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Dynamics of Underwater Discharge: A Scenario of Multiple Events from Pre-discharge to Post-discharge

水中放電のダイナミックス：放電前から放電後までのシナリオ

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A laser Schlieren technique has been applied for the visualization of the pressure field of a single-shot underwater pulsed discharge. A needle-to-plane electrode submerged in distilled water was used. The detailed time- and space-resolved observation of both streamers and pressure waves was performed. As a result, several phenomena, such as the phase change prior to the initiation of the discharge, primary and secondary streamers propagation, shock wave generation, and the bubble formation, were observed. From these observations, a scenario of multiple events from pre-discharge to post-discharge was proposed.

1. Introduction

Recently, liquid-related electrical discharges, such as discharges in water or discharges on the water surface, have been widely studied for environmental and bio-medical applications as well as nanomaterial processing. However, the underwater discharge mechanisms are more complicated compared to the discharge in air. In addition, several phenomena, such as the radical formation, UV radiation, and shockwave generation, are involved in the underwater discharge. Although the discharge observation based on the optical emission is widely performed, the obtained information is limited on the streamer propagation stage. To clarify the initiation and post-discharge phenomena, another optical observation, such as shadow/Schlieren imaging and Mach-Zehnder interferometry has been investigated [1-2].

In this study, a laser Schlieren technique was used for visualization of the pressure field of underwater discharge. To avoid the influence of former discharge, a single-shot pulsed discharge was used instead of repetitive pulsed discharges and liquid-gas dynamics was observed from the initiation to after the extinction of the discharge.

2. Experimental Procedures

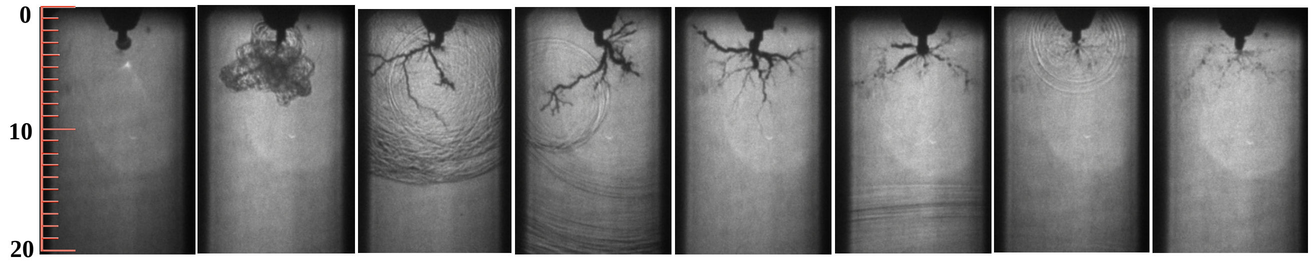
A laser Schlieren imaging technique was used to study the liquid-gas dynamics in the discharging reactor. KrF excimer laser was used as a pulsed light source. A needle-to-plane electrode with a 40 mm gap submerged in distilled water (3 μS/cm) was used. A pulsed high-voltage circuit with a MOS-FET switch was used to generate a single-shot underwater pulsed discharge. The ICCD camera was used to obtain Schlieren images at various time delays between the laser pulse and the pulsed high-voltage.

3. Results and Discussion

Fig.1 shows the typical temporal and spatial evolution of the Schlieren images for various delay times after the application of the high voltage pulse. Each image presented in Fig.1 was selected from a set of different observation at the same conditions (applied voltage 23 kV, pulse duration 10 μs, ICCD gate time 300 ns).

At first, the appearance of opaque region with a spherical shape can be observed at the tip of the needle electrode before the initiation of the discharge as shown in Fig.1(a). It is considered that a phase change is occurred prior to the discharge initiation. One possible mechanism for the instability initiation is modification of electric field with a sharp variation in permittivity near the powered electrode [3]. Since the change of permittivity or density variation leads to a change in refractive index in water, therefore we can observe this effect as the generation of opaque region by the Schlieren photograph. Pre-existing microscopic gas bubbles within the opaque region may contribute for the initiation of electron avalanche, leading to the generation of primary streamers with tree-like morphology.

After primary streamers, secondary streamers propagate beyond the opaque region and a few long



(a) - 30 ns (b) 600 ns (c) 4.7 μs (d) 9.0 μs (e) 17.6 μs (f) 50 μs (g) 87 μs (h) 140 μs

Fig. 1. Time evolution of Schlieren images.
(applied voltage: 23 kV, discharge current:4-6 A, needle-to-plane electrode gap: 40 mm, distilled water)

filamentary discharge channels create due to the field induced dissociation and ionization at the tip of the streamer head [1]. The propagation velocity of the secondary streamer head is $3x10^4$ m/s [4]. Moreover, the several shock waves appear with the streamer propagation as shown in Fig. 1(b). The reason for the multiple shock wave generation is due to the step-like streamer propagation similar to the stepped leader of a lightning.

After the propagation of secondary streamers, the charge accumulation occurs at the interface between gas and liquid, causing the re-illumination. As a time elapses, the outgoing shock wave is often generated from the tip of the needle electrode (Fig.1(c)). A spherical wave is also created at the node of streamer branching, and by superposition of all of the waves a complex wave pattern is generated (Fig.1(d)).

On the post discharge stage, tracks of streamer propagation near the power electrode become gaseous channels and those diameters become thicker than that of secondary streamer (Fig.1(e)). Although the applied pulsed voltage diminishes by ~14 μs, the shock wave is still actively expanding and then reflecting by the plane electrode as shown in Fig. 1(f). The gas channels are disrupted and develop into gas bubbles which grow and decay, causing the generation of bubble wave (Fig. 1(g)). Finally the trace of streamers fades away in time and several disrupted bubbles are sustained in liquid, moving upward direction (Fig. 1(h)).

From these observations, Fig. 2 depicts a plausible scenario of multiple events from pre-discharge to post-discharge.

4. Conclusion

The commonly observed phenomenon of underwater discharge generated by a single shot pulsed high-voltage was investigated experimentally. A definite sequence of events starting with the generation of opaque region, followed by the discharge initiation, the primary/secondary streamers and re-illumination as a typical discharge mode, shock wave propagation, localized gas channel at the trace of streamer propagation, and eventual bubble formation at the tip of the needle electrode was observed by using a laser Schlieren technique.

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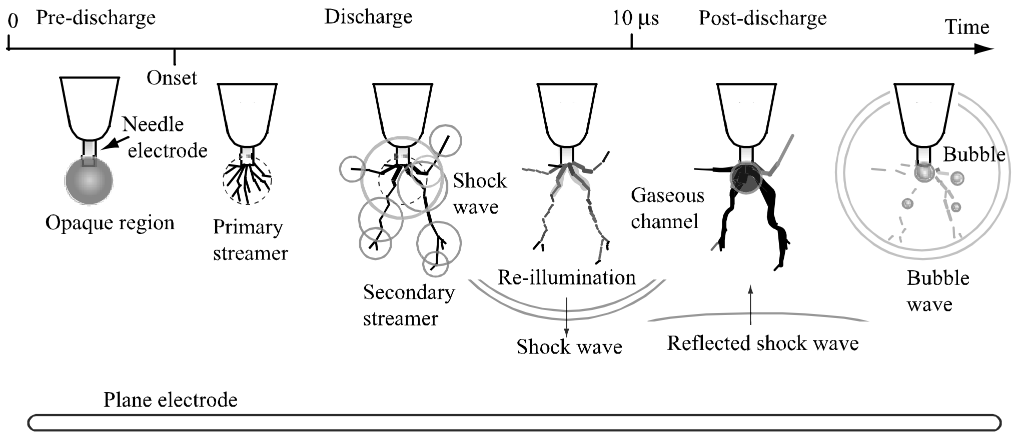

Fig. 2. Illustration of a scenario of multiple events from pre-discharge to post-discharge in underwater discharge.