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Time Resolved Imaging of Pulsed Streamer Discharge at the Air/Water Interface

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Pulsed positive streamers over the water surface were observed in the needle-to-plate electrode configuration with a gap of 20 mm. The characteristics of streamer propagation were investigated by using the ICCD camera. The filamentary streamers propagate in radial direction from the needle electrode and their progression distance increases with the increase of the applied voltage. A branching discharge pattern with the channel diameter of 250-450 μm was observed. When the tip of the needle is set on the water surface, the streamers start from the needle stem located above the water surface and then reach the water surface, where they propagate on it. The propagation velocity of the streamer head was 7-8 x 10^4 m/s at the early propagation stage and 4-5 x 10^4 m/s in the middle of water surface propagation stage. Moreover, the discharge features were evaluated in terms of the fractal aspect and the fractal dimension was estimated for our surface streamer discharges.

Keywords: Pulsed discharge, Discharge over water, Atmospheric-pressure, Surface discharge, Streamer, Water treatment, Fractal

1. Introduction

The research of surface discharges along solid insulator surfaces has long history since the discovery of the Lichtenberg figure [1-3]. As a discharge on a liquid surface, some researches have been conducted so far in relation to the surface flashover phenomena on wet and polluted insulators [4, 5]. Recently, the extension in the use of such discharge over the water surface has been received considerable attention from the view point of the treatment of polluted water aimed at removal of dye and harmful components [6, 7]. In this case, features of the surface discharges over water surface are considered to be different from those of the discharges over a solid insulator. In addition, it is known that the discharge pattern depends on the polarity of the stressed electrode for both the discharges on the insulator and water [2-5].

In this paper, we present the results of the time resolved imaging of pulsed positive streamer discharge over water surface because the positive polarity is suitable for water treatment. The characteristics of the discharges (streamer length and its diameter, propagation velocity, branching structure and its fractal dimension) are determined using an ICCD camera and compared with the discharges in air and in water.

2. Experimental Apparatus and Methods

Fig. 1 shows the schematic diagram of the experimental setup. A pulsed high voltage circuit with a self-trigger spark gap switch was used to generate streamers. A needle-to-plate discharge electrode system shown in Fig.2 was set into an acrylic reactor. A stainless-steel needle (0.31 mm in inner diameter, 0.57 mm in outer diameter) was used as the stressed electrode, while a brass plate (70 mm in diameter) with the cover of carbon plate (80 mm in diameter, 2mm in thickness) was used as the grounded electrode. The use of the carbon plate is to reduce the reflection light when we observe the discharge from the top side. The water level was adjusted for the needle-to-plate discharge electrode and for the experiment of surface discharges the tip of the needle electrode is in contact with the water surface. The electrical conductivity of the water was measured by a conductivity meter (Delta OHM, HD2156.1). An intensified charge coupled device (ICCD) camera (Andor, i-Star) was used to observe the streamers. In order to synchronize the discharge and the ICCD camera, a PIN photodiode detected a light emission from the spark gap switch and sent a signal through a delay generator (Stanford DG535) to trigger the ICCD camera. The time relationship between the voltage pulse, discharge current pulse and gate opening time of the ICCD camera was monitored with a digital oscilloscope (Tektronix, TDS5104, 1.5 GHz, 5 GS/s). Hence, although the pulse high voltage circuit with the spark gap switch had a jitter, knowing the timing of the high voltage pulse, discharge current pulse and exposure time of the ICCD camera, it was possible to determine the phase of streamer evolution. The streamer emission spectrum was measured by a spectrometer

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(Ocean Optics, USB2000) through an optical fiber. To detect the light emission securely, the plate electrode with carbon plate was replaced by a rod electrode (6 mm in diameter, 80 mm in length). The experiment was carried out at room temperature under atmospheric pressure.

