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CHARACTERIZATION OF NANO-SECONDS PULSED STREAMER DISCHARGES

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Abstract

Pulsed power technology has been used in many applications such as control of NOx and SOx from exhaust gases, treatment of dioxins, removal of volatile organic compounds, generation of ozone and excitation of excimer laser. Since pulse duration of applied voltage to discharge reactor has a strong influence on energy efficiency of pollutants removal, the development of short pulse generator is paramount important for practical applications. The discharge observation of the short duration pulse voltage is an essential aspect for understanding plasma physics of this new field.

In the present work, the characteristics of the developed nano-seconds (ns) pulse generator, which has the pulse duration of 5 ns, and the observation results of nano-second (ns) pulsed streamer discharges in atmospheric air are presented. The developed ns pulse generator consists of a high pressure spark gap as a lower inductance self-closing switch, a triaxial Blumlein line as a pulse forming line, a coaxial energy transmission line as a connection between the Blumlein and a load, and a pulse charging source. The triaxial Blumlein line is filled up with transformer oil as insulation and dielectric medium. The ns pulse generator outputs the positive voltage, having 2 ns of rise time and 5 ns of pulse duration. The maximum output voltage reaches up to 100 kV. The propagations of the positive and the negative ns pulsed streamer discharges in a coaxial electrode were observed using a high speed gated ICCD camera and a high dynamic range streak camera. During the both polarities of ns pulsed streamer discharges, the primary and the secondary streamers propagated from inner wire to outer cylinder electrodes. This phenomenon has good agreement to the previous works which are observed in the cases of sub-µs pulsed streamer discharges. However, the propagation velocity of the primary streamers in the present work is approximately 6 times faster than the previous one. This is because that the velocity of primary streamers dependent on applied voltage to electrode and ns pulse generator is able to apply the higher voltage to electrode than sub-µs pulse generator.

I. INTRODUCTION

Pulsed streamer discharges in atmospheric pressure gases have been studied for many years since it is one of the promising technologies for the removal of the hazardous environmental pollutants [1, 2]. In this decade, especially, some literatures reported that the shorter pulsed power gives the improvement of the energy efficiency to treat pollutant gases [3, 4]. Therefore, the development of a nano-second (ns) pulse generator is paramount important for practical applications [5]. Besides, the more investigation of streamer development in discharge reactor is beneficial to produce higher energy efficiency. Until now, the studies, related to the structures, the propagation velocity, the temperature, and the formation mechanisms of the streamer discharges produced by sub-µs pulsed power, have been reported [6, 7].

In the present work, ns pulse generator, which has 2 ns of rise time and 5 ns of pulse duration, was developed. The propagation of ns pulsed streamer discharges was investigated using a high speed gated ICCD camera and a high dynamic range streak camera.

II. EXPERIMENTAL-SETUP

Fig. 1 shows the schematic diagram of and the photograph of the nano-second (ns) pulse generator developed in the present work. The ns pulse generator consisted of a high-pressure spark gap switch (SGS) as a low inductance and high speed self-closing switch, a triaxial Blumlein line as a pulse-forming line, and a energy transmission line from the Blumlein line to a load. The SGS has 1 mm of the gap separation and was filled up with SF6 insulation gas. In the operation of the ns pulse generator, amplitude of an output voltage from the ns pulse generator was regulated by varying the pressure of the SF6. The triaxial Blumlein line consisted of an inner rod conductor, a middle cylinder conductor, and an outer cylinder conductor, and the conductors were made of brass and were placed concentrically. The triaxial Blumlein line was filled up with transformer oil as insulation and dielectric medium. The inner and the outer conductors were connected through a charging inductor and the outer conductor was grounded. The middle conductor was charged up by a simple pulse forming circuit, which consisted of a charged capacitor, a thyratron switch (CX1685, E2V Technologies, Ltd., UK), and a pulse transformer, through the charging port in the operation. The unit inductance of and the unit capacitance of the triaxial Blumlein line, calculated from its configuration geometry, were 322 nH/m and 76 pF/m, respectively, which give 130 Ω of characteristic...
impedance. The length of the Blumlein line was 500 mm and it gives 5 ns of the calculated pulse duration of the triaxial Blumlein line. In the paper, the triaxial Blumlein line was charged by a negative pulse voltage and the ns pulse voltage with positive polarity was applied to a load. For the energy transmission from the Blumlein line into a load, the coaxial transmission line, which has 130 Ω of characteristic impedance, was used. A handmade capacitive voltage divider (ratio: 1:6,700) was mounted on the transmission line to measure the output voltage of the ns pulse generator. The output current from the ns pulse generator was measured using a current transformer (Pearson Current Monitor Model 6585, Pearson Electronics, USA) located on the end of the transmission line.

Fig. 2 shows an experimental set-up for observation of ns pulsed streamer discharges. A coaxial cylindrical electrode was employed to observe ns pulsed streamer discharges. A central wire electrode made of tungsten, 0.5 mm in diameter and 50 mm in length, was placed concentrically in a copper cylinder electrode. The diameter of the outer cylinder was 76 mm. A short length of the electrode was necessary to render clear images of the ns pulsed streamer discharges. To prevent a discharge formation at the tip of wire electrode, which enhances electrical field, the tip of wire was covered by a ceramic tube. For the observation of ns pulsed streamer discharges, a ICCD camera with high speed gate (C8484-05C, Hamamatsu Photonics, Japan) and a streak camera with high dynamic range (C7700, Hamamatsu Photonics, Japan) were utilized. The both cameras have sensitive MCP (Micro Channel Plate, maximum gain 10,000). In the case of flaming observation, the exposure time of the ICCD camera was fixed at 200 ps. In the case of streak imaging, the sweep time of the streak camera was fixed at 10 ns. In the experiment, a digital delay generator (DG535, Stanford Research Systems, USA) made synchronization between the ns pulsed generator and the cameras.

