Water Purification Using Non-thermal Plasma Driven by Blumlein-line Stacked Pulsed Power Generator

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A water purification by streamer discharge using a stacked Blumlein line pulsed power generator under the water containing pollutants has been investigated. The pulsed power generator consisted of six stacked Blumlein line to generate high voltage with low charging voltage. The output voltage was applied to a wire electrode to generate streamer discharge in the water. The wire electrode was set on an array of small size holes of an air tube. The air bubbles were injected into the water through the holes to assist the discharge development. A plane electrode was used as ground electrode and was placed in the water apart from several cm from the high-voltage wire electrode. Acid Blue 64 solution was employed as a specimen. Number of discharges increased with increasing number of the holes. Energy efficiency for decolorization of the solution was improved by increasing number of discharges produced simultaneously at same input energy. The degradation efficiency and energy transfer from the pulsed power generator to the reactor decreased when a streamer-to-arc transition occurred. The solution of 2000 μS/cm conductivity was successfully decolorized using the wire electrode placed in the air tube to reduce ohmic loss with high-conductive solution.

Keywords: Streamer discharge, Bubbling, Water purification, High conductivity, Acid blue 64

1. Introduction

A pulsed discharge plasma for treating pollutants in water has been attracted much attention. The pulsed discharge makes it possible to instantaneously form a strong electric field and also to produce a non-thermal plasma in which various active species exist. These species play important role in degradation chemical organic compounds [1-5].

Discharges in water require high electric field strength and the large volume discharge is produced by pulsed power technologies. The formation mechanism of the discharge in water is considered that the initial discharge could start in a small bubble on the electrode surface and propagates into the water. The current in the high electric field region causes heating and vaporization of the liquid, forming bubbles [6]. Introducing gas bubbles into the vicinity of the electrode improves the energy balance with more energy used to produce chemically active species because of the reduction of energy loss caused by vaporization [7-9].

Energy efficiency for the discharge production and propagation in the water is strongly affected by conductivity of the water [10, 6]. In general, the volume of discharge decreases with increasing of the conductivity at same input energy. As the result, the energy efficiency for water treatment by the discharge is low under high conductivity water condition. As actual wastewater is generally conductive, ozone treatment process has been employed. The disadvantages of the ozone treatment process are high cost for ozone generation and large scale of an ozone generation system [11].

The objective of the present work is to clarify an influence of various parameters such as water temperature, gap length, additives on water purification efficiency and to purify high conductivity water with high energy efficiency using pulsed power discharge assisted by air bubbling.

2. Experiment

A schematic diagram of a stacked Blumlein line pulsed power generator is shown in Figure 1 [12]. The pulsed power generator consisted of six stacked Blumlein line. The impedance of the generator is 600 Ω, since the impedance of a coaxial cable employed in the Blumlein line generator is 50Ω. The length of a line is 8 m which is consistent with 80 ns of pulse width of an output pulse voltage. A resistance of 10 MΩ is inserted between the outer conductor of the coaxial cable and the ground to prevent a short-time decay of the output voltage. The line is charged up to V_C using high voltage power supply V_S (Pulse electronics MODEL-600F). When the gap switch is closed, a pulse voltage (v_O) is produced and applied to a high-voltage electrode in the reactor. A pulse repetition rates (N_R) is controlled to be 5-50 pps. The pulse voltage and current are measured by high voltage probe (Tektronix

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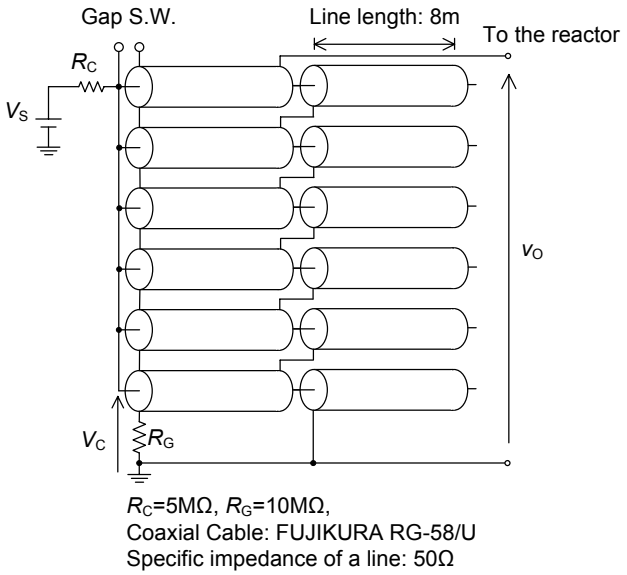

