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Communication

Oscillation of Gas Density in the Gas Filament Remained by a Streamer Discharge in Water

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Abstract: When a streamer discharge occurs in water, several luminous plasma filaments will be created in the water during the discharge. After the discharge, these plasma filaments turn into neutral gas phase and remain in water. The gas filament remained in water is a good object for studying the basic processes involved in the streamer propagation. We investigated the evolution of the gas filaments remained in water after a streamer discharge at different experimental conditions. We recorded eight successive images during one discharge pulse. The density of gas in the gas filament and the radius of the gas filament were measured from the obtained images. We found that the radius of the gas filament and the density of gas in the gas filament are almost not influenced by the impulse voltage within the range studied. While the conductivity of water has strong effect on the radius of the gas filament and the density of gas in the gas filament. The radius of the gas filament becomes thicker and expands faster as the conductivity of water becomes larger. The density of gas in the gas filament remained in water oscillates between 400 to 800 kg/m^3 with an duration of ~10 µs during the expansion period of 4–39 µs after the HV pulse starts. Both the impulse voltage and the conductivity of water do not affect the oscillation duration of the density of gas in the gas filament.

Keywords: electric discharge in water; gas filament; gas density oscillation

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1. Introduction

A streamer discharge in water produces chemical reactive species (H, OH, H_2O_2, etc.) directly in bulk water [1–3], releases shockwaves as it propagates through water [4–6] and radiates ultraviolet rays [7,8]. In recent decades, it has attracted intensive attention of researchers from multidiscipline for a variety of promising applications, such as biomedicine [9], material synthesis [10,11] and organic pollution removal [12,13].

Generally, a streamer discharge in water creates several luminous plasma filaments during the discharge [14,15]. After the discharge has finished, these streamer filaments turns into neutral gas phase filaments, and experience an expansion and collapse process, and then vanish from the bulk water. In some case, the entire process lasts ~200 µs [16]. To date, the consensus about the physical mechanism of initiation and propagation of streamer discharge in water (or liquid) has not been achieved [17–21]. There are two competing theories about the ignition mechanism of the electric discharge in water (or liquid). One is so-called electron impact ionization theory, and the other is so-called bubble theory [17]. The microsecond impulse electric discharge in water favors the bubble theory [22,23], while the nanosecond impulse electric discharge in water prefers electron impact ionization theory [24–26]. Generally speaking, the nanosecond duration high-voltage pulses are very suitable for investigating the initiation processes, while the microsecond pulses take the advantage for studying the propagation mechanism of the streamer discharge in water. To reveal the basic processes involved in the electric discharge in water, much more studies (experimental, theoretical or modeling) on the physical feature of the streamer filament are necessary, for example, the density of the gas, density and temperature of electron, plasma volume, plasma conductivity and electric field in and near the head of the streamer filament. To date, the diagnostic method for the electric discharge in liquid are limited, mainly relying on the imaging technique or the spectroscopy. Developing some suitable diagnostic methods for these physical parameters is also an important challenging task.

The gas filament remained by a streamer discharge in water is an important and interesting object for exploring the basic processes involved in the streamer propagation. Considering the gas filament as a quasi-cylindrical bubble in water, it will be a valuable object for the experimental study of non-spherical bubble dynamics [27]. In our previous work [28], we developed a method, so-called modified optical refraction method, for studying the density of gas in the gas filament remained by a streamer discharge in water. Based on this method, the average density of the gas in the gas filament remained in water by a microsecond impulse streamer discharge were investigated [29]. The average density of the gas in the gas filament is about 610 to 880 kg/m^3, being sensitive to the conductivity of water. Based on the deduced energy needed for producing gas of a unit mass in the streamer filament, we found that the vapor in the gas filament could not be created through a heating process because the energy needed for generating the vapor of a unit mass is insufficient for the vaporizing the liquid water of a unit mass. According to the dielectric barrier discharges (DBDs) analogy, the ion-impact sputtering maybe takes an essential role in creating a segment of gas in front of the streamer filament [30].

In this paper, the temporal evolution of the gas filament remained in water by a microsecond impulse streamer discharge was studied. The radius of the gas filament and the density of gas in the gas filament was measured. We found a periodic oscillation of the density of gas in the gas filament while the gas filament expands.

2. Methods

All the experiments were performed in a water bin at room temperature (~23 °C). The experimental setup has been described elsewhere [29,30]. Briefly, a needle anode and a plane cathode was installed in the water bin, fixing the distance between the needle anode and the plane cathode at 40 mm. The curvature radius of the needle anode was polished to ~30 μm at its tip. High voltage (HV) pulses similar to as shown in Figure 1 were applied to the needle anode to create streamer discharges in water. The injected energy per pulse was about 10 to 300 mJ, depending on the impulse voltage and the conductivity of water.

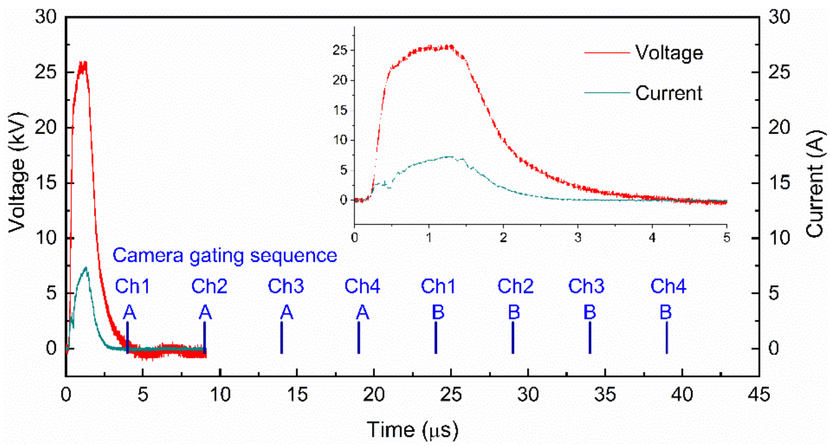

Figure 1. Example of the waveforms of the discharge pulse, as well as the sequence of the camera gating.

In present experiments, the HV pulse drops to ~0 V 4 μs after the HV pulse starts. The plasma filaments have changed into neutral gas phase filament since 4 μs after the HV pulse starts and remains in the water. The temporal evolution of the gas filament was observed from 4 μs after the HV pulse started by utilizing an ultrahigh-speed camera. The camera consists of four ICCD channels and each channel can expose twice in an interval of ≥500 ns. The camera gating was synchronized with the HV pulse. In this way, eight successive shadow images of the expansion phase of the gas filament was obtained during one discharge pulse. In this case, 30 sets of images were recorded at the same experimental condition. Each image set corresponds one discharge pulse and consists of eight successive images. The sequence of camera gating is also shown in Figure 1. The four ICCD channels are denoted as Ch1, Ch2, Ch3 and Ch4, the first and the second exposure are denoted as A and B, respectively. Eight successive shadow images without electric discharge in water were also acquired before applying the HV pulses to the electrodes.

3. Results

An example of the temporal evolution images of the gas filament remained by a single discharge pulse at 250 µS/cm and 26 kV are shown in Figure 2. During a discharge pulse, 1 to 5 main branches remain in the water. Based on the modified optical refraction method [28,29], the density of gas in the gas filament were measured from the eight shadow images. A gas filament was divided into several segments and each segment was considered as a short cylinder (~0.5 mm in height). At each segment of the filament, the light intensity profile along a line perpendicular to the axis of the gas filament were extracted. The refractive index n_g of the gas in that segment and the radius of that segment of the gas filament were deduced from the obtained light intensity profile with and without discharge in water. The density of gas in the gas filament were obtained from the Gladstone—Dale relationship,

$$\frac{\rho_g}{\rho_0} = \frac{n_g - 1}{n_0 - 1} \tag{1}$$

where ρ_0 and n_0 are the density and the refractive index of water vapor at standard state, respectively. The measured densities of gas and the radii at different position were averaged and taken as the density of gas in the gas filament and the radius of the gas filament, respectively.

