Impacts of electrode structure on plasma discharge in pre-breakdown period for water environment treatment

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Abstract. Since the liquid discharge problem has been incorporated into the line of sight, many scholars have done a lot of research on it. In this paper, experiments on the pre-breakdown period in underwater plasma discharge were carried out. Among the parameters of underwater plasma discharge, the electrode structure is firstly taken account by virtue of its intuitive, easy-to-process, and diversity. With the refinement of the application of liquid discharge in liquid-electric processing, research on the effect of electrode structure on underwater plasma discharge is deepening. In this paper, two sets of electrode groups were proposed in a pioneering manner through the theoretical analysis and precise control of the experimental parameters. Based on the experimental results, rigorous and reliable analysis and summary were demonstrated. The conclusions of this paper would be helpful for water environmental treatment.

1. Introduction

The underwater plasma acoustic source has the characteristics of wide spectral coverage, high repetition frequency, good safety and so on. In recent years, it has been gradually incorporated into underwater environmental applications. In the underwater plasma discharge period, the mechanical effect of strong destructive action is accompanied by abundant optical and chemical effects. The plasma in the water will produce strong ultraviolet radiation. The vaporization and ionization of water will produce strong oxidized particles such as H₂O₂ and O₃, which could not only degrade the organic matter dissolved in the water, but also effectively kill harmful microorganisms such as bacteria. Therefore, underwater plasma discharge is widely used in wastewater treatment [1].

The characteristics of the aqueous medium make the physical process of discharge in the liquid more complicated than that in the air [2-13]. Especially in the pre-breakdown stage, there is no accepted mechanism till now. The ‘tip-plate’ structure electrode is a structure widely used in the study of liquid discharge. It is composed of an elongated tip electrode and a thin plate electrode. The radius of curvature of the tip electrode head is tiny, and could even reach the magnitude of micron based on the processing precision. An electric high voltage is applied to the tip electrode to form a high distortion electric field at the electrode head, which is easy to generate a discharge streamer. The electric field between the positive and negative electrodes is a non-uniform electric field, which might be controlled by tuning the radius of curvature of the electrode tip. Therefore, this kind of structure electrode is suitable for the study of arc discharge and corona discharge. On the other hand, the ‘tip-tip’ electrode structure, also a commonly used structure in the laboratory, is consist of a positive head and a negative electrode head with both heads are of small radius of curvature. This structure makes it
easier to produce a strong distortion electric field between the electrodes. The extremely uneven distribution of electric field near the electrode is conducive to studying the influence of the electric field on the development of the streamer.

Apart from the two common laboratory electrode structures mentioned above, various electrode structures have been proposed for specific research purposes or application needs. As shown in Figure 1, Taiyun Zhu’s work demonstrated a special electrode structure, ‘ball-ring’ electrode structure [14], in which the spherical electrode is coated with a layer of silicone rubber coating, which can generate multiple radial streamer discharges in tap water. Different from the previous voltage conditions of high field intensity and short pulse duration, this electrode structure is accessible to generate large volume streamer discharge under low voltage conditions in water. Meanwhile, they also studied the development characteristics of the ‘ball-plate’ electrode with insulating coating [15], as shown in Figure 2, and discussed the effect of electrode polarity, water conductivity and environmental pressure on the transmission mechanism of the streamer.

![Figure 1. Schematic diagram of the ‘ball-ring’ electrode structure experimental warehouse [14].](image1)

![Figure 2. ‘ball-plate’ electrode experimental device of unwater discharge [15].](image2)

Different from the electrode structure based on the refinement of experimental parameters in the laboratory, the underwater plasma discharge system oriented as a strong acoustic source requires a long-time service stability in a non-laboratory environment. The high-intensity repeated discharge process inevitably causes severe erosion on the surface of the metal electrode. Therefore, in practical applications, those effects such as the precise radius of curvature of the electrode tip, the harsh smoothness of the electrode surface and the high loss of the electrode surface coating are not the main parameters in the design, as they will inevitably degenerated rapidly. In this paper, the experimental parameters which we focus on are the structural design of the electrode and the adaptability of the electrode structure to conductivity.

2. Experimental design

One of the main applications of underwater plasma discharge systems is as an underwater acoustic source, where water is the working medium. We know that water is electrically conductive, and its conductivity changes greatly in the natural water environment. For example, seawater, which has a good electrical conductivity, the conductivity varies significantly with the composition of electrolytes and tiny particles. In this paper, the adaptability of the electrode structure to conductivity is our primary consideration, which is also the focus of the experimental design.

This paper proposed two types of electrode groups. The anode is a positive high voltage loading electrode, the structure of the anode plays a crucial role in the pre-breakdown process and the formation of the discharge plasma. When the electrode discharges, a shock wave is generated, which
has a strong destructive effