) I(t) dt = 80 \text{ J/pulse} \quad (2)$$

The actual value of the spark energy per pulse was expected to be between the two calculated values.

2.4 Measurement of APB and SRB concentrations in pre- and post-treated water

Water samples used in this study were from shale formations explored by hydraulic fracturing to produce natural gas (Springville, PA) and crude oil (Eagle Ford, TX). The produced water from shale-gas appeared transparent, while that from shale-oil production was almost black. Both produced waters were used in static batch tests as well as in once-through flow tests. However, the plasma treatment did not give any positive results in the case of black produced water from shale-oil production in batch test, likely because of the limited penetration depth for UV in dark, opaque wastewater. Accordingly, test results from this case are not included in the paper.

Initial concentrations of APB and SRB varied from 10^3 to 10^7 cfu/mL. The cfu counts were determined using the most probable number (MPN) method as per NACE Standard TM0194-2004 [32]. Total nine tests were performed in batch test mode, and total five tests were conducted in once-through flow mode.

In batch tests, two 100-mL water samples were collected from the plasma reactor before and during the plasma treatment for the measurements of cfu counts at each of the following points: $t = 0, 1, 3, 5, 10$, and 15 min. One of the two water samples was incubated immediately for cfu measurement, while another sample was held for 24 hr prior to incubation so that the residual effect of active plasma species on bacteria inactivation could be examined.

In once-through dynamic flow tests, produced water was recirculated and mixed at the pre-treatment reservoir (#1 in Fig. 1) using the bypass line (#3) for 5 min in order to have a uniform

dispersion of bacteria. At the end of this recirculation period, two 100-mL produced water samples were collected from the reservoir (#1) and the bypass line as control and were incubated for cfu measurements. Then, produced water was pumped through the plasma reactor for a series of experimental tests at three different flow rates (i.e., 0.063, 0.189 and 0.315 L/s). For cfu measurements after plasma treatment, two 100-mL samples were collected from the post-treatment reservoir (#13). A portion (one of two 100-mL bottles collected at each time point) of all water samples were held for 24 hours and incubated for cfu measurement to examine the residual effect of plasma treatment in produced water. After the completion of each test, the entire system was cleaned with 30% bleach solution first, then rinsed thoroughly with tap water four times and dried for the next test.

For the incubation of water samples for cfu measurements of APB, 1-mL water sample was collected using a 3-mL sterile syringe with needle (23 gauge) from 100-mL water sample, which was continuously stirred with vortex mixer (Fisher Scientific: Genie 2). The 1-mL sample was added to the first serial dilution bottle of 9 mL (Phenol Red Dextrose, gold cap, OSP Microcheck Inc.) and each 1-mL collected from subsequent 10-mL diluted samples was transferred to the next dilution bottle. This dilution process was repeated six times sequentially as shown in Figure 6(a). Six loaded Phenol Red Dextrose samples were then incubated at 35 ± 0.5 °C for 14 days. After the 14-day incubation period, the APB concentration was determined in cfu/mL by observing how many vials within the serial dilution had changed color from red to yellow, which indicates a positive reading of APB presence. For example, Figure 6 shows 10^3 cfu/mL for APB.

For SRB assessments, cfu values were determined using SRB check bottles (Modified Postgate's B, red cap, OSP Microcheck Inc.) (see **Fig. 7(a)**), where each 2-mL water sample

from 100-mL water sample was added to bottle, respectively. Then, loaded SRB check bottles were incubated at $35 \pm 0.5^{\circ}\text{C}$ up to 10 days. A positive reading indicating the presence of SRB was shown by a color change from clear to black color in the bottle (see **Fig. 7(b)**). No color change (i.e., liquid remains transparent) indicated a negative reading, i.e., absence of SRB. Color changes were monitored daily from day 1 to day 10, and the cfu/mL value was determined by the duration required for color changes as shown in the chart at Figure 7(c).

