Propagation Velocity of Pulsed Streamer Discharges in Atmospheric Air

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***Abstract*—Pulsed streamer discharges have been extensively used in many applications such as control of NO_X and SO_2 from exhaust gases, treatment of dioxins, removal of volatile organic compounds, generation of ozone, and laser excitation. An operation with a high energy efficiency is necessary for practical applications. It is very important to know the propagation mechanism of streamer discharges in order to improve the energy efficiency of pulsed discharge systems. In this paper, the emission from pulsed streamer discharges in a coaxial electrode system in air at 0.1 MPa was observed using a high-speed gated intensified charge-coupled display camera. A concentric wire-cylinder electrodes configuration was used. A positive pulsed voltage having a width of about 100 ns was applied to the central electrode. The streamer discharges were initiated at the inner electrode and terminated at the outer electrode. The propagation velocity of the streamer discharges was 1.8–3.3 mm/ns.**

***Index Terms*—Atmospheric air discharge, coaxial electrode, pulsed streamer discharges, streamer images, streamer in air, streamer propagation.**

I. Introduction

Acid RAIN arising from the combustion of fossil fuel produced by thermal power stations, certain industrial plants, and motor vehicles poses a serious problem to the environment. Several types of electrical discharges, such as surface, silent, and corona have been applied in the removal of NO_X and SO_2 from exhaust emissions at various energy efficiencies. Currently, developments in the pulsed power technology have enabled the production of efficient streamer discharges to remove NO_X and SO_2 [1]–[5].

Since the pulsewidth of the applied voltage has a strong influence on the energy efficiency of the removal of pollutants [6], [7], a detailed understanding of the development of streamer discharge using very short duration pulses is important for practical applications. The most effective condition of streamer discharges might be obtained from investigating the streamer propagation across the electrodes gap. The streamer discharge was originally proposed by Loeb [8], [9], Meek [10], [11], and Raether [12]. The electric field at the head of and the propagation velocity of the streamer were theoretically studied using computer simulations [13]–[18]. The light emission from streamer discharges was measured using an optical fiber and a photomultiplier tube in the vicinity of a central wire in coaxial electrodes geometry [19], [20]. The images of streamer discharges were observed using a high-speed gated camera in a coaxial electrodes system at 74 kPa of air [21] and a point-plane electrodes gap at 100 kPa of N_2 [22] and air [23].

In this paper, the emission from pulsed streamer discharges in coaxial electrodes geometry at 100 kPa of air pressure was observed with the intensified charge-coupled display (ICCD) camera having a high-speed gate. It was found that the streamer discharges started from the inner electrode and gradually extended toward the outer electrode. The propagation velocity of the streamer was found to depend on the applied voltage across the electrodes gap and was 1.8–3.2 mm/ns.

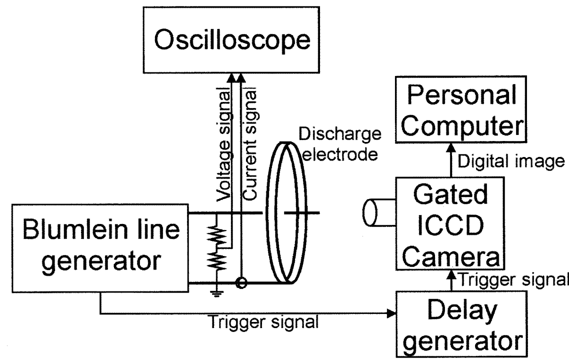

Fig. 1. Schematic diagram of the apparatus.

