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Inactivation of bacteria by the application of spark plasma in produced water

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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-h 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.

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., ($^{\cdot}OH$, $^{\cdot}O$, $^{1}O_2$, O_3, $^{\cdot}HO_2$, 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

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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).

Fig. 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 L), 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

Fig. 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. Fig. 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. Fig. 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,