3. Results

Figure 8 shows performance results for APB inactivation as a function of plasma treatment time using clear produced water in batch test. The values of cfu/mL were determined for water samples collected at $t = 0, 1, 3, 5, 10$ and 15 min applying two different incubation protocols: immediate incubation and 24-hr delayed incubation to observe the residual effects of active plasma species in produced water.

The log reduction of APB calculated from cfu/mL data increased with plasma treatment time with both incubation protocols. In the case of immediate incubation, spark plasma treatment resulted in 0.7-log reduction for one-min treatment and 2.5-log reduction for 15-min treatment. On the other hand, for 24-hr delayed incubation, spark plasma treatment resulted in 1-log reduction for one-min treatment and 3-log reduction for 10-min treatment. Delaying incubation for 24-hr yielded improved bio-decontamination performance over immediate incubation.

Figure 9 shows SRB inactivation results versus plasma treatment time obtained using clear produced water in static batch tests. Treatment of produced water for 1 min did not demonstrate detectable reductions in SRB. However, plasma treatment began to show observable reductions in SRB at 3-min or longer treatment durations, and SRB inactivation performance increased with treatment time using both incubation protocols. In the case of immediate incubation, plasma

caused a 0.3 ± 0.2 log reduction for 3-min treatment, 0.7 ± 0.5 log reduction for 5-min treatment, and 1.2 ± 0.2 log reduction in colony-forming units per mL water for 10-min treatment. On the other hand, after a 24-h delayed incubation, plasma treatment resulted in a 0.7 ± 0.3 log reduction for 3-min treatment, 1 ± 0.5 log reduction for 5-min treatment, and 2 ± 0.01 log reduction for 10-min treatment—a nearly twofold performance increase over immediate incubation.

Energy efficiency for the inactivation of bacteria using plasma treatment was determined using the D-value (kJ/L per 1-log reduction) calculated from the energy per pulse, frequency of pulses, treatment time, and the volume of water (i.e., 1.8 L) as described in the following equation:

$$\text{Energy cost (kJ/L)} = (E_d/\text{pulse}) \times 8 \text{ Hz} \times \text{treatment time (min)} \times 60 \text{ s} / 1.8 \text{ L} \quad (3)$$

Figure 10 presents the energy costs for APB and SRB inactivation as a function of plasma treatment time using clear produced water for both incubation protocols. With immediate incubation, the energy cost for the inactivation of SRB was approximately 3.6 times greater than that for the inactivation of APB. The energy costs after 24-delayed incubation were consistently lower, by approximately one-half, for both APB and SRB compared to those obtained after the immediate incubation. Note that plasma treatment of dark produced water in static batch mode tests did not reduce cfu/mL for both APB and SRB.

Figure 11 presents APB inactivation results after 24-hr delayed incubation with plasma treatment in once-through dynamic flow tests for both clear and dark produced water. The tests with clear water were conducted with an initial APB concentration of 10^7 cfu/mL, whereas the

tests with dark produced water were conducted with an initial APB concentration of 10^4 cfu/mL. The difference in the initial APB concentrations was due to baseline differences in the two produced water samples from two different locations. In tests with clear produced water, two different flow rates of 0.063 and 0.189 L/s were used, while in the tests with dark produced water, three different flow rates of 0.063, 0.189 and 0.315 L/s were used. Incubation of clear water samples was repeated three times, delivering a 2 ± 1 log reduction in APB concentration after plasma treatment for two flow rates of 0.063 and 0.189 L/s after 24-hr delayed incubation. The energy costs corresponding to 0.063 and 0.189 L/s cases with clear water samples were 5.1 and 1.7 kJ/L/1-log reduction, respectively, see Figure 12.

In the case of dark produced water with initial APB concentration of 10^4 cfu/mL, 1-log reduction was observed at flow rate of 0.063 L/s with an energy cost of 10.1 kJ/L/1-log reduction. In the case of 0.189 L/s, a 0.7-log average reduction was observed at an energy cost of 4.8 kJ/L/1-log reduction. For a flow rate of 0.315 L/s with initial APB concentration of 10^5 cfu/mL, a 1.3-log average reduction was observed with an energy cost of 1.7 kJ/L/1-log reduction, see Figure 12.

It is noted, however, that the SRB concentrations remained unchanged in once-through flow tests, maintaining their initial values of 10^4 cfu/mL. Hence, the energy efficiencies for plasma treatment were reported based on APB reductions. In general, at higher flow rates, the energy cost for each 1-log reduction in APB was reduced in once-through flow tests. It was also shown that APB inactivation was more efficient in clear produced water, a fact that may be attributable to more effective UV irradiance in clear water, as opposed to dark, opaque water.

In addition, pH and ORP (oxidation reduction potential) in pre- and post-plasma treated water were measured, but there was no significant change in either pH and ORP with plasma even after 15 min of treatment in static batch tests.

4. Discussion

The experimental results in the present study provided supporting data for the validation of spark treatment of produced water. Specifically, the effectiveness of spark plasma discharge with its active plasma species and UV radiation was demonstrated for the inactivation of APB and SRB in produced water. Although plasma treatment effectively inactivated APB and SRB in both clear and dark produced water in once-through dynamic flow test mode, and the plasma treatment of clear produced water in the static batch mode also effectively reduced the cfu/mL levels, plasma treatment of dark produced water in static batch mode did not yield reductions in cfu/mL levels for both APB and SRB cases. The fact that plasma treatment of dark produced water did not deliver successful bio-decontamination in static batch mode but worked well in once-through dynamic flow tests strongly suggests that plasma treatment of dark produced water requires closer proximity between microbiological content with spark plasma discharges for effective inactivation.

The study also demonstrated the residual effect of plasma treatment on bacterial inactivation. The energy cost for 1-log reduction of APB for both clear and dark produced water in the present study was 1.5 kJ/L at a flow rate range of 0.063 – 0.315 L/s in once-through flow tests (i.e., see Fig. 12). Note that energy efficiencies for the inactivation of bacteria in clear water previously reported ranged from 3.3 to 33.3 kJ/L for 1-log reduction, depending on types of plasma used, for example, corona, capillary discharge and dielectric barrier discharge (DBD) [33-35], and 0.34 kJ/L for 1-log reduction for pulsed spark discharge [36].

Comparing the energy cost from the present study with the values reported in previous studies, the pulsed spark discharges used in the present study can be considered as one of the most energy-efficient plasma techniques for water treatment. Note that the energy cost in previous studies were obtained primarily in tests using *E. Coli* bacteria added to relatively clean water volumes (i.e., distilled water or saline solutions) in order to provide bacterial with a stable environment. In contrast, the present study focused on the inactivation of APB and SRB, which are considered to be more resilient than *E. Coli*, in volumes of actual produced water. Furthermore, the analyses of produced water, comparing pre- and post-plasma treatment water samples, was more complicated than in prior bio-decontamination studies using plasma because produced water also contained biological and chemical contaminants such as organics other than APB and SRB, fracking additives, elevated levels of metals (i.e., calcium, magnesium, barium, strontium, etc.), dissolved solids, and radionuclides that occur naturally in deep ground waters. Produced water can also include lead, ethylene glycol, diesel, and formaldehyde, as well as benzene, toluene, ethyl-benzene, and xylene (BTEX) compounds [7, 9, 37-39]. Spark plasma energy may have been consumed to oxidize and dissociate some of these materials, generating additional treatment benefits, which were not monitored in this study.

In terms of mechanisms of action, UV radiation generated from spark discharge may have played a pivotal role in the inactivation of APB and SRB in produced water. The energy cost of plasma treatment for APB was much lower in transparent produced water than in opaque water samples, thereby permitting UV radiation to penetrate deeper in the clear water samples.

