Self-cleaning filtration with spark discharge in produced water

Hyoungh-Sup Kim^a, Kamau Wright^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 (194 words)

The objective of the present study was to investigate the feasibility of using spark type plasma discharges as a self-cleaning mechanism for filtration in 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 $\leq$ 50,000 mg/L and TSS level $\leq$ 2,500 mg/L.

Key Words: Spark discharge, plasma water treatment, self-cleaning filter, water treatment, pressure drop, and filtration.

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

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

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 and physical water treatment processes. For example, plasma discharges in water produce UV radiation, strong electric fields, focal areas of high temperature over 2000K, various reactive species ($\cdot\text{OH}$, $\cdot\text{O}$, $^1\text{O}_2$, O_3 , $\cdot\text{HO}_2$, 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 ≥ 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 not be used because the propagation of electric pulses from the HV electrode via high-conductivity water interrupted the data acquisition activity in the pressure transducer. For those cases, the variations in an analog pressure gage (see #16 in Fig. 2) installed at the inlet of the filter were recorded with a video camera during the tests, and the pressure over time was analyzed later. The pressure measurements with the digital pressure transducer were calibrated with the analog pressure gauge.

2.2. Co-axial electrode system

Fig. 3(left) shows the schematic drawing of the co-axial electrode configuration, and Fig. 3(right) shows the electrode assembly installed vertically in a filter housing. The co-axial cylindrical electrode consisted of the following components: (1) a negative HV electrode made of a 316 stainless steel acorn nut (see #2 in Fig. 3) (Part No. 92994A007, McMaster-Carr) connected to a HV power supply via a long stainless steel extension tube (see #3 in Fig. 3) with an inner diameter of 1.4 mm, and (2) an outer cylindrical ground electrode (see #1 in Fig. 3) made of 316 stainless steel with an inner diameter of 15.8 mm. The two cylindrical electrodes formed a co-axial configuration and were electrically separated by an insulating material (see #4 in Fig. 3) (i.e., glass-filled Teflon, Part No. 8546K14, McMaster-Carr) except for the acorn-nut tip having 5-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 which was submerged in highly conductive water was 4.5 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 (see #3 in Fig. 3) to the gap space between the tip of the HV electrode and surrounding ground electrode. After experimentally varying compressed air flow rates, airflow of 2.4 liter per min was found to be the optimum value for the present study. At this airflow rate, stable spark discharges could be ignited and sustained relatively easily. The airflow rate was controlled and monitored using a flow meter with a control valve (see #18 in Fig. 2).

The co-axial electrode system was installed vertically at the top of the horizontally positioned filter housing (see #9 in Fig. 2) so that compressed air would remain in the gap space between the two electrodes and create an air pocket, thereby enabling stable generation of spark

discharges in water. The filter housing was made of transparent PVC pipe (4 in, Schedule 80, inside diameter = 97.0 mm and length: 330.0 mm) for visual observation purposes, which held a 10-in long stainless steel cartridge filter (outside diameter of 63.5 mm, length of 254.0 mm). Two different pore size filters of 3 and 5 microns were used in the study.

When test water entered the filter housing, water moved inwardly across the filter surface (see #6 in Fig. 3) in the radial direction (i.e., from outside to inside). Hence, particles greater than the pore size were accumulated on the filter surface. As spark discharges generated strong shock waves, impacting the outside filter surface, the accumulated particles were pushed away from the filter surface. Accordingly, the dislodged particles fell downward by gravity, falling down into a particle storage tank (see #7 in Fig. 3) located at the bottom of the filter housing and drained periodically with a solenoid valve such that the particles were removed from circulation. As described above, since compressed air was continuously injected to the gap between the two electrodes for generating spark discharges, an air vent (see #8 in Fig. 3) was installed at the top of the filter housing. The air vent was opened slightly during experimental tests to permit compressed air but not water to escape from the filter housing. Since the flow rate of air injection to the electrode was very small, i.e., 0.04 L/s, the air inside the housing was removed stably through the vent during the experiment. Under normal operating conditions water did not escape through the vent.

2.3. Power supply and the characterization of spark discharges

Considering the shortcomings of an air spark-gap switch, 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 in the present

study. Fig. 4 shows the schematic circuit diagram of a HV power supply, which was designed to produce short-pulse spark discharges in produced water. The power supply consisted of a capacitor-charging HV direct-current (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.

Fig. 5 shows voltage and current profiles produced by the DC HV spark power supply, 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 HV pulses was 8 Hz, a value that was determined from time period of each pulse of 125 ms measured with 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 should be between the two calculated values.