Fig.1 Schematic diagram of the stacked Blumelein line pulsed generator.

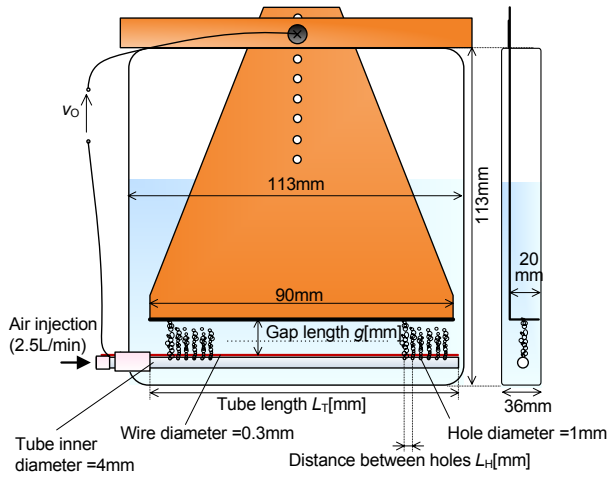

Fig.2 Schematic diagram of the reactor.

P6015A) and current monitor (Pearson 110A), respectively. The signals are monitored with a digital oscilloscope (Tektronix TDS2034B) and are transmitted to a computer to calculate the energy consumed in the reactor.

A schematic diagram of a reactor is shown in Figure 2. Wire-to-plane electrode is used and immersed in liquid. The wire electrode (0.3 mm diameter) is placed above tiny holes on a tube. The plane electrode (90 mm length, 20 mm width) is used as ground electrode and is placed in the water apart gap length g from the high-voltage wire electrode. The room air is supplied into the tube with flow rate of 2.5 L/min and air bubble is injected in water through the holes to assist the discharge development. The diameter of the holes is 1 mm and the distance between holes (L_H) is 2.5-20 mm. The tube is made of polypropylene with a length (L_T) of 40-100 mm and a diameter of 4 mm.

A dye solution dissolving Acid Blue 64 (CAS No. 860-22-0) into 100 ml of tap water at concentration of

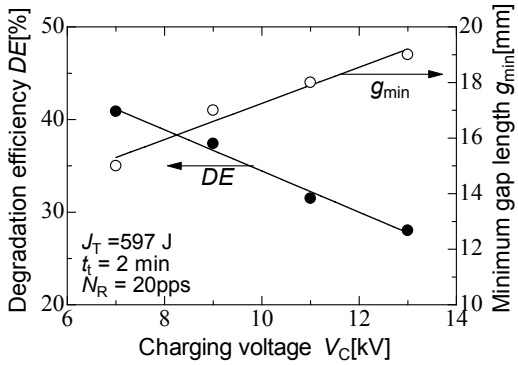

Fig.3 Degradation efficiency and critical gap length as a function of charging voltage.

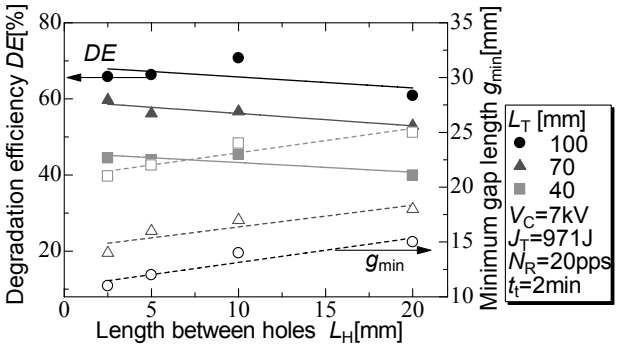

Fig.4 Degradation efficiency and critical gap length as a function of length between holes for various length of tube.