3. Results and Discussions

Typical voltage and current waveforms for the discharge over the distilled water surface are shown in Fig.3. The rise time of the pulsed high voltage used in this study is about 70 ns and pulsewidth is about 15 μs. After a displacement current appears at the rising edge of the pulsed voltage, the discharge current with a 6 A peak and a 1.4 μs pulsewidth flows. The streamer discharge spreads radially over the water surface and its radius increases with increasing the applied voltage. A discharge initiates from the stem of the needle electrode and propagates obliquely in air as shown in Fig.4 and then lands to the surface of water. This result suggests that initial electrons in air are responsible for the discharge onset. After that, positive surface streamer propagates at the interface between the air and water surface. During their propagation, some of the streamer channels bifurcate into two or three branches, generating many lateral branches (see Fig.6). At the applied voltage higher than 25 kV, the streamers reached to a position corresponding to the edge of the plate/rod electrode.

Fig. 5 shows the typical emission spectrum of the streamer along the water surface above the rod electrode. We found the emission of hydrogen atoms (Hα, 656.3 nm) and OH radicals ($A^2\Sigma^+ - X^2\Pi$, 309 nm). Also the atomic line of oxygen (OI, 777nm) was found as well as N_2 second positive system. The production of OH radicals, which play an important role in water treatment, was confirmed at the air/water interface.

Fig.6 shows the typical time evolution of the streamer over water surface for different ICCD camera exposure times after applying a pulsed high voltage of 27 kV. The gate of the ICCD camera was opened for a given time just after the streamer had started. We observed these streamers from the vertical position using the mirror as shown in Fig.1. Each image presented in Fig.6 was selected from a set of different discharge observation at the same conditions. The diameter of the streamers over water surface is in the range of 250-450 μm, which is also estimated from the streamer image shown in Fig.4. The luminous part of the discharge is a head of the streamers. From Fig.6(f), the head of the streamers reached to the position corresponding to the edge of the plate electrode until about 750 ns. As the branching pattern of the streamers and their trajectories were different for each discharge, the accumulations of 20 images of the individual discharges for different ICCD camera exposure times are shown in Fig.7. From the time evolution of the accumulated discharges, the velocity of the streamer head was found to about 7-8 x 10^4 m/s at the early propagation stage and 4-5 x 10^4 m/s in the middle of water surface propagation stage. These values are in-between those of the streamers in air (3 x 10^5 m/s) [8] and in water (3 x 10^4

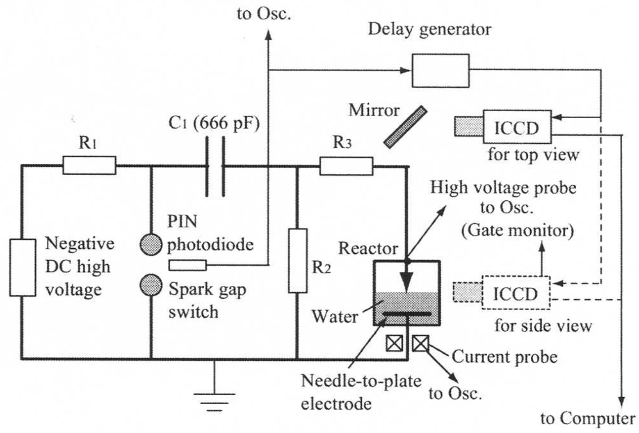


Fig.1 Schematic diagram of the experimental apparatus.

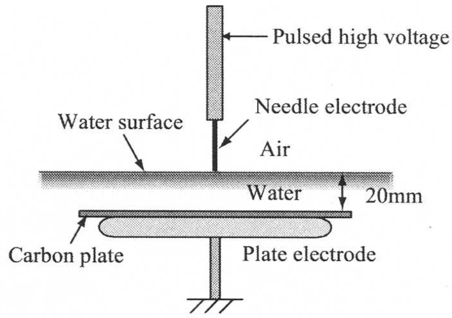


Fig.2 Schematic diagram of the electrode system.