2.4. Preparation of synthetic produced water

A series of experiments was conducted with synthetic produced water and actual produced water. To simulate produced water with similar total dissolved solids (TDS) and total suspended solids (TSS), synthetic produced water was made by adding calcium chloride (CaCl_2), sodium carbonate (Na_2CO_3), and NaCl into municipal tap water (Camden, NJ) in the proportions shown in Table 1. The reaction among the chemicals can be shown as:

In order to prepare synthetic produced water with a high TSS, the reservoir was first filled with tap water at a total volume of 15 gal, CaCl_2 powder was then added to the reservoir, and the water was continuously circulated through a bypass line for 3 min for mixing. Next, Na_2CO_3 powder was added to the reservoir, and the water was again circulated through a bypass line for another 3 min for mixing. Then, 100 mL of water sample was taken out from the sampling port-1 (see #13 in Fig. 2) for water chemistry measurements. For higher TDS water cases, NaCl was added to the reservoir containing dissolved CaCl_2 and Na_2CO_3 . After NaCl was added, the solution was circulated for another 3 min, and then, 100 mL of water sample was taken out from the sampling port-1 for water chemistry measurements. This solution was employed for experimental tests as synthetic water having comparable electric conductivity levels as produced water.

3. Results

Fig. 6 shows four photographs of spark discharges in a transparent plasma reactor taken during the propagation of spark discharges produced by the co-axial electrode submerged in synthetic produced water. Since the pulse duration (full width at half maximum) of spark discharges was relatively short (i.e., $\sim 22 \mu\text{s}$, see Fig. 5), multiple photographs were taken, showing the transient nature of spark discharges. Because the synthetic produced water was relatively transparent, the UV radiation from the spark discharge propagated outwardly from the co-axial electrode through the water of low turbidity [30], illuminating the volume inside the plasma reactor. In such transparent water samples, the UV radiation can work as a predominant mechanism when this spark discharge applies to the disinfection of water.

For validation tests using this SASC filtration system, the pressure drop across the filter surface was measured both for synthetic produced water and for actual produced water by varying flow rates, TDS, TSS, and the pore size of filter. All baseline tests were performed without spark discharges. For baseline tests, the pressure drop across the filter surface eventually reached either an asymptotic level or a point of pump failure due to excessive increase in the pressure drop when operating at higher flow rate and higher TSS and TDS levels. After each test, the test setup was thoroughly cleaned with tap water, and new synthetic produced water was prepared according to the aforementioned procedure. Then, spark discharges were applied, and the pressure drop was measured across the filter surface over time.

Fig. 7 shows the variations in pressure drop across the stainless steel filter surface in synthetic produced water with 3,000-ppm TDS and 2,500-ppm TSS. The pressure drop data obtained in the baseline test (i.e., no spark) are shown in open symbols, whereas those obtained with spark are shown in half-closed symbols. The pressure drop data from the baseline tests (see

curves marked as 1, 3, and 5 in Fig. 7) showed sudden increases during the first minute of the experimental test runs with both 3- and 5-micron pore size filters. Particularly, in the two baseline tests (see curve #3: 5 gpm + 5- μ m pore filter and curve #5: 10 gpm + 3- μ m pore filter in Fig. 7), pressure drops continued to increase to levels that forced the pump to fail as indicated by “PF” at the end of the curves. For example, in the baseline test described by curve #3 in Fig. 7, the main flow pump failed after 9 min due to excessive pressure build-up caused by severe particle accumulation at the filter surface, whereas the baseline test described by curve #5 in Fig. 7 failed after only 30 s. In the baseline test shown as curve #1 in Fig. 7 (2 gpm + 5- μ m pore filter), pressure drop gradually increased over time, reaching an asymptotic value of 186 kPa at 25 min without pump failure.

In the experimental tests with spark employed to clean the filter cartridge, variations in the pressure drops across the filter surface were much lower than those in the baseline test. In the cases with 5-micron pore filter (see curves #2 and #4 in Fig. 7), the pressure drop data did not increase over time. Rather, the initial pressure drops corresponding to a clean filter at both 2 and 5-gpm flow rates were maintained until the end of the test runs without pump failure. The pressure drop for curve #4 in Fig. 7 was slightly greater than that for curve #2 because of the higher flow rate used. In the cases using 3-micron pore filter at 10-gpm flow rate (see curve #6 in Fig. 7), the pressure drop across the filter initially increased to a high value of approximately 205 kPa within the first 2 min but then began to level off, gradually increasing to 220 kPa at $t = 13$ min, when the pump failed.

Fig. 8 shows photographs of mesh surfaces of the 5-micron stainless steel filter after filtration tests with synthetic produced water of 3,000-ppm TDS and 2,500-ppm TSS at two different flow rates of 2 and 5 gpm. For comparison, the photographs of the clean filter surfaces before the tests

are also shown on the left panels. The photographs in the middle panels (i.e., baseline tests) show the white-powder (i.e., CaCO_3 particles) accumulated on the filter surface. A small hole in the middle of each photograph was created by the compressed air coming out of the co-axial cylindrical electrode during the test. Note that the compressed air was also injected in the test without spark to standardize test procedures and also to prevent water from flowing back into the HV electrode channel, thus keeping the HV electrode dry. The photographs in the right panels show relatively cleaner filter surfaces at the end of the test with spark discharges.

Fig. 9 shows the variations in pressure drops across filter surfaces in synthetic produced water with 10,000-ppm TDS and 1,250-ppm TSS. The pressure drop data from the baseline tests marked as curves 3 and 5 in Fig. 9 show sudden increases to 300 kPa immediately after start of the test. The main flow pump failed after 4 min in the case of curve #3 in Fig. 9 (5 gpm + 5- μm pore size), whereas it failed after 30 s in the case of curve #5 (10 gpm + 3- μm pore size) due to higher pressure built-up on the filter surface caused by high flow rate. In both baseline tests shown as curves #3 and #5 in Fig. 9, severe particle accumulations were observed on the filter surfaces, resulting in early pump failures. In the baseline test shown in curve #1 (2 gpm + 5- μm pore filter), the pressure drop also increased rapidly during the first 2 min but leveled off after that, gradually increasing over time during the next 33 min and reaching an asymptotic value of 150 kPa at $t = 35$ min. The sudden jump in the pressure drop observed at $t = 27$ min was due to a manual flow rate adjustment, which was done to maintain the constant flow rate during the test.

In the tests with spark, variations in the pressure drops across the filter surface were much lower than those in the baseline test. In the case with 2 gpm + 5-micron pore (see curve #2 in Fig. 9), the pressure drop gradually increased over time, reaching an asymptotic value of 75 kPa. In the case with 5 gpm + 5-micron pore (see curve #4 in Fig. 9), the pressure drop initially

increased rapidly but leveled off, reaching a value of 255 kPa due to the high flow rate but without pump failure. In the case with 10 gpm + 3-micron pore (see curve #6 in Fig. 9), the pressure drop across filter surface initially increased rapidly. Although the pressure drop across filter surface was much less when compared to that obtained during the baseline test, the pump eventually failed at $t = 9$ min due to the relatively high flow rate of 10 gpm.

Fig. 10 shows the variations in pressure drop across the 5-micron filter surface in synthetic produced water with 10,000-ppm TDS and 2,500-ppm TSS at two different flow rates of 2 gpm and 5 gpm. The pressure drop from the baseline test shown as curve #1 in Fig. 10 (i.e., 2 gpm) consistently increased over time, reaching 155 kPa at $t = 26$ min without pump failure, whereas the pressure drop obtained with spark discharges increased to 45 kPa at $t = 27$ min also without pump failure, a significantly smaller value than that obtained without spark discharges. The pressure drop from the baseline test shown as curve #3 in Fig. 10 (i.e., 5 gpm) increased rapidly, reaching 290 kPa after less than 3 min, resulting in pump failure, whereas the pressure drop obtained with spark discharges consistently increased (see curve #4 in Fig. 10), reaching 255 kPa at $t = 13$ min, a much smaller value compared to that obtained without spark discharges.

Fig. 11 shows the variations in pressure drop across the 5-micron filter surface in synthetic produced water with 50,000-ppm TDS and 2,500-ppm TSS at two different flow rates of 2 gpm and 5 gpm. The pressure drop from the baseline test shown as curve #1 in Fig. 11 (i.e., 2 gpm) consistently increased over time, reaching 300 kPa at $t = 14$ min with pump failure, whereas the pressure drop obtained with spark discharges shown as curve #2 could maintain the initial value of 13 kPa throughout the entire test duration without pump failure, a significant achievement by the spark discharge. The pressure drop in the baseline test shown as curve #3 in Fig. 11 (i.e., 5 gpm) rapidly increased after start, reaching 300 kPa after in less than 2 min, resulting in pump

failure, whereas the pressure drop obtained with spark discharges consistently increased, reaching 280 kPa at $t = 6$ min also with pump failure.