The results of the present study showed that spark plasma treatment in once-through dynamic flow tests yield more energy-efficient performance for bio-decontamination than static batch tests. This difference could have been a result of greater uniformity of mixing, closer

proximity between active plasma species and their treatment targets, resulting in more efficient APB inactivation. Accordingly, the present study indicated that the energy cost for 1-log reduction of APB for both clear and dark produced water improved (i.e., decreased) as the flow rate increased. This can be attributed to the fact that active plasma species produced by the spark discharge could be better dispersed throughout the entire volume of produced water at a higher flow rate, leading to more efficient inactivation.

The effects of active plasma species on the APB and SRB inactivation can be illustrated by the test results in the static batch mode comparing immediate incubation with 24-hr delayed incubation after the completion of the plasma treatment. The reductions in cfu/mL levels for APB and SRB show that the residual effect of active plasma species diffusing within the post-treatment holding tank provided further inactivation during the 24-hr residual period. Biological inactivation by active plasma species from the plasma-liquid interaction was validated by a number of prior studies. These reports show that thermal and non-thermal discharges of ionized gases can generate active plasma species such as OH, O, O₂^{*}, H₂O₂ and NO_x which are effective as antibiotics and as strong oxidizers as explained in chemical reactions (1) to (9) below [17-20, 40].

These reactions occur with the dissociation of water molecules at the plasma-water interface. When air is the carrier gas, nitrogen oxides are formed from gas-phase reactions of dissociated nitrogen and oxygen [41-47].

Additionally, the plasma-liquid interaction likely generated other oxidizing species such as hypochlorous acid (HOCl) [48, 49] working as biocides as described in reactions (11) to (13) because of the higher concentrations of Cl^- and NaCl in produced water [37]. Ozone (O_3) in reaction (12) was almost certainly produced as well from plasma-gas-phase discharge [20, 48].

Plasma treatment of water can also induce oxidation of Fe^{2+} into $\text{Fe}(\text{OH})_2$ and $\text{Fe}(\text{OH})_3$ which assist in the coagulation and flocculation [20, 50, 51] of the bacteria and solids in produced water as shown in the reactions from (14) to (16) [37].

However, the present study did not specifically monitor any of these active plasma species. Based on the results of this work, it is not clear which species contributed mechanistically to bacterial inactivation nor how much of each species were generated by the spark plasma system used herein.

5. Conclusions

The present study investigated the effect of pulsed spark discharges on the inactivation of both clean and dark produced waters. Spark treatment tests in both batch and once-through flow modes were performed, and the reduction in cfu/mL of APB and SRB were evaluated. UV radiation together with active plasma species produced by the spark discharge was instrumental in the inactivation of APB and SRB in both clear and dark produced water. Residual effects of active plasma species were found to improve the inactivation process of bacteria in produced water. 10-min plasma treatment using spark discharges could inactivate APB and SRB by 3-log and 2-log reductions, respectively, from the initial concentration in the batch test. The spark treatment in once-through flow test showed more efficient inactivation results in terms of the energy cost for 1-log reduction than in batch test.

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Fig. 1. Schematic diagram of the present test setup in the dynamic once-through flow mode; 1- Water reservoir (pre-treatment), 2- Water pump (3/4 hp), 3- Bypass flow line for flow rate control, 4- Water flow meter (Max. 0.63 L/s), 5- Pre-treatment water sampling port, 6- Spark plasma reactor vessel, 7- Coaxial spark electrode, 8- HV Spark power supply, 9- Air injection flow meter, 10- Plasma-treated water line, 11- Post-treatment water sampling port, 12- Reactor drain, 13- Water reservoir (post-treatment)

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(unit: mm)

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hrs after PT = incubation 24 hours after the completion of plasma treatment

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dark produced water.

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(c)

Interpretation of color change	
Days to turn positive	SRB (cfu/mL)
1 - 2	10,000 +
2 - 4	1,000 - 10,000
4 - 6	100 - 1,000
6 - 8	10 - 100
8 - 10	1 - 10
10 +	Negative

Figure 8
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