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Characteristics of laser-induced streamer corona discharge in a needle-to-plate electrode system

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Abstract

The purpose of this study is to understand the development of pulse laser-induced streamers from glow/streamer coronas created in a needle-to-plate electrode system at atmospheric pressure. The effect of the position of laser irradiation against the gap, its energy and the height of laser sheet on the discharge dynamics was investigated experimentally. Time-dependent properties of streamer propagation were observed as well as the trajectories between the gap using an ICCD camera with a few nano-second-order time resolution. It was found that there was a time delay between the laser irradiation and the start of the induced streamer discharge, depending on the position of laser incidence. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: DC positive streamer corona; Laser-induced discharge; Laser-induced fluorescence; NO removal; UV pulsed laser; Corona discharge; Streamer discharge

1. Introduction

A positive streamer is widely used in the field of air pollution control such as NO_x/SO_x removal and destruction of VOCs based on non-thermal plasma chemical reactions. The control of streamer corona discharge is a key issue to obtain stable plasma and improve the process efficiency since the energetic electrons and radicals

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responsible for chemical reactions are produced in the streamer. On the other hand, in order to understand the non-thermal plasma process for modeling the chemical reaction and developing a well-designed reactor, it requires an understanding of the gas molecule and radical dynamics inside the reactor. Laser-induced fluorescence (LIF) is a useful diagnostic method to observe the radicals and molecules in processing plasmas [1–3]. However, LIF measurements have so far been conducted after the discharge using a pulsed high voltage. The light emitted by the discharge can interfere in the LIF signal, because LIF signal is weaker than the discharge emission. Moreover, from our preliminary experiment, it is found that a UV pulsed laser employed to generate the LIF signal induces streamer discharge if a dc high voltage is applied to the electrode. Therefore, characteristics of the laser-induced streamers become important because the streamers can make the LIF measurement in the dc corona discharge difficult or even impossible.

In this study, in order to know how the laser induces streamers in the situation of LIF measurement, the characteristics of laser-induced streamer are investigated in a needle-to-plate electrode in air. In a needle-to-plate electrode configuration, positive corona discharge has several modes such as glow, brush, and streamer. Streamers propagate from the tip of the needle electrode to the plate electrode, which bridges the gap between the electrodes. The streamer is an important mode for flue gas treatment. Especially, the spatial and temporal dependence of streamer corona is also of interest as it provides information on NO removal process [4]. This paper describes the characteristics of the streamer induced by the UV pulsed laser. Although there have been several experiments on laser-induced electrical discharge using an excimer laser [5–8], the objects were different from this research and they were elementally studied to realize a laser-induced lightning.

2. Experimental apparatus

The schematic diagram of the experimental apparatus is shown in Fig. 1. The laser system consists of an excimer laser, a dye laser with SHG, an ICCD camera and a computer for synchronization of the operation of all units. This is a typical setup based on a tunable UV laser, suitable for the LIF measurement. We used the same system in order to investigate the characteristics of the laser-induced streamer that might become an obstacle for the LIF measurements. Taking into account the situation of LIF measurements in the NO removal process, the wavelength of pulsed UV laser used in this study was fixed at 226 nm, which corresponds to the $X^2\Pi(v''=0)\rightarrow A^2\Sigma^+(v'=0)$ transition of NO molecule. The laser pulses from a XeF excimer laser (Lambda Physik, COMPex 150, tuned at 351 nm) pumped a dye laser (Lambda Physik, SCANmate) with Coumarin 47 that generated a laser beam of a wavelength tuned around 450 nm. A BBO crystal pumped by the tuned dye laser beam produced the second harmonic radiation of a wavelength correspondingly tuned around 226 nm. The 226 nm-UV laser beam pulses with energies of 0.8–2 mJ and duration of $\approx$20 ns were transformed into the form of 1 mm-wide and 13–30 mm-high laser sheet passed in air between the needle-to-plate electrodes with 30 mm gap.