III. RESULTS AND DISCUSSIONS

A. Nano-second pulse generator

Fig. 3 shows typical waveforms of the output voltage from the developed ns pulse generator to a matched load (=130 Ω resistor) at different SF₆ pressure in the spark gap switch. It is observed that the ns pulse voltage with positive polarity was applied to a matched load. The rise time of and the pulse width of the output voltage was approximately 2 ns and 5 ns, respectively. The peak applied voltage increased with SF₆ gas pressure. Typically, the peak voltages were 23, 44 and 69 kV for 0.3, 0.4 and 0.5 MPa of SF₆ pressure.

B. Images of ns pulsed streamer discharges

In the observation of ns pulsed streamer discharges, the SF₆ gas pressure, which filled in SGS of ns pulse generator, was fixed at 0.5 MPa. Typical applied voltage to the central wire of the discharge coaxial electrode was shown in Fig. 4. It is shown in Fig. 4 that the peak value of the applied voltage was 100 kV.

Fig. 5 shows the flaming images of emissions from streamer discharges as a function of time after application of 100 kV ns voltage pulse. Each image in Fig. 5 was taken at different ns pulsed streamer discharges. In the observation of ns pulsed streamer discharges, the synchronization between ns pulse generator and camera trigger could not be performed perfectly in ps range. Therefore, the time, t in Fig. 5 was defined as the time when first discharge emissions appeared in the discharge electrode. The bright filaments of the images show the position of the streamer heads during the exposure time of 200 ps. The streamer heads are associated with a higher density of ionization due to the high electric field therein [7-13] and subsequently enhanced recombination which is followed by increased light emission. The main wavelengths of the emissions might be 337.1 nm and
391.4 nm from the second positive band of N₂ and the first negative band of N₂⁺, respectively [14-16]. It is well known that the pulsed streamer discharge consists of the primary streamer discharge and the secondary one which follows the primary one [17]. It is observed from Fig. 5 that the approximately ten primary streamers were initiated at the vicinity of the central wire in the discharge electrode and then propagated toward the outer cylinder electrode. After the fully development of the primary streamers, the discharge emissions were observed only at the vicinity of central electrode because of the enhanced electric field due to electrode geometry. In addition, the secondary streamers appeared near the central wire immediately after the propagation onset of the primary streamers and then followed the primary one. However, the secondary streamers could not reach to the outer cylinder as the primary one since it disappeared in the middle of the electrode gap when the primary one bridged the electrode gap. This is because that the electric fields at heads of secondary streamers become weaker when the plasma channel produced by the primary streamers fully developed between the electrodes. These phenomena have good agreement to the previous report by Namihira et al [6] and Wang et al [17].

In Fig. 6, the time dependence of the distance from the surface of the central wire electrode to the primary streamer heads was shown. From Fig. 5 and Fig. 6, the time to cross the electrode gap (≈38 mm) of the primary streamers was approximately 4 ns. The averaged propagation velocity of the primary streamers calculated from Fig. 6 was 8.8 mm/ns. The calculated velocity is approximately 6 times faster than that of previous one. In the previous works [6, 17], Namihira and Wang summarized that the primary streamers propagate between electrodes gap with the velocity of 1-2 mm/ns when the pulse power having 40-60 kV peak voltage, 20 ns rise time, and 100 ns duration, applied to the coaxial discharge electrode. In addition, Wang [17] indicated that the velocity of the primary streamers depends on the applied voltage to the central wire in the coaxial electrode and become faster exponentially to the applied voltage. In
the present work, the applied voltage to the inner wire in the coaxial electrode reached up to 100 kV since the ns pulse had 10 times faster voltage rise time. Therefore, the primary streamer propagation velocity of 8.8 mm/ns is reasonable.

Fig. 7 shows the streak image of the ns pulsed streamer discharge at the same condition as the flaming images were taken. In Fig. 7, the vertical and the horizontal axis display the position in radial direction of the coaxial electrode and the time, respectively. The bottom of and the top of the image in Fig. 7 correspond to the surface of the central wire electrode and the inner surface of the outer cylinder electrode, respectively.

**Figure 7.** Streak image of ns pulsed streamer discharges

**IV. CONCLUSIONS**

The images of the nano-second pulsed streamer discharges in a coaxial electrode filled up with atmospheric air have been observed using a high speed gated ICCD camera and a high dynamic range streak camera. The followings have been deduced from the works.

1) The ns pulse generator, having 2 ns of rise time and 5 ns of pulse duration, have been developed to observe ns pulsed streamer discharge.
2) Immediately after an application of positive ns pulse voltage to a central wire of coaxial electrode, primary streamers are initiated at surface of central wire and then propagate toward an outer cylinder electrode.
3) During propagation of primary streamers in coaxial electrode, its average velocity is 8.8 mm/ns.
4) Secondary streamers appear in vicinity of central wire of coaxial electrode immediately after development of primary streamers.
5) On fully development of primary streamers in coaxial electrode, secondary streamers disappear and glow-like discharge cause at around of central wire.

**V. REFERENCES**