20 mg/l is used as a pollutant specimen to evaluate by a decolorization efficiency. The absorbance of the dye solution is measured by a spectrometer (Hitachi U-1800) and the degradation efficiency DE is obtained by following equation.

$$DE = \frac{absorbance(initial) - absorbance(treated)}{absorbance(initial)} \quad \cdots(1)$$

Here, the absorbance is obtained at wavelength λ=612 nm. The electrical conductivity of the solution (σ) is adjusted by adding NaCl.

3. Results and discussion

3.1 Dye decolorization characteristics

Figure 3 shows DE and a critical gap length bridged with the streamer discharge between electrodes (g_{min}) as a function of charging voltage V_C of the coaxial cable. The values of g_{min} are determined with monitoring 1000 times discharges without present of the arc transition. The decrease of g_{min} indicates that the electric field and the energy of individual discharge decreases with increasing number of discharges produced simultaneously at same input energy. The values of L_T, L_H, σ, and t_t are 100 mm, 2.5 mm, 127 μS/cm, and 2 min, respectively. The total input energy to the reactor (J_T) is fixed at 597 J controlled by N_R with a constant t_t for various V_C values. The input energy to the reactor per pulse increases with increasing V_C. DE increases and g_{min} decreases with decreasing V_C.

Figure 4 shows DE and g_{min} as a function of L_H for

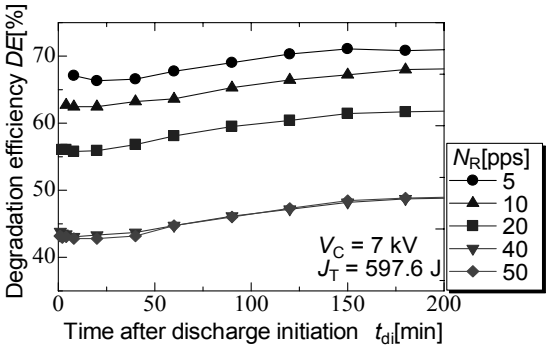

Fig.5 Degradation efficiency as a function of time after discharge initiation for various pulse repetition rates.

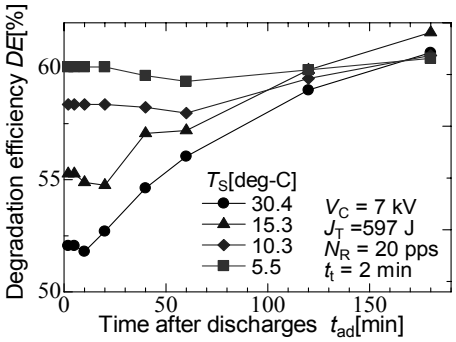

Fig.6 Degradation efficiency as a function of time after discharge for various temperatures of the solution.

various L_T values. The values of V_C, N_R, σ, and treatment time t_t are 7 kV, 20 pps, 127 μS/cm, and 2 min, respectively. The number of holes changes by L_T and L_H. The number increases with increasing L_T and decreasing L_H. The number of discharges increases with increasing number of holes. *DE* increases with decreasing L_T and increasing L_H.

Figure 5 shows *DE* as a function of time after discharge initiation for various N_R values. The time of first plots shows the time just after water treatment by the discharge. The decolorization after discharge-off is caused by active species in the solution produced by discharges. *DE* increases with decreasing N_R. The active species are locally concentrated with increasing energy of the discharge. The high concentration of active species leads increasing reactions between active species through a recombination of OH radicals. This is one of mechanisms that *DE* increases with increasing number of discharges and decreasing V_C and N_R.