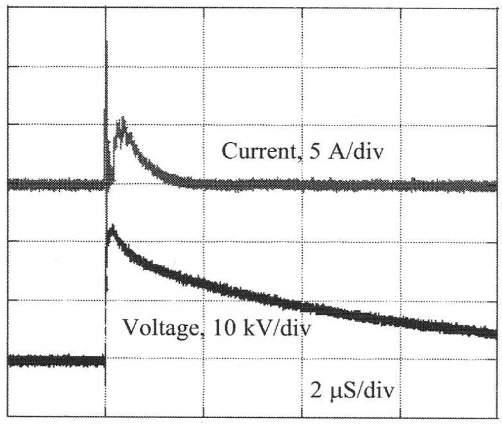


Fig.3 Voltage and current waveforms for the discharge over the distilled water surface.

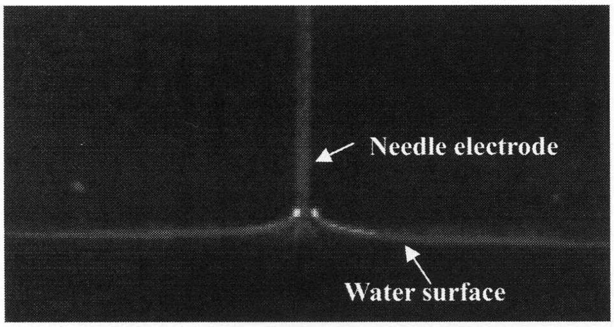


Fig.4 ICCD image of surface discharge at the interface between the air and water surface. The needle-to-rod electrode was used here. (Side view: 27 kV, distilled water: 3 μS/cm)

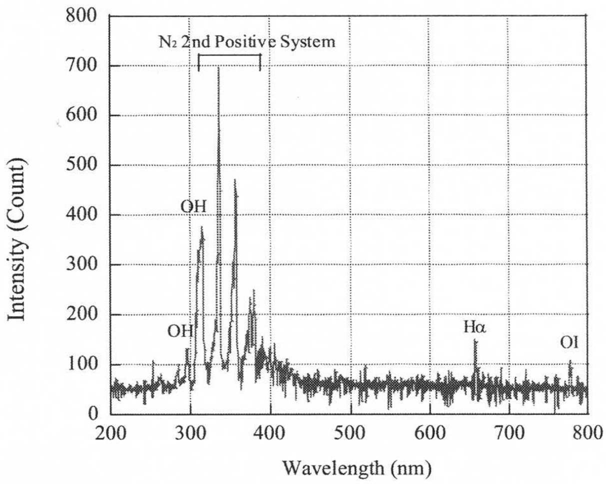
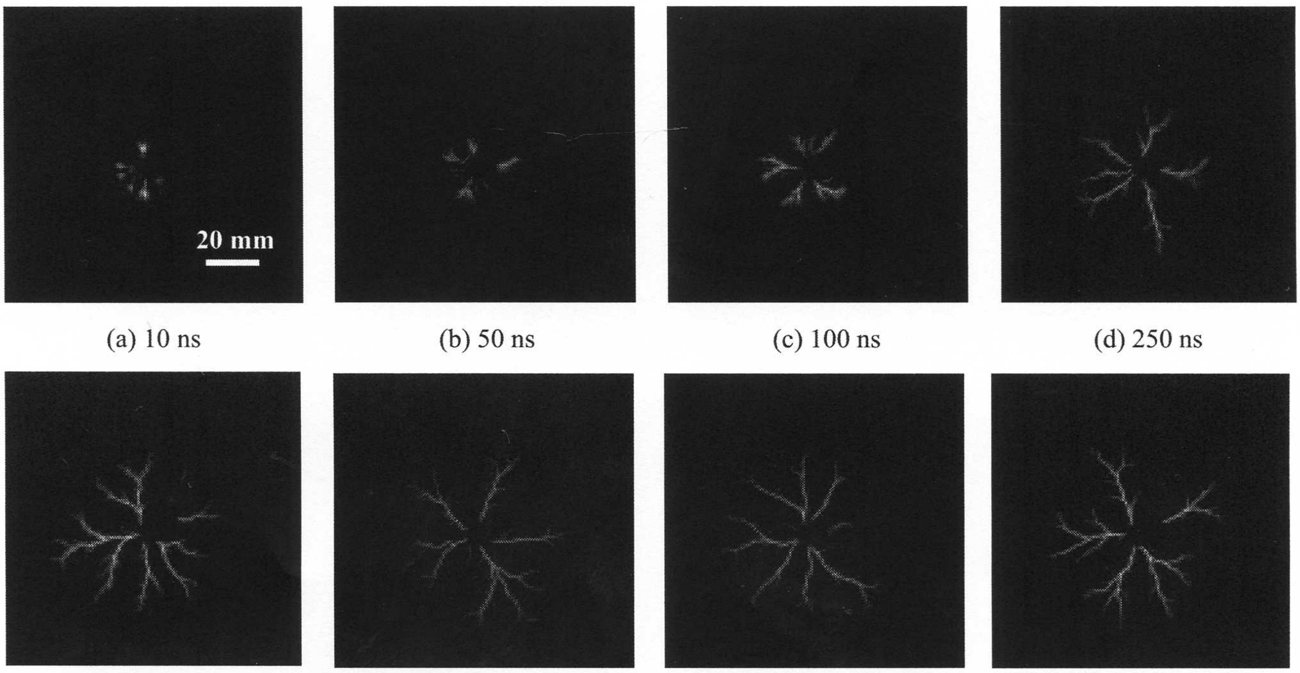