Fig. 12 shows the variations in pressure drop across the 5-micron filter in actual produced water with 50,000-ppm TDS at a flow rate of 2 gpm. The pressure drop obtained without spark shown in as curve #1 in Fig. 12 rapidly rose to a value of 325 kPa in 30 s with immediate pump failure, whereas those obtained with spark shown in curve #2 increased to 150 kPa at $t = 15$ min and then over the next 55 min, increased to 190 kPa without pump failure, a remarkable achievement obtained with spark discharges.

Fig. 13 shows photographs of the mesh surfaces of 5-micron stainless steel filter after filtration tests with actual produced water of 50,000-ppm TDS at a flow rate of 2 gpm. For comparison, the photograph of the filter surface before the tests is shown in the left panel. The photograph in the middle panel obtained without spark shows the filter surface with a large number of tiny spots (staining caused by filtered hydrocarbons), resulting in immediate pump failure after 30 s. The photograph in the right panel obtained with spark shows a similar looking filter surface, but with a large number of slightly bigger particles (staining caused by hydrocarbons and deposition of coagulated particles) than those from the baseline test. In particular, the filter surface near the co-axial electrode system, where the benefit of the spark cleaning effect should be at the maximum level, appears visually to be cleaner than the rest of the filter surface (see the photograph in the right panel in Fig.13), suggesting that SASC was able to prevent pressure drop across filter surface from rising over time.

4. Discussion

The results of the present study show that the application of spark discharges using the co-axial electrode configuration helped to keep cartridge filter surface clean, and the pressure drop across the filter surface obtained with spark was consistently lower than that obtained without spark. However, as the flow rate increased from 2 gpm to 5 and 10 gpm, and TDS values of water increased, the efficacy of SASC filtration decreased. This performance reduction which was observed at higher flow rates and higher TDS levels might be due to the physical size of the cartridge mesh filter (i.e., 10-in long) used in the present study.

It should be noted that high TDS can increase viscosity of water, by an estimated 10% for seawater, and even more for waters with even higher salinity and associated dissolved solids content. In addition to this attribute of saline waters, in the presence of TSS content, it was observed that large increases in TDS could have an effect on pressure drop. To help mitigate this effect, it is recommended that a larger-size filter should be utilized for waters containing high TDS in the presence of TSS content. While the filter used in the present study was a good size for water with TDS of 10,000 ppm, it was undersized for water with TDS of 50,000 ppm.”

For high flow rate and high TDS case, a larger overall filtration surface may be required to take advantage of the SASC system. Alternatively, if two or three filters connected in parallel were used, the spark discharges might have been able to keep the filter surface clean even at a high TDS water as manifested by curve #2 in Fig. 11.

The unique feature of the co-axial electrode configuration is that both HV electrode and ground electrode are positioned together at the same location (i.e., same side). This feature is useful in the implementation of the SASC filtration technology as this co-axial electrode can be installed through a single hole on the sidewall of a filter housing. Furthermore, since the filter

surface is not used as the ground electrode, the filter does not have to be made of metal. In other words, any filter material such as fabric, polymer, and ceramic can be used.

Since the tip of the HV electrode in the present study was nearly hemispherical in shape, increasing the reliability of the electrode over time, the erosion problem associated with the sharp needle electrode did not take place. In addition, because the co-axial electrode utilized two concentric cylindrical geometries, the gap between the two electrodes was maintained constant, unlike in a point-to-plate electrode, which erodes and widens the gap with increasing use. As the gap distance is one of the most critical parameters in the generation of spark discharges, the co-axial electrode geometry provides stability and reliability in the generation of spark discharges over time.

Because the spark discharges remove accumulated particles from filter surfaces, the concentration of the suspended particles in the annulus space between the filter and filter housing increases almost linearly over time, a phenomenon which will degrade the performance of SASC filtration. These solid particles, e.g., CaCO_3 in the present study, are often 2-3 times heavier than water and fall by gravity if there is room. In other words, if the filter housing is designed such that these particles fall down by gravity from the filter surface to a storage space below the filter housing, the concentration of the suspended particles in the annulus space can be maintained at a certain threshold value for the optimum performance of the SASC filtration technology.

Produced water has sufficient concentrations of cations such as ferrous iron (Fe^{2+}) [1, 9], and spark discharge in produced water may be able to convert these dissolved ions to solid particles in produced water. For instance, in plasma-treated produced water, the hydroxyl radical (OH) is generated from the dissociation of water molecules; see chemical reactions in Eqs. (4) - (5) [10, 31, 32].

