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Self-cleaning filtration with spark discharge in produced water

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ABSTRACT

The objective of the present study was to investigate the feasibility of using spark type plasma discharges to provide a self-cleaning effect for filtration of produced water. A new co-axial electrode system was developed for the generation of spark discharges in high-conductivity produced water. The validation experiment was conducted with the spark-assisted self-cleaning (SASC) filtration system in both synthetic produced water and actual produced water at different total dissolved solids (TDS) and total suspended solids (TSS) levels and at three different flow rates of 0.126, 0.315, and 0.631 L/s (i.e., 2, 5 and 10 gpm). The pressure drop across the filter surface was measured over time. The pressure drop obtained without spark discharges increased consistently over time, often resulting in pump failure due to excessive pressure buildup at the pump. The pressure drop obtained with spark discharges was significantly smaller than those obtained without spark discharges. The present study sufficiently demonstrated the validity of the SASC filtration concept. The range of water properties that were shown to be treatable with the SASC filtration system using 10-in cartridge filter of 3- and 5-micron pores was TDS level $\leqslant$50,000 mg/L and TSS level $\leqslant$2500 mg/L.

1. Introduction

Produced water is a form of wastewater produced from the hydraulic fracturing of shale formations for the extraction of natural gas and oil. Produced water contains not only fracking additives but also elevated levels of metals (e.g., calcium, magnesium, barium, strontium, etc.), dissolved solids in brine, organics, and radionuclides that occur naturally in deep ground waters [1,2]. In addition, produced water can also include lead, ethylene glycol, diesel, and formaldehyde, as well as benzene, toluene, ethyl-benzene, and xylene (i.e., BTEX) compounds.

Natural gas is considered a relatively clean energy source because its combustion process produces much smaller amounts of harmful emissions (i.e., carbon dioxide, nitrogen oxide and sulfur oxide) than either combustion of coal or oil [3]. Particularly, natural gas from shale in the U.S. is now widely viewed as a key element for fundamental economic growth. Accordingly, its extraction through horizontal drilling and hydraulic fracturing is expected to continue to grow in the U.S. [2,4–6]. Future increases in drilling and fracking activity will be paralleled with subsequent increases in produced water volumes. Accordingly, the rapid growth of shale-gas and shale-oil extraction in recent years has drawn significant public and regulatory concerns to the potential environmental risks, especially the impact on surface water quality [7,8].

Currently, produced water is treated through a variety of different physical, chemical, and biological methods. Since there are multiple needs that should be addressed in the treatment of produced water, a number of different methodologies are used [1,9]: activated carbon, various forms of filtration (such as sand filters, cartridge filters, multi-media filtration, and membrane filtration), organic-clay absorbers, chemical oxidation, UV disinfection, chemical biocides, air strippers, chemical precipitation, water-softening by applying lime soda, clarifiers, settling ponds, ion exchange, reverse osmosis, evaporation, steam stripping, and acidification. In nearly all of the above cases, each modality of technology can hit a single target, i.e., each process has application to a limited number of basic functions [1,9]. No single technology can meet all of the treatment requirements for produced water such as surface discharge, reuse in the formation process, and other beneficial use by de-oiling, soluble organics removal, disinfection, removal of suspended particles, softening and NORM (naturally occurring radioactive materials) removal.

The present study utilized high-voltage (HV) plasma discharges for the treatment of produced water. The application of strong electric fields in water has been studied for many years as such fields can create plasma discharges that initiate a range of chemical

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Nomenclature

C	electrical capacitance	Hz	frequency
F	unit of electrical capacitance (=C/V)	U	peak to peak voltage
V	electric potential	I	peak to peak current
J	energy of spark discharge	$U(t)$	voltage profile
A	electric current	$I(t)$	current profile

and physical water treatment processes. For example, plasma discharges in water produce UV radiation, strong electric fields, focal areas of high temperature over 2000 K, various reactive species ($^{\cdot}$OH, $^{\cdot}$O, $^1O_2$, O_3, $^{\cdot}HO_2$, H_2O_2, NO, NO_2) and charged particles [10,11]. These plasma products are useful in the degradation of organic compounds, the destruction of bacteria, the oxidation of inorganic ions and organic matter, and mineral fouling (scaling) prevention [12–14]. Because plasma has the effect of creating multiple plasma products, plasma discharges have the potential to address multiple treatment requirements for produced water simultaneously.