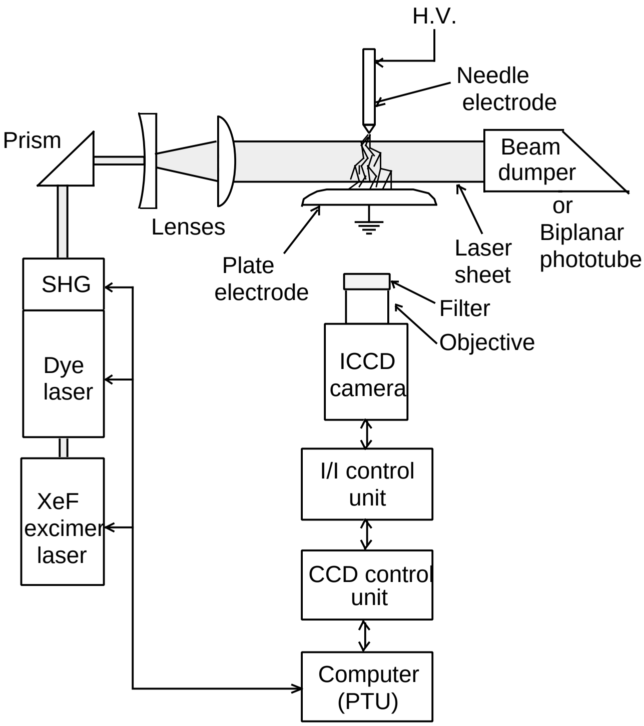

Fig. 1. Schematic diagram of experimental apparatus.

In the experiment, first, a dc high voltage with positive polarity was applied to the needle electrode, while the plate electrode with 100 mm diameter was grounded and corona discharge was generated. Then the UV pulsed laser sheet with 226 nm wavelength was shot in air between the needle-to-plate electrode. The two-dimensional images of laser-induced streamers were recorded by the ICCD camera (LaVision, Flame Star II). As the needle electrode, a tip of brass rod with 6 mm diameter was processed as a tapered profile (curvature radius of the tip = 0.5 mm). The effect of the position of laser irradiation against the gap, the height of laser sheet, and its energy on the discharge dynamics was investigated experimentally. The position of laser irradiation against the gap is defined as shown in Fig. 2. Laser energy was varied by changing the applied voltage to the excimer laser tube. The experiment was carried out at room temperature and under atmospheric pressure.

3. Results and discussion

3.1. Trigger characteristics of streamer discharge

Fig. 3 shows the time-averaged current-applied voltage characteristics for the needle-to-plate electrode system used in this experiment. Corona starts at 9 kV and

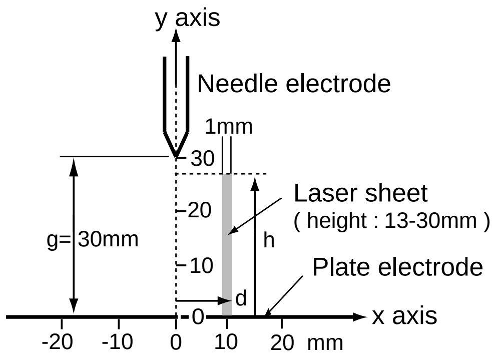

Fig. 2. Definition of the laser sheet position.

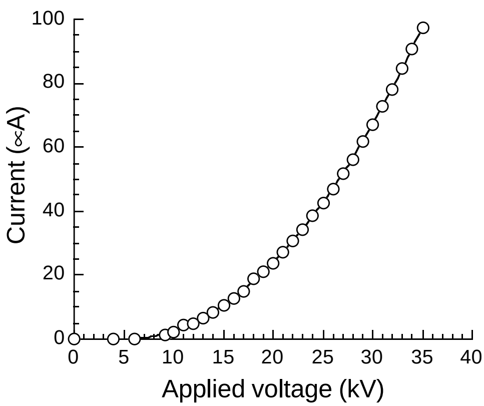

Fig. 3. Corona current as a function of applied voltage.

current increases with increase in the applied voltage. In this case, the discharge was a glow mode.

Fig. 4 shows the probability of the laser-induced discharge as a function of incident laser energy. The applied voltage and discharge current were 25 kV and 43 μA, respectively. Each data point in Fig. 4 is an average of 100 shots for the given laser energy. The triggering probability increases with increase in the laser energy, and 100% triggering can be achieved when the laser energy is higher than 1.1 mJ.

Fig. 5 shows the typical time relationship between laser sheet irradiation and induced streamer corona. In this case, the laser sheet with 30 mm height was irradiated to the position of 10 mm in a horizontal direction from the needle electrode. After 220 ns from a laser incidence, the induced streamer corona is initiated and continues for about 350 ns, while, in the NO molecule visualization using the LIF system, LIF image appeared immediately after the laser incidence and continued about 30 ns [9]. From these results, it was found that we could observe the

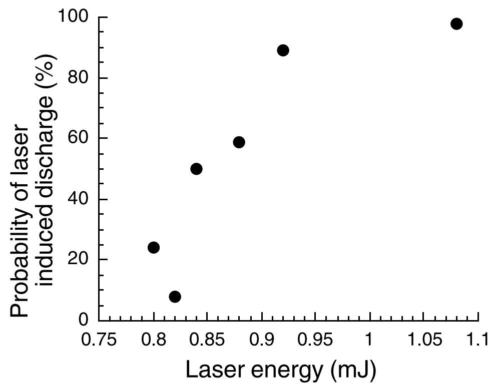

Fig. 4. The probability of the laser-induced discharge as a function of incident laser energy (laser sheet: $h = 30\,\text{mm}$, $d = 0\,\text{mm}$, applied voltage = 25 kV).