3.2 Influence of water temperature

Figure 6 shows *DE* as a function of time after discharges for various temperatures of the solution (T_S). *DE* increases rapidly with increasing T_S. Figure 7 shows *DE* as a function of initial temperature of the solution. *DE* increases with decreasing initial temperature. Generally, reaction rate between active species in the solution

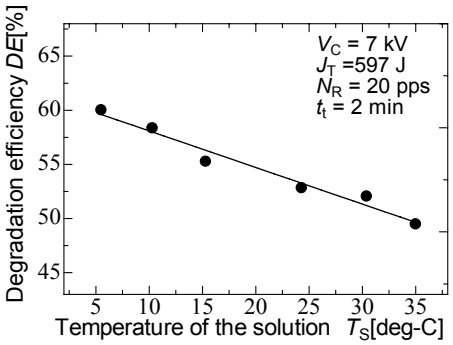

Fig.7 Degradation efficiency as a function of initial temperature of the solution at time after discharge.

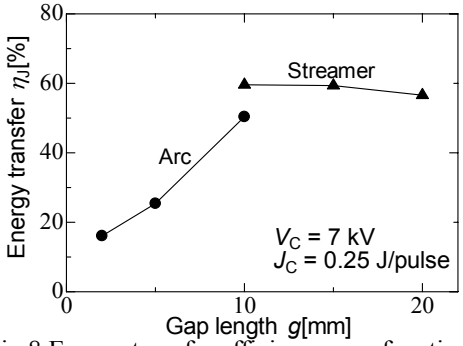

Fig.8 Energy transfer efficiency as a function of gap length.

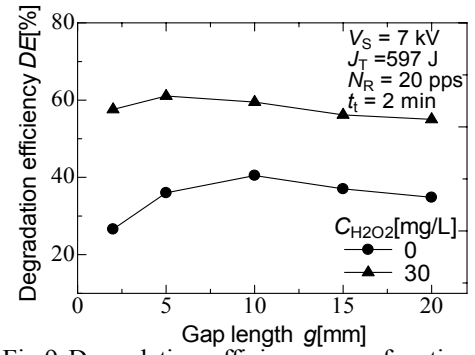

Fig.9 Degradation efficiency as a function of gap length with and without H_2O_2 as additive.

with decreasing temperature. In the contrast, Henry's constant of the active species into the water through dissolution process decreases with decreasing temperature.

3.3 Influence of gap length

Figure 8 shows energy transfer efficiency from the pulsed power generator to the reactor (η_J) as a function of *g*. When *g* is smaller than 10 mm, streamer-to-arc transition occurs and energy transfer efficiency decreases due to low value of the load impedance. Figure 9 shows *DE* as a function of *g* with and without 30 mg/L H_2O_2 addition. *DE* reaches maximum at 10 mm of *g* without H_2O_2. The intensity of ultraviolet light radiation in case of arc discharge is much higher than the case of streamer discharge [13]. An ultraviolet radiation causes photolytic decomposition of H_2O_2 to OH radicals. Thus, although η_J decreases, *DE* increases with decreasing *g* in case with

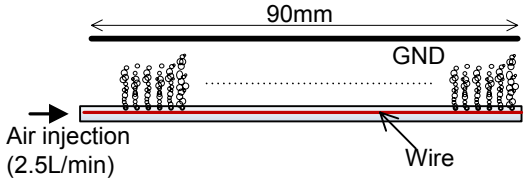

Fig.10 Schematic diagram for treatment of high conductive solution.

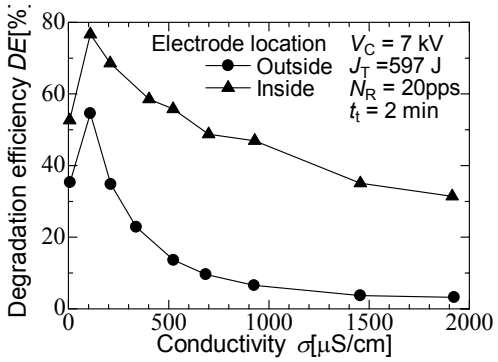

Fig.11 Degradation efficiency and critical gap length as a function of conductivity of the solution for two different electrode configurations (outside type: figure 2, inside type: figure 10).

H_2O_2 addition.

