Generation of Liquid-Cathode Atmospheric Pulsed Microdischarges Assisted with a DC Discharge

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We discuss the reduction of the amplitude of repetitive pulsed voltages to generate atmospheric-pressure microdischarges with a liquid cathode. The pulsed voltage was applied to a low-current DC glow discharge in a nozzle-to-liquid electrodes system. The pulsed microdischarges were operated at a voltage of less than 2.2 kV. The delay time of breakdown for the pulsed microdischarges increased with repetition frequency. At high repetitive operation, the liquid surface under the nozzle electrode deformed.

Keywords: microplasma, pulsed microdischarge, liquid cathode, atmospheric

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Atmospheric-pressure glow discharges are studied for various applications such as destruction of toxic compounds, detection of trace contaminants, deposition of films, and surface processes [1, 2]. They are obtained easily by employing microplasmas, which are 0.1-1.0 mm in size. We reported an atmospheric-pressure pulsed glow discharge with a miniature helium gas flow in a nozzle-to-plate electrodes system powered by fast high-voltage pulse trains [3]. Glow discharges were also generated with a DC high voltage using a cathode of electrolyte solution [4]. Submicrosecond pulsed plasmas in air with water cathode were reported by Bruggeman *et al.* [5]. An issue in generating liquid-cathode pulsed microdischarges, which are operated with instantaneous high-power, is that pulsed voltages of 5.0 kV and a few kilohertz are required to have stable repetitive discharges. Such a high-voltage pulsed generator is expensive and large in size relative to the microdischarges. This paper reports a reduction of pulsed voltages from 5.0 kV to less than 2.2 kV in generating the liquid-cathode pulsed microdischarges by applying pulsed voltages to a DC discharge channel. Besides, a high repetitive operation can cause a deformation of a liquid surface, which is characteristic of the pulsed high-power microdischarges using the liquid cathode.

Figure 1 shows an experimental setup including the nozzle-to-liquid electrodes system and power sources for the low-current DC discharge and for the pulsed microdischarges. The electrode system had the nozzle anode with an inner diameter of 500 μm and an outer diameter of 800 μm and a liquid cathode, which was a sodium sulfate solution with a concentration of 1.0%. The gap separation was varied in the range of 1.0-1.5 mm. The helium gas flow rate was kept at 210 sccm throughout the experiment.

Pulsed voltages were generated using a Pulse Forming Network (PFN) charged to 1.9 kV and switched on by four series-connected IGBTs (BUP313 with 1.2-kV breakdown voltage). The PFN was designed to have a characteristic impedance of 45 Ω and a pulse width of 1.2 μs using 16-stage *LC* ladders with inductors *L* of 2.0 μH and capacitors *C* of 1.0 nF. The repetition frequency was varied from 100 to 1000 Hz. Four series-connected diodes (STTA812D with 1.2-kV breakdown voltage), which were placed between the IGBTs of the PFN and the nozzle anode, were employed to prevent the current with the DC power from flowing to the PFN. Without the diodes, the DC discharge could not be sustained because the current with the DC power did not flow into the discharge space but into the PFN after the pulsed microdischarges. The DC power source was connected to the electrodes by a diode (ED-75X1 with 75-kV breakdown voltage) and a 100-μH inductor. They were used to decouple from the pulsed high voltage and its high frequency components.

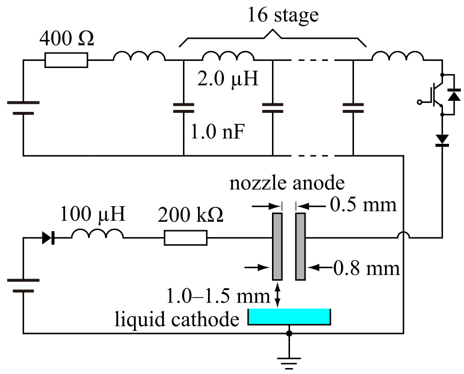

Fig. 1 Experimental setup for liquid-cathode atmospheric pulsed microdischarges with DC discharge.

Figure 2 shows typical waveforms of gap voltage and

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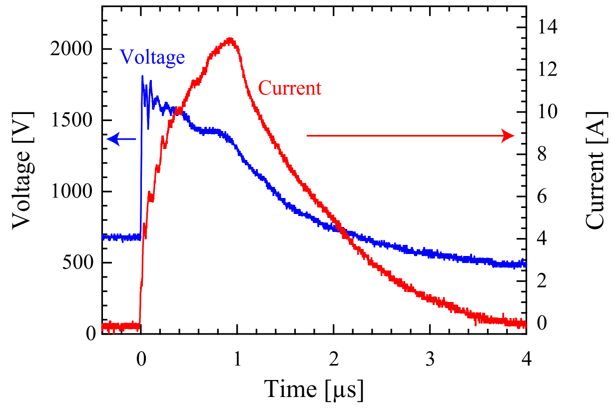

Fig. 2 Typical waveforms of gap voltage and discharge current.