Fig.5 Optical emission spectrum of the discharge at the interface between the air and water surface. The needle-to-rod electrode was used here. (27 kV, distilled water: 3 μS/cm)

m/s) [9].

In general, the streamers over water surface exhibit brighter and fewer channels than those along the solid insulator. In order to obtain more detailed information of surface discharges over water, the fractal analysis was carried out and compared them with the results of the conventional surface discharges took place on the surface of an insulator. According to the fractal analysis, random and complicated pattern such as the discharge can be characterized and classified quantitatively by fractal dimensions. Especially, there is no report for the surface discharge over water surface. The box-counting method [10] was applied to calculate the fractal dimensions for the ICCD images. A fully developed streamer discharge pattern was used and the number of boxes, N(r), which cover the streamer channels was measured by changing the box size r. Fig.8 shows the relationship between the box size r and the number of boxes N(r). A linear relationship in the plot of log N(r) – log r can be seen in Fig.8, which means that the surface streamer discharges over water surface have a fractal structure. The fractal dimensions, D_f, are in the range from 1.3 to 1.4 for the streamers under various water conductivities. These dimensions are slightly smaller compared with the values of surface discharge along the solid insulator (D_f = 1.7-1.8) [10, 11].



(a) 10 ns (b) 50 ns (c) 100 ns (d) 250 ns

(e) 500 ns (f) 750 ns (g) 1000 ns (h) 2000 ns

Fig. 6 Time evolution of the pulsed surface streamers generated by a single discharge on the surface of distilled water. (Top view, applied voltage: 27 kV, water conductivity: 42 μS/cm)

4. Conclusions

The characteristics of the pulsed positive streamer discharge over water surface, such as the streamer inception, propagation, and branching, were investigated using an ICCD camera. The streamer over water surface exhibited long radial expansion compared to the length of the streamers in air and in water. While, the streamer velocity at the interface between the air and water surface (4-8 x 10^4 m/s) is in-between those of the streamers in air (3 x 10^5 m/s) and in water (3 x 10^4 m/s).

It is also found that the branching structure of positive surface streamer over water surface has fractal characteristics. Typical fractal dimension of the streamer is about 1.3 - 1.4 for the surface discharges under the present experimental condition.