4. High conductive solution treatment

Figure 10 shows electrode configuration improved to treat high conductive solution. The wire electrode placed in inside of the tube to insulate from surrounding solution by air. The values of L_T and L_H are 100 mm, 2.5 mm, respectively.

Figure 11 shows *DE* as a function of conductivity of the solution (σ) for two different electrode configurations. The value of V_C, N_R and t_t are 7kV, 20pps, and 2min, respectively. The value of *DE* drastically decreases from 55 to 3 % with increasing solution conductivity in case of the wire electrode set on solution side of the air tube shown in figure 2. However, the value of *DE* in case of the wire electrode set inside the tube decreases from 80 to 35 % with increasing solution conductivity. Therefore, *DE* increases by changing the electrode configuration and the solution of 2000 μS/cm conductivity is successfully decolorized using inner type electrode.

Figure 12 shows energy transfer efficiency η_J and maximum output voltage V_{Omax} as a function of *g* for two different electrode configurations. When *g* is smaller than 10 mm, the streamer-to-arc transition occurs. Although η_J is almost same value for both electrode configuration, whereas V_{Omax} of the outside type electrode is larger than that of the inside type electrode. This result indicates that the discharge occurs more active and the ohmic loss decreases by changing electrode configuration from the outside type to the inside type.

5. Conclusion

The decolorization of Acid Blue 64 solution as pollutant specimen by pulsed power discharges was investigated experimentally. Experimental results show

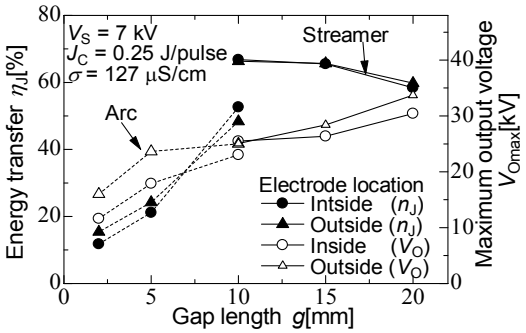

Fig.12 Energy transfer efficiency and maximum output voltage as function of gap length for various type of electrode configuration.

that increasing number of discharges and temperature for preservation and decreasing temperature of solution before discharges were effective to enhance the degradation efficiency. The solution of 2000 μS/cm conductivity was successfully decolorized and degradation efficiency increased using the wire electrode placed in inside of the tube to insulate from surrounding solution by air.

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[1] S. Sato, Jpn. J. Appl. Phys. **69**, 3, pp. 301-304 (2000). [in Japanese]

[2] H. Akiyama, IEEE Trans. Dielectr. Electr. Insul. **7**, 5, pp.646-653 (2000).

[3] A.T. Sugiarto *et al*., IEEE Trans. on Plasma Sci. **58**, pp.135-145 (2003)

[4] D. Moussa *et al*., J. Electrostatics. **35**, 2, pp.444-452 (2007)

[5] H. Nakanishi *et al*., IEEJ Trans. FM **123**, 7, pp.618-622 (2003)

[6] J. S. Clements *et al*., IEEE Trans. Ind. Appl **23**, 2, pp.224-235 (1987)

[7] J. Choi *et al*., IEEE Trans. on Plasma Sci. **34**, 5, pp.1744-1750 (2006)

[8] T. Namihira *et al*., IEEE Trans. on Plasma Sci. **35**, 3, pp.614-618 (2007)

[9] K. Takahashi *et al*., JIEED Japan **51**, 1, pp.21-24 (2008)

[10] B. Yang *et al*., Chinese Chemical Letters **15**, 10, pp.1215-1218 (2004)

[11] K. Kawamoto., *Kankyo yukikagaku bussitu ron* (Environmental Organic Chemistry)(KYORITSU SHUPPAN, Tokyo, 2006) pp.277-278 [in Japanese].

[12] K. Takahashi *et al*., Ext. abst. (9th Spring Meet., 2008); The Institute of Electrostatics Japan, 1p-3, pp.39-42 [in Japanese].

[13] A. T. Sugiarto et al., Thin Solid Films **386**, pp.295-299 (2001)