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Fundamental characteristics of discharge plasma generated in a water cavitation field

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ABSTRACT

In this study, the fundamental characteristics of discharge plasma, which is produced in water cavitation fields, was investigated experimentally. A high voltage was applied across the electrodes located in the cavitation field inside the treatment reactor. The maximum applied voltage corresponding to the discharge onset voltage was approximately 1 kV. The power consumption P of the reactor was measured as the conductivity of the treatment water was varied by changing the NaCl concentration up to 3.0% and as the frequency of the applied voltage was varied from 10 to 30 kHz. The power consumption P had a peak value during the changes in the conductivity of the treatment water. The emission intensity from ·OH and O in the plasma decreased as the conductivity increased. The emission from ·OH was detected at an NaCl concentration of 2.5%. The energy deposited to the plasma E_p and the conduction current in water E_w were estimated from the voltage and current waveforms. The E_p/E_w ratio, which is an important factor for efficient treatment, was approximately 3% at an NaCl concentration of 0.7% and a frequency of 10 kHz. This ratio increased to approximately 8% when the frequency was increased to 20 kHz. The experimental results indicated that increasing the frequency is an effective way of improving the treatment efficiency.

1. Introduction

Various studies have been conducted to develop water purification techniques using plasma, e.g., the decomposition of organic compounds, such as persistent substances [1–6], decolorization of dye [7–9], sterilization of bacteria, and inactivation of microorganisms [10–17] have been investigated. These studies show that plasma production in water is effective for wastewater treatment. In research on water treatment and purification using plasma, various plasma generation and reaction methods with water have been devised and experimentally tried. In addition, the mechanisms of plasma generation (dielectric breakdown) are also examined from detailed observation. These are comprehensively summarized in review pappers [18,19]. However, a large amount of industrial wastewater to be purified, which includes waste oils, toxic and persistent substances, and pharmaceuticals from hospitals and pharmaceutical industries, is generated at production factories all over the world [20]. Thus, a technology that can treat a large amount of wastewater being generated in a short period of time is required.

In this study, a method involving water cavitation and plasma is used for high-volume wastewater treatment. Generally, cavitation is the formation of vapor cavities in a liquid. It usually occurs when a liquid is subjected to rapid changes in pressure, causing the formation of a bubble cloud from the gas dissolved in the water. Using this method, plasma is produced in the bubble cloud, that occurs downstream of the nozzle in the reactor by cavitation. An electrode pair is mounted in reactor, and plasma is produced through the application of a high voltage. The advantages of using this method are as follows:

(1) A relatively low-cost power supply could be produced as the discharge onset voltage is reduced by the bubble cloud.
(2) Equipment configuration could be simplified because a source of raw gas, which is usually used for promoting the discharge onset, is not required.
(3) Both bacteria and microorganisms could be inactivated by the intense shock waves generated through the implosion of cavitation bubbles.

In reference 21, the method of plasma production using bubbles without external raw gas have been proposed [21]. In this report, bubbles were formed by vaporized water at electrode surface at which the conduction occurs. In our proposed method, the bubble is generated at nozzle due to the cavitation, which is not electrode process, and contributes to the remarkable reduction of the discharge onset voltage.

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The reason why plasma can be generated at lower voltage is presumed to be that the reduced electric field *E/n* (*E*: local electric, *n*: density of medium), increases due to cavitation bubbles between the electrodes.

In our previous research, the effectiveness of the treatment method for the sterilization of *Escherichia coli* was demonstrated and the concentration of hydroxyl radicals (·OH), which is a typical radical generated in plasma, was measured. Furthermore, the DNA damage induced by the treatment was investigated to elucidate the molecular mechanism underlying the sterilization abilities of this treatment method. The experimental results indicated that oxidative DNA damage is one of the mechanisms underlying the sterilization capability of the pulsed discharge method [22,23].

One of the important parameters for investigating the practicality of the treatment method is the conductivity of the treatment water because the conductivity depends on the treatment objects and the level of pollution of the wastewater. In addition, it considerably affects the process of plasma production and the consumption power of reactor. Distilled water has a conductivity of about 0.5–3 μS/cm. River water typically has a conductivity of several tens to several thousands of μS/cm, but it depends significantly on location and environmental conditions. Municipal wastewater and sewage also significantly depend on the conditions, they are several 100 to several 1000 μS/cm. Industrial wastewater often has a large conductivity as high as several 10000 μS/cm (several S/m). In the case of seawater with a salt concentration of 3%, the conductivity is about 4–5 S/m. Based on the above, in our study, experiments were conducted assuming conductivity of sea water at maximum [24–29].

In this study, the consumption power of the reactor and the intensity of the emission from radicals were experimentally measured by varying the conductivity of the treatment water. Furthermore, the ratio of the energy deposited to the plasma to the ion current flow was estimated based on the experimental results. The results of these investigations are described and discussed herein.

2. Experimental apparatus and methods

Fig. 1 shows a schematic the experimental apparatus. This system comprises a plasma reactor, a high-voltage alternating current (AC) power supply to generate discharge, a water reservoir, and a water pump. The water is circulated between the reactor and the water reservoir at a fixed flow rate of 20 L/min through a water pump. The total volume of the water was 2.0 L. The power supply used here has a rectifier, an inverter, and a step-up transformer. The 60-Hz 100-V commercial power was first converted to direct current (DC) voltage by the rectifier, after which the DC voltage V_i was supplied to the inverter. The output voltage of invertor was served as an input to the step-up

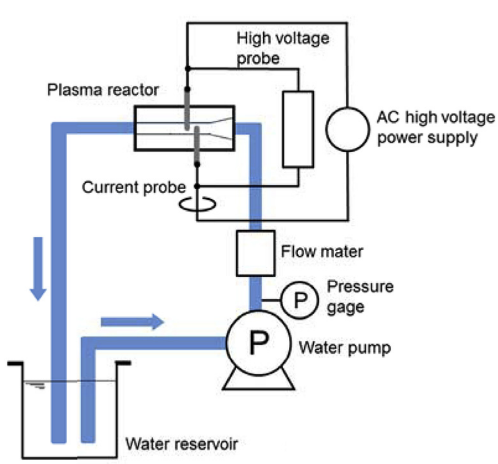
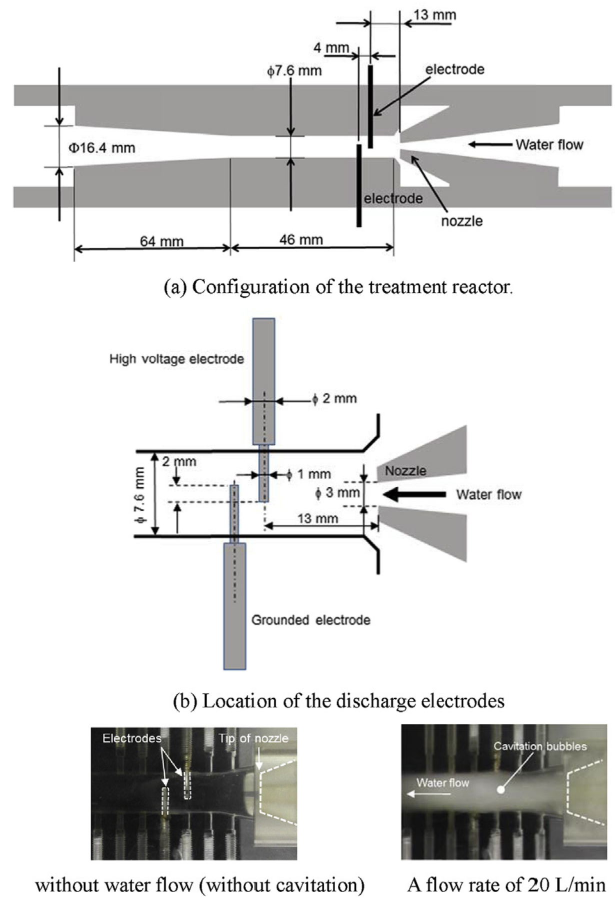


Fig. 1. Schematic of the experimental apparatus.



(a) Configuration of the treatment reactor.

(b) Location of the discharge electrodes

(c) Photographs of bubble production.

Fig. 2. (a) Configuration of the treatment reactor. (b) Location of the discharge electrodes. (c) Photographs of bubble production.

transformer. The high-AC voltage frequency *f* was obtained from the secondary terminal of the step-up transformer, and this *f* was varied from 5 to 30 kHz by changing the switching frequency of the inverter. The applied voltage and the current flow through the reactor were measured using a high-voltage probe (P6015A, Tektronix, Inc.) and a current probe (Model 2877, Pearson Electronics), respectively.

Fig. 2(a) and (b) show the configuration of the reactor and the discharge electrodes, respectively. The reactor has a nozzle (with an aperture that has a diameter of 3 mm) for the generation of cavitation bubbles. The material of the reactor is acrylic resin. The diameter of the water flow path was 7.6 mm downstream of the nozzle. At 46 mm downstream from the nozzle, the diameter of the path further increases linearly, which then narrows to 16.4 mm at the end of the reactor. The high-voltage electrode was positioned 13 mm from the tip of the nozzle, and the grounded electrode was installed on the opposite side at a position 4 mm downstream from the high-voltage electrode. The diameter of the electrodes was 1 mm within the discharge region of the water flow. The composition of the both electrodes was stainless steel. All conditions of the reactor and the electrode positions were fixed during the experiments. Fig. 2(c) is a photograph that shows the cavitation bubble production by the nozzle. The cavitation bubble was not produced when no water flow as shown in left side. The right side of Fig. 2 shows bubble production by the nozzle when the water flow rate was 20 L/min. From this photograph it was found that the cavitation bubble was produced at the downstream of nozzle, and the electrodes was surrounded by bubbles.

The conductivity of the water was changed by adjusting the NaCl concentration *N*. The input voltage V_i was fixed and its frequency were