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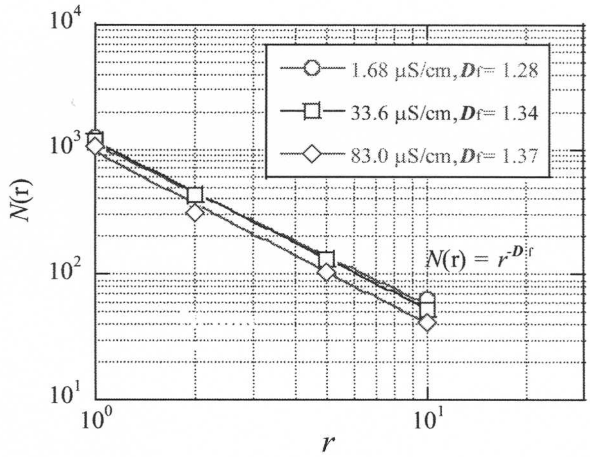

Fig.8 Plot of log N(r)-log r for streamer images using box-counting method. D_f is the fractal dimension. (27 kV, distilled water: 3 μS/cm)

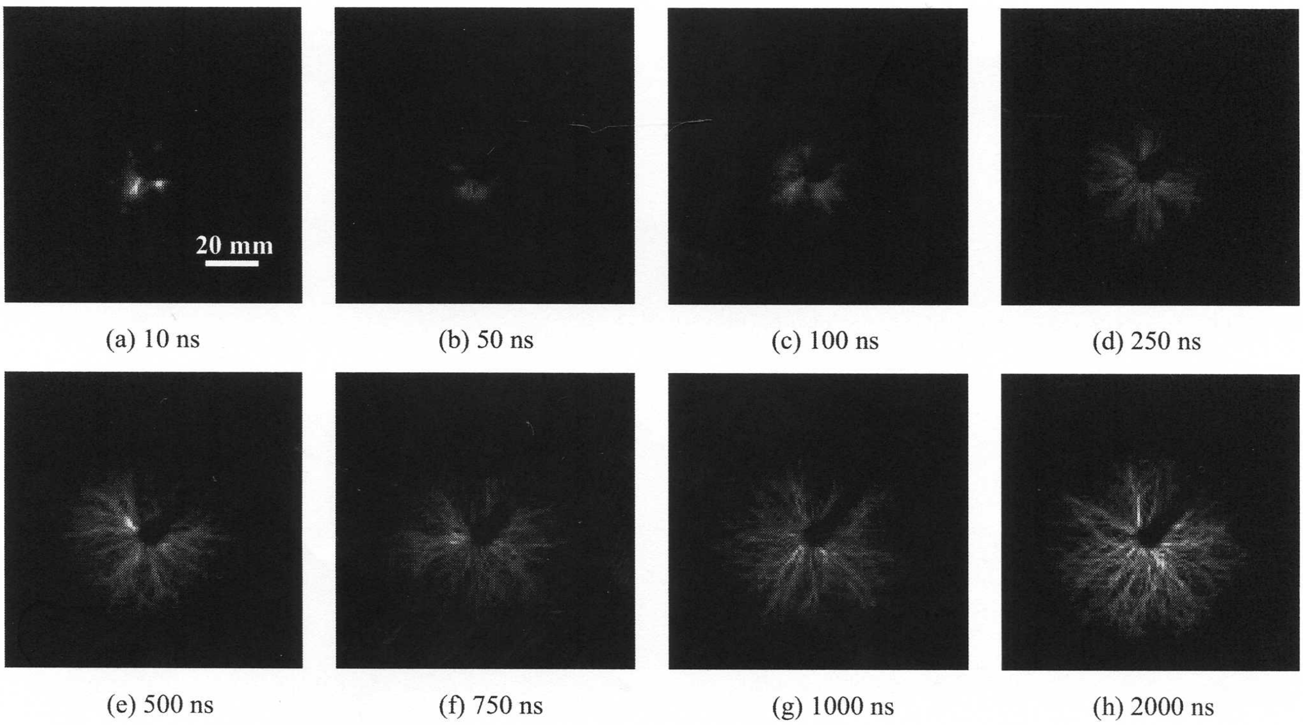

Fig. 7 Accumulated images of 20 surface streamers on the surface of distilled water.
(Top view, applied voltage: 27 kV, water conductivity: 42 μS/cm)