II. Apparatus and Procedure

Fig. 1 shows a schematic diagram of the experimental arrangement. A three-staged Blumlein line generator with a pulsewidth of 100 ns was used [2]. This generator was charged at 20, 25, and 30 kV. A rod made of tungsten, 0.5 mm in diameter and 10 mm in length, was placed concentrically in a copper cylinder. The diameter of the outer electrode was either 76 or 152 mm. A short length of the electrodes was necessary to render clear images of the streamer discharge. Dry air at 0.1 MPa was used. A positive voltage polarity was applied to the wire and measured using a voltage divider $(1\ \Omega/10\ \mathrm{k}\Omega)$. The discharge current was measured using a Rogowski coil (Pearson current monitor, Model 2878, Pearson Electronics, USA) on the ground wire. A high-speed gated ICCD camera (C7972-01, Hamamatsu Photonics, Japan) with a sensitive MCP (Micro Channel Plate, maximum gain $=$ 10 000) was used to observe the images of streamer discharges. The exposure time was fixed at 5 ns. The delay time after application of voltage was varied in steps of 10 ns in the range of 0–130 ns.

Manuscript received April 17, 2003; revised May 30, 2003.

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Digital Object Identifier 10.1109/TPS.2003.818765

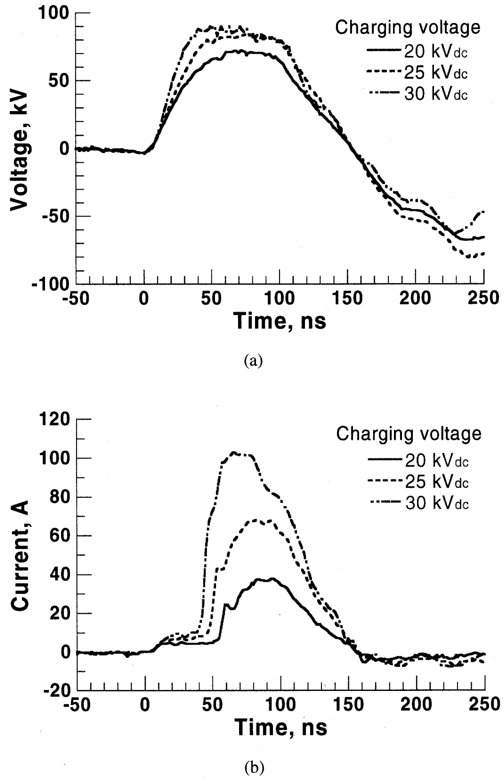

Fig. 2. (a) Applied voltage to and (b) discharge current in the coaxial electrodes gap for varying dc charging voltages to the Blumlein generator. Wire: 0.5 mm. Outer cylinder diameter: 76 mm.

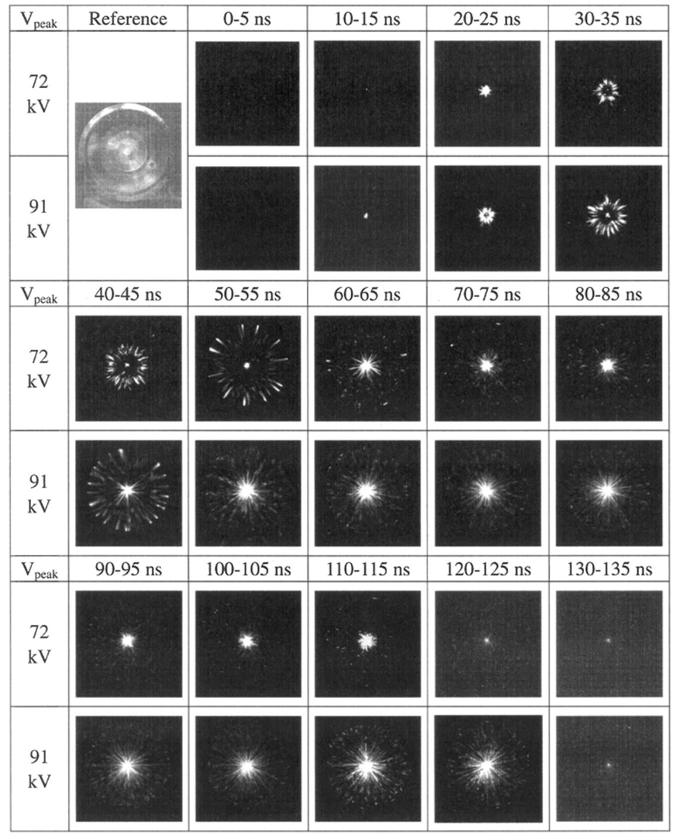

Fig. 3. Images of light emissions from streamer discharges as a function of time after initiation of the discharge current. Peak voltages: 72 or 91 kV. Outer cylinder diameter: 76 mm.