Subsequent chemical reactions between $OH^\bullet$ and Fe^{2+} generate the coagulants of $Fe(OH)_2$, or $Fe(OH)_3$; see chemical reactions in Eqs. (6) - (8) [10, 33-35].

As a result of these chemical reactions, suspended particles as well as organic contaminants in produced water react with $Fe(OH)_3$ and then they are precipitated in the form of coagulated and flocculated solid particles [33, 34, 36]. Note that ferric oxide particles are highly adherent, accelerating the coagulation and flocculation of other suspended particles with the help of mixing caused by shock waves from spark plasma discharges. In the case of actual produced water, the particle size on the filter surface after SASC filtration was bigger than that from the baseline test (see Fig. 13). We speculate that the spark plasma may have coagulated and flocculated the other suspended particles in produced water. The pressure drop results from the present study suggest that to maximize the performance of SASC filtration, a range of parametric optimization steps are needed, including filter pore size, filter surface area, flow rate, TDS, and TSS.

Although the present study focuses on the use of the shockwaves generated by spark discharges to keep filter surface clean, spark plasma discharges also generate UV radiation, electric fields, reactive oxygen and nitrogen species, and charged particles as mentioned earlier. These plasma products give spark plasma discharges the potential to address multiple treatment requirements of produced water such as disinfection, de-oiling, mineral fouling prevention, and the oxidation of dissolved hydrocarbon.

5. Conclusions

The present study investigated the feasibility of using short-pulse spark plasma discharges to keep filter surfaces clean over time. Suspended particles of calcium carbonate in synthetic produced water were used for a series of experimental validation tests, and produced water samples were also used for a separate series of tests. Shock waves generated by the spark discharges prevented the accumulation of the particles on the filter surface, keeping the pressure drop across the filter surface close to the initial low values at a flow rate of 2 gpm, TDS of 3,000 ppm, and TSS of 2,500 ppm. As the flow rates, TDS, and TSS levels were increased, the efficacy of SASC filtration decreased due to the limited filter surface area in this study. The range of water properties that were shown to be filtered with the current spark discharge using 10-in long stainless steel mesh filter was TDS level $\leq 50,000$ mg/L and TSS level $\leq 2,500$ mg/L. The authors believe that the range could be further expanded with a larger filter size than the one used in the study. In general, the spark discharges maintained the pressure drop across filter surface at a level corresponding to the case of clean filters or significantly less compared to those obtained in the baseline test. An optimization study is recommended to determine the specific condition of the SASC filtration, including filter pore size, filter surface area, flow rate, TDS,

and TSS. Furthermore, the filter housing should be redesigned such that the suspended particles pushed away from the filter surface by the shock waves of spark discharge are permitted to fall to a pre-determined space by gravity, and as a result would not adversely affect the performance of SASC filtration.

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Table 1. Amounts of chemicals to make synthetic produced water, and corresponding TDS and TSS in water. (CaCl_2 : $M_w = 110.98 \text{ g/mol}$, Na_2CO_3 : $M_w = 105.99 \text{ g/mol}$, NaCl : $M_w = 58.49 \text{ g/mol}$, CaCO_3 : $M_w = 100.09 \text{ g/mol}$)

Test No.	Amount of chemicals to be added to tap water (mg/L)			TSS and TDS in synthetic produced water (mg/L)	
	CaCl_2	Na_2CO_3	NaCl	TSS as CaCO_3	TDS as NaCl
1	2,846	2,718	-	2,565	3,000
2	1,423	1,359	10,300	1,283	10,000
3	2,846	2,718	10,300	2,565	10,000
4	2,846	2,718	51,500	2,565	50,000

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Fig. 1. Spark electrode used in the previous study and subsequent filter damage due to cathodic hot spot.

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Fig. 3. (left) Configuration of co-axial electrode used to generate spark discharge and (right) filter housing with co-axial electrode installed vertically; 1- ground electrode made of stainless steel pipe, 2- HV electrode made of metal acorn nut, 3-Stainless steel tube connecting to HV electrode, 4- Teflon insulation, 5-Co-axial electrode, 6- Stainless steel filter, 7-Particle drain, 8-Air vent.

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Fig. 11. Changes in differential pressure between inlet and outlet of stainless steel filter at 50,000-ppm TDS and 2,500-ppm TSS in synthetic produced water.

Fig. 12. Changes in differential pressure between inlet and outlet of stainless steel filter at 50,000-ppm TDS in produced water.

Fig. 13. Photographs of filter surfaces of 5-micron stainless steel filter at 2-gpm flow rate in produced water.

Fig. 1.

Fig. 2.

Fig. 3

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