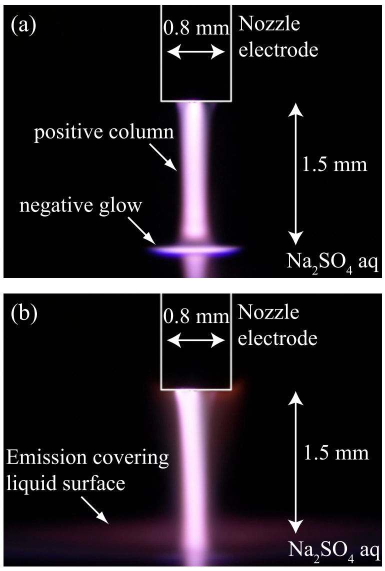

Fig. 3 Visible light emissions. (a) DC discharge. (b) DC and pulsed discharges.

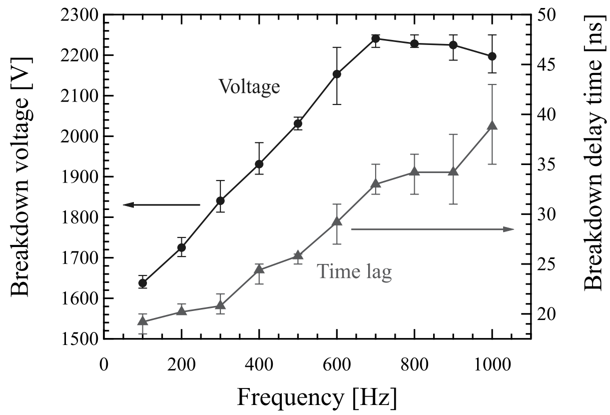

Fig. 4 Dependencies of breakdown voltage and its delay time on the repetition frequency.

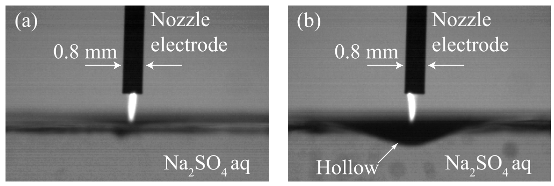

Fig. 5 Deformations of the liquid surface affected by pulsed discharges at (a) 100 Hz and (b) 500 Hz.

discharge current when pulsed voltages with a repetition frequency of 100 Hz were applied between the electrodes with a gap separation of 1.5 mm. The gap voltage for the DC discharge was 700 V when the DC current was 3.0 mA. The high-power microdischarges were generated with pulsed voltages of less than 2.2 kV because electrons and ions formed by the DC discharge facilitated the development of the pulsed microdischarges. The peak instantaneous power and the injection energy for the single pulse were 19 kW and 25 mJ, respectively. The discharge current increased up to 13.5 A nonlinearly for 1 μs. Similar results were reported by Bruggeman *et al.* [5]. The slow increase of the current was not observed in the discharges with metal cathodes. Figure 3 shows visible light emissions of only the DC discharge and the DC and pulsed discharges with the liquid cathode. The exposure time of each photograph was 20 ms. The DC and pulsed discharges had an uniform emission distribution. Visible light emissions of the DC discharge were different for the DC and pulsed discharges; a positive column and a negative glow existed in the DC discharge; however, the negative glow disappeared and an emission covering the liquid surface was observed in the DC and pulsed discharges.

The breakdown voltage and the delay time of breakdown for the pulsed discharges increased with repetition frequency, as shown in Fig. 4. At a repetition frequency of more than 700 Hz, the breakdown voltage saturated at 2.2 kV, which was the maximum applied voltage. Breakdown voltages usually decrease in the discharges with metal cathodes because of the existence of residual charged particles between electrodes. However, this result indicates the inverse characteristic for the breakdown using the liquid cathode. Figure 5 shows photographs taken by a fast camera, with exposure time and frame rate of 0.2 ms and 5000 fps, respectively. After the pulsed microdischarge ended, the liquid surface under the nozzle electrode deformed slightly and returned to a flat shape within 8.4 ms. Therefore, the deformation of the liquid surface did not appear by the pulsed discharges of less than 100 Hz. When the repetition frequency was 500 Hz, the deformation had grown gradually by each pulsed voltage before the liquid surface returning and it saturated finally. The gap separation between the nozzle and liquid electrodes increased with the repetition frequency. So, the increase of the gap separation seems to be a factor in increasing the delay time of breakdown.

In conclusion, the liquid-cathode pulsed microdischarges are operated at a voltage of less than 2.2 kV with a DC discharge in air. Without the DC discharge, the generation of pulsed microdischarges needs a 5.0-kV pulsed voltage. The reduction of the pulsed voltage allows us to relax the specification of high-voltage pulse generators. One reason for increasing the delay time at a high repetition frequency is the increase of the gap separation.

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