III. Results and Discussions

Fig. 2 shows typical waveforms of the applied voltage to and the discharge current in the electrode gap for different dc charging voltages to the generator. The output voltage from the generator was applied at $t = 0$. The maximum values of the pulsed voltage and the discharge current increased with increasing dc charging voltage. Typically the peak current increased from 38.0 A at 20 kV_{dc} to 105.0 A at 30 kV_{dc} charging voltages.

Fig. 3 shows the images of emissions from streamer discharges as a function of time after initiation of the discharge current using 72- and 91-kV pulses. The images had good reproducibility under the same experimental conditions because the interactions between the electric fields near the neighboring streamer heads are the same at somewhere in the coaxial electrode geometry [24]. The bright areas of the images show the position of the streamer heads during the exposure time of 5 ns. The streamer heads are associated with a higher density of ionization due to the high electric field therein [8]–[18], [25] and subsequently enhanced recombination, which is followed by increased light emission. The main wavelengths of the emissions were 337.1 and 391.4 nm from the second positive band and the first negative band of N_2, respectively [26]–[28].

It is observed from Fig. 3 that the primary streamers propagate from the central electrode to the outer electrode. The time to cross the gap of the primary streamer discharges was reduced from 55 to 40 ns with increasing peak voltages from 72 to 91 kV. Before the arrival of the primary streamers to the outer cylinder, the discharge current was small [$\sim$10 A, Fig. 2(b)]. This was because the charged species largely decayed by electron-ion recombination. Effectively, the capacitance between the streamer head and the outer electrode acted as a limiting impedance [21]. After the arrival of the fully developed primary streamers, the current was large [$\sim$40–105 A, Fig. 2(b)]. This was due to large ionization, which was sustained by a high space charge field (Fig. 3). This effectively resulted in the disappearance of the capacitance between the streamer heads and the outer electrode.

The secondary streamers started from the central electrode at 30–35 ns (Fig. 3). The secondary streamer disappeared at the middle of the electrodes gap because its electric field was insufficient to sustain the ionization.

After bridging the gap, the emission from the streamer discharges was observed in the vicinity of the central electrode. This is attributed to the strong electric field at the wire [29], [30].

Fig. 4(a) and (b) shows the dependence of the peak applied voltage and the velocity of the streamer heads on time after the application of the voltage for the 76- and 152-mm diameters of the outer cylinder, respectively. Previous results of streamer propagation simulations indicated that the radius of streamer heads was about 100 μm [14], [16]. The velocity $(V_{\rm streamer})$ of the streamer heads is given by the following equation:

$$V_{\rm streamer} = \frac{L}{t_{\rm exposure}} \quad (1)$$

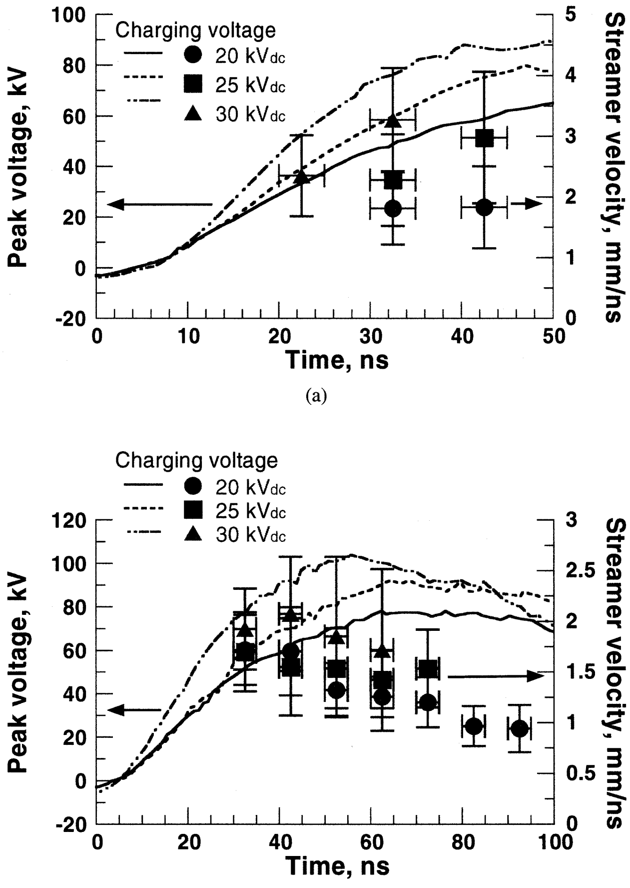

Fig. 4. Dependences of peak voltage to the central wire and the velocity of streamer head on time. Outer cylinder diameter: (a) 76 mm and (b) 152 mm.

where L and t_{exposure} (5 ns) are the length of the bright filament on each images (Fig. 3) and the exposure time of gated ICCD camera, respectively.

Fig. 5 show the dependence of the velocity of streamer heads on the applied voltage for the reactors (calculated from Fig. 4).

It is observed from Fig. 4(a) that the velocity of the streamer heads increases with increasing peak applied pulsed voltage to the electrode gap. The streamer discharges with maximum speeds of 1.8–3.3 mm/ns were greatly influenced by the electric field strength on the wire surface (Fig. 5). These results agree with previous work [15]–[18], [23]. Fig. 4(b) shows that for the larger outer cylinder the propagation velocity decreases with increasing delay time, and therefore with increasing distance from the wire (Fig. 5). This is attributed to the decreasing field with increasing distance from the central electrode in the coaxial geometry.

IV. SUMMARY

The images of the streamer discharges in a coaxial electrode at atmospheric pressure have been observed using a high-speed gated ICCD camera. The following have been deduced.

1) The head of the streamer discharge propagated from the central rod to the outer cylinder.
2) The maximum propagation speed of the streamer discharges was 1.8–3.3 mm/ns in the range of 72–91 kV of peak voltage. These velocities have good agreements to the computer simulations and the measurements in point-plate electrode geometry.
3) The propagation speed of the streamer discharges was influenced by the electric field strength on the wire surface.

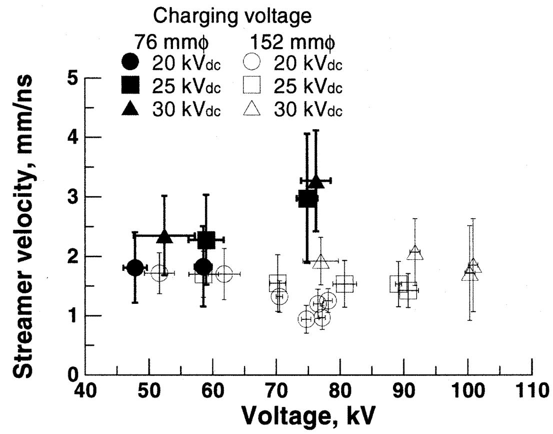

Fig. 5. Dependence of the velocity of streamer heads on the applied voltage for the two reactors. Outer cylinder diameter, covered mark: 76 mm. Uncovered mark: 152 mm.

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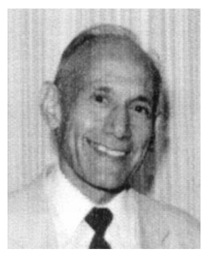

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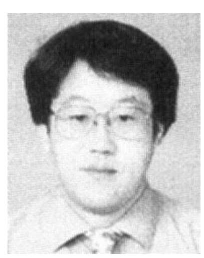

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