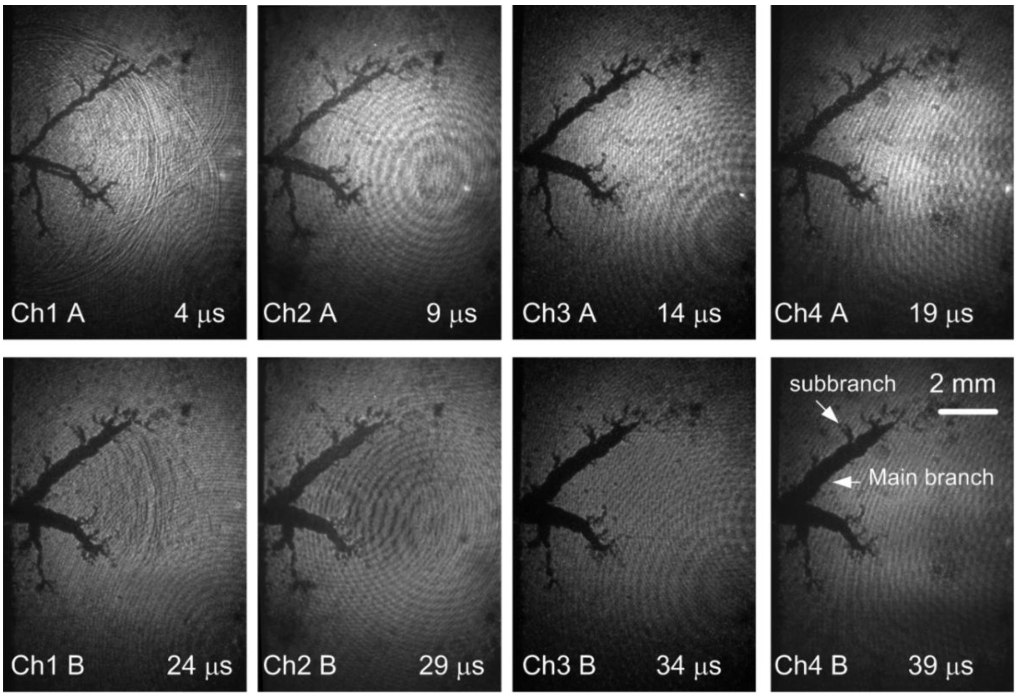

Figure 2. Temporal evolution images of the gas filament remained in water by a single discharge pulse (250 µS/cm and 26 kV, exposure 20 ns and interval 5 µs).

We have performed many experiments by changing the conductivity of water and the impulse voltage. The radius of the gas filament and the density of gas in the gas filament were measured from the eight successive shadow images. The results on the evolution of the radius of the gas filament and the density of gas in the gas filament are shown in

Figure 3. For comparing the density of gas in the gas filament with the density of water in liquid phase (1000 kg/m^3), we adopted kg/m^3 unit for the density of gas in the gas filament. The radius of the gas filament is almost not influenced by the impulse voltage within the range studied. However, the conductivity of water has strong effect on the radius of the gas filament, which becomes thicker and expands faster as the conductivity of water becomes larger, suggesting that the pressure in the gas filament increases as the conductivity of water becomes larger. The density of gas in the gas filament drops from ~800 to ~400 kg/m^3 as the gas filament expands. The impulse voltage does not significantly affect the density of gas in the gas filament. With increasing the conductivity of water, the density of gas in the gas filament decreases.