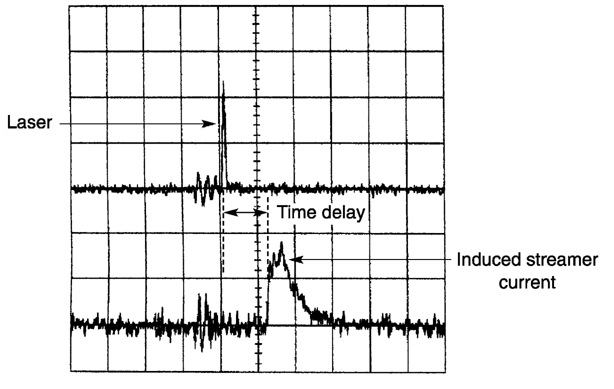

Fig. 5. Time relationship between laser and induced streamer (laser sheet: $h = 30\,\text{mm}$, $d = 10\,\text{mm}$, laser energy density = ca. 3.3 mJ/cm^2, applied voltage = 25 kV, 200 ns/div., current = 20 mA/div.).

LIF image and laser-induced streamer corona separately by changing the delay time and gate time of the ICCD camera. Moreover, the probability of overlap of regular streamer coronas and laser irradiation/LIF is considered to be very low.

Fig. 6 shows the relationship between the triggering probability of the streamer coronas and the time from a laser incidence to an induction of streamers. The effect of the height of laser sheet on the triggering probability and the delay time is shown in Fig. 6(a). The delay time closely relates to the triggering probability. As the gap between the top of the laser sheet and the tip of the needle electrode increases (i.e. the height of laser sheet decreases), the triggering probability decreases and the delay time increases. The effect of the horizontal position of laser sheet on the triggering probability and the delay time is shown in Fig. 6(b). The same tendency is observed in the case of Fig. 6(a).

In contrast with positive coronas, no laser-induced streamer discharge was observed for negative coronas. One of the reasons is the difference of the behavior of

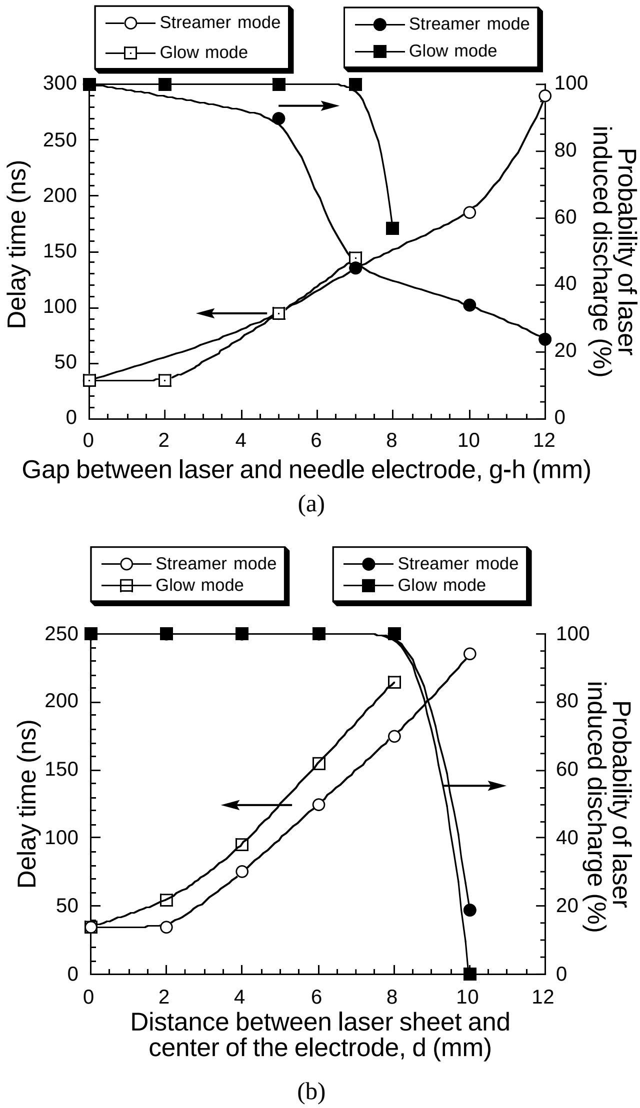

Fig. 6. Characteristics of laser-induced streamer discharge (laser energy density = ca. 3.3 mJ/cm^2, applied voltage = 25 kV); (a) effect of the vertical position of laser on the induced discharge ($d = 0$ mm); (b) effect of horizontal position of laser on the induced discharge ($h = 30$ mm).

electrons in the electric field at different polarities. Namely, UV pulse laser produces the electrons by photo-ionization [5–7] or photo-detachment of O^- ions [8]. In the case of positive coronas, these electrons are considered to produce the avalanche during their acceleration towards the needle electrode, and streamer starts from the needle electrode (see Fig. 7). Whereas, in the negative coronas, the electrons produced move towards the plate electrode and they are trapped in between the

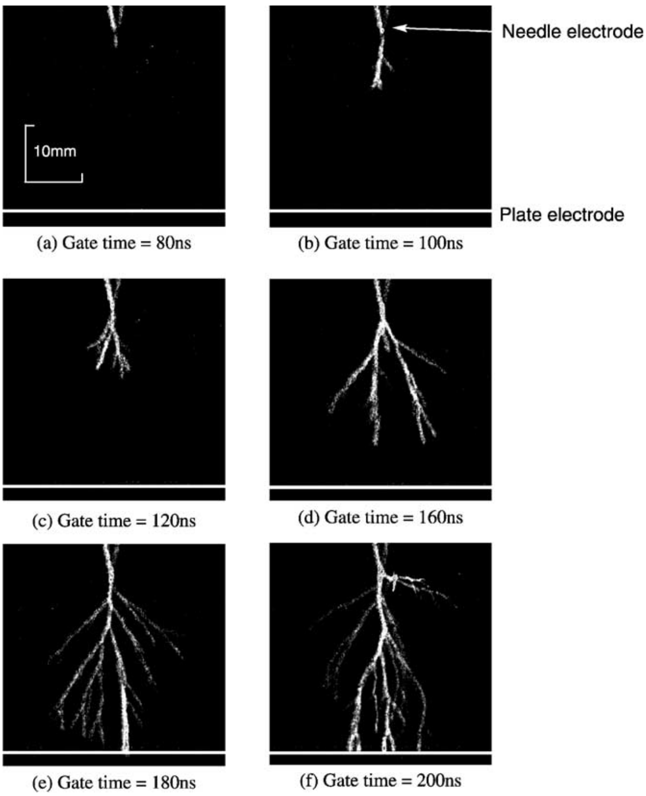

Fig. 7. Characteristics of laser-induced streamer discharge (laser sheet: $h = 30\,\text{mm}$, $d = 2\,\text{mm}$, laser energy density = ca. 3.3mJ/cm^2, applied voltage = 25 kV).

electrodes to form negative ions due to the attachment. Consequently, it can be considered that the behavior of electrons in the gap plays an important role in having an influence on the discharge.

3.2. Features of the induced streamer discharge

Fig. 7 shows images of the streamers induced by a single shot of the laser sheet pulse in air. The energy density of the laser was $\approx 3.3\,\text{mJ/cm}^2$. Each image was taken in separate laser irradiation experiments by changing the gate time. The times in each figure show the gate time of the ICCD camera. Because of the good reproducibility of the phenomena, these images represent temporal variation of the propagation of the streamer discharge and hence the velocity of the streamers. In Figs. 7(e) and (f), the streamer consists of several branches and bridges the gap between the electrodes. Each streamer channel propagates along the laser sheet. Similar laser-induced streamers have been observed in dc glow corona with an intense laser beam [10]. From the time evolution of the streamer discharge in Fig. 7, the estimated velocity of the streamer is $\approx 3 \times 10^5$ m/s. This result is in agreement with our previous results measured using a photo-multiplier tube [4].

4. Conclusions

The characteristics of UV pulse laser-induced streamers have been presented and discussed qualitatively. The results are summarized as follows:

(1) Timing between laser irradiation, LIF signal and the laser-induced streamer corona was identified. It is possible to observe the LIF signal and the laser-induced streamer corona separately by adjusting the delay time and the gate time of the ICCD camera.
(2) The time evolution of the induced positive streamer corona was visualized in the needle-to-plate electrode system. The estimated velocity of the streamer is $\approx 3 \times 10^5$ m/s.
(3) As the gap between laser sheet and the needle electrode increases, the triggering probability decreases and the delay time increases.
(4) No laser-induced streamer discharge was observed for negative coronas.

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