Inactivation of microorganisms is one of the most important goals in produced water treatment. Pulsed plasma has been previously reported to be a potential solution to meet the target of microbial inactivation in cost-effective and environmentally friendly manner [13,15]. There are two main approaches for using HV pulse plasma discharges for water sterilization, depending on the amount of energy deposited to water: one is to use high-energy pulsed arc-type discharges of $\geqslant 1$ kJ/pulse [13,16], and the other is to use low-energy corona-type pulses of ~ 1 J/pulse [13,15].

Among the aforementioned multiple plasma products, the present study focused on the utilization of shock waves generated by short-pulse spark discharges to a filtration media. In the vast majority of filtration technologies, the pressure drop across the filter surface gradually increases or the flow rate gradually decreases over time. In other words, the accumulation of suspended particles on the filter surface reduces filter performance. Accordingly, the filter cartridge, media or membrane should be replaced frequently, a process that is prohibitively expensive in most industrial water applications. To overcome the drawbacks of the frequent filter replacement, a backwash process is often used in wastewater treatment, reversing the direction of flow during the cleaning phase using clean filtered or fresh makeup water [17–20]. However, as the volume of water increases, the backwash operation itself can become cost-prohibitive and impractical.

The present study attempted to utilize HV spark discharges in order to keep cartridge filter surfaces clean. When a HV spark discharge is created between two submerged electrodes in water, a thermal plasma channel is formed, producing intense shockwaves [10] in addition to the aforementioned plasma products which are useful in the water treatment [12,13,21].

In order to generate spark discharges in liquid, a pulsed HV power supply is needed having voltage rise times shorter than the Maxwellian relaxation time of the liquid [14,22]. High electric field strength can usually be achieved by using a needle-shaped electrode, from which a strong electric discharge usually initiates. Although the needle-shaped electrode is useful in generating short-pulse spark discharges in water, such an electrode configuration is prone to the erosion due to high temperature of spark [23,24], and thus, the short lifetime of the needle electrode is a major drawback [25,26].

Historically, an air spark-gap switch made of two needle-shaped electrodes separated by a gap has been used to allow short-pulse sparks to discharge in liquid. The main advantages of this traditional spark-gap switch are simplicity and low cost. However, there are disadvantages of the traditional approach: (1) discharge frequency is not stable; (2) the spark-gap distance gradually increases with time due to electrode erosion [25,26], requiring periodic adjustment of the gap distance. Hence, there is a need to have an improved pulse generation switch whose performance does not degrade with time.

In the case of the needle-and-plate electrode geometry, the ground plate electrode used as the cathode often develops what is called “cathodic hot spot”, resulting in thermal erosion at a single focal point which grows over time [27]. For example, our previous study used a stainless steel mesh cartridge filter as the ground electrode, while a HV electrode (anode) was installed through the sidewall of filter housing to generate short-pulse spark discharges in cooling water, as shown in Fig. 1(a) [28]. The distance between the HV needle electrode and the filter surface was approximately 3 mm to ensure stable generation of spark discharges. The shock waves generated by spark discharge were strong enough to prevent suspended solids from being accumulated on the filter surface [22,28,29]. However, a hole was found on the outer surface of stainless steel filter surface at the end of test, as shown in Fig. 1(b). The stainless steel filter surface was damaged due to the intense local heat (i.e., cathodic hot spot) generated by spark discharges [10,27].

Through our prior studies, we recognized a need to develop a new electrode system that could generate spark discharges in water without the development of a cathodic hot spot or the erosion problem. The objectives of the present study were to introduce a new co-axial electrode configuration and an electronic pulse generator so that the aforementioned problems associated with the generation of spark discharges could be solved and also to investigate the validity of a spark-assisted self-cleaning (SASC) filtration system through experimental tests.

2. Experimental methods

2.1. Experimental test setup

Fig. 2 shows the experimental test setup, which consisted of a reservoir tank, a centrifugal pump, a flow meter with a flow-control valve, a stainless steel cartridge filter (see #6 in Fig. 2) with pore size of either 3 or 5 microns, and a filter housing. A co-axial electrode (see #5 in Fig. 2) that was connected to a HV power supply and pulse generator was installed vertically at the top of the filter housing (see #9 in Fig 2). The pressure drop across the filter surface was measured over time with both digital and analog pressure sensors, which were installed at the inlet and outlet of the filter housing. The pressure at the outlet (post-filtration) was measured by an analog gauge and found to be consistently zero Pa during tests. The inlet pressure (pre-filtration) was measured with both an analog gage (see #16 in Fig. 2) and a digital pressure transducer (see #15 in Fig. 2) (Omega, PX409-100GUSBH: range 0–690 kPa) installed in the same pipeline prior to the filter.

The entire test system was flushed thoroughly with tap water after each test. In the tests with spark discharges using synthetic and actual produced waters, the digital pressure transducer could