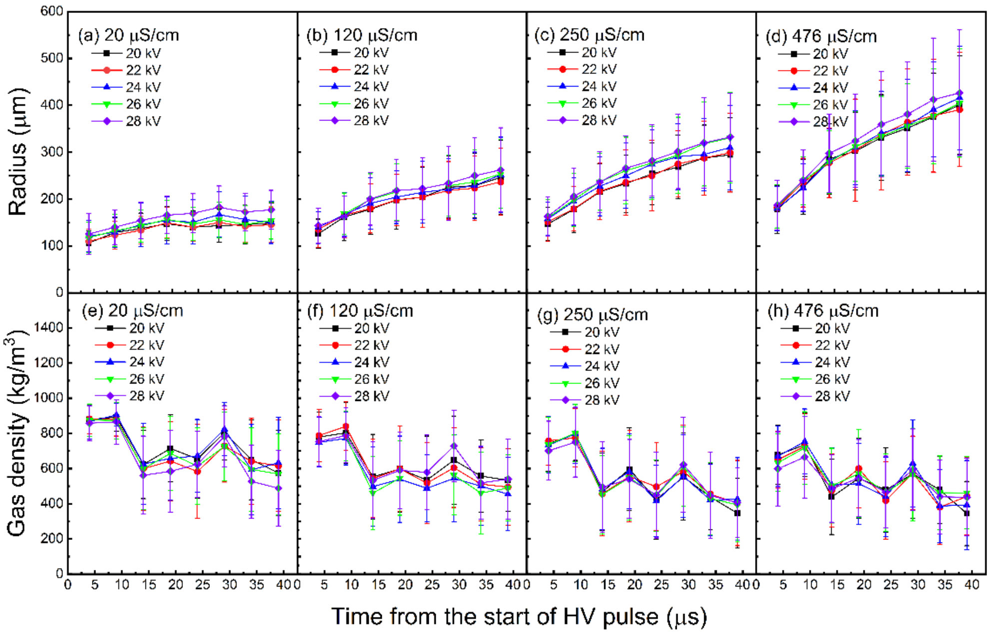

Figure 3. (**a**–**d**) Expansion of the radius of the gas filament. (**e**–**h**) The temporal evolution of the density of gas in the gas filament corresponding to (**a**–**d**), respectively. The value of each point is averaged from many filaments that were remained by different HV pulses.

Surprisingly, the density of gas in the gas filament oscillates while the gas filament expands. The duration of the oscillation is about 10 µs, which is either dependent on the impulse voltage nor on the conductivity of water. At present, we suspect that the oscillation of the density of gas in the gas filament maybe attributes to the shock release behavior during the streamer propagation. As the streamer filament propagates about every 160 µm through the water, it releases a circular shock front from its head [30,31]. When the streamer filament reaches its maximum length, several tens of shock front have been released in total. Even though the shock release do not affect the propagation of the plasma filament through water, the several tens of shock would be propagating in the preformed plasma filament and reflecting by the metal anode, causing the relative long-term oscillation of the density of gas in the gas filament after the discharge. Moreover, the several tens of isolated shock front forms a shockwave chain around the streamer filament and overlaps each other. This would cause an oscillation in the ambient water near the streamer filament, making the gas filament expands in an oscillating way. For a clear understanding about the oscillation of the density of gas in the gas filament, the detail knowledge about how a gas phase microsegment emerges in front of the head of the streamer filament during the discharge is necessary.

4. Conclusions

We have studied the temporal evolution of the gas filament remained in water by a streamer discharge. For observing the temporal evolution of the gas filament, eight successive shadow images were recorded during one discharge pulse. Based on the modified optical refraction method and the recorded images, the density of gas in the gas filament and the radius of the gas filament at different experimental conditions were investigated. We found that the radius of the gas filament, as well as the density of gas in the gas filament, are almost not influenced by the impulse voltage within the range studied. However, the conductivity of water strongly affects the radius of the gas filament and the density of gas in the gas filament. The radius of the gas filament becomes thicker and expands faster, while the density of gas in the gas filament decreases as the conductivity of water becomes larger. The density of gas in the gas filament oscillates between 400 to 800 kg/m^3 with a duration of ~10 µs during its expansion period of 4–39 µs after the HV pulse starts. The oscillation duration of the gas density is not influenced by both the impulse voltage and the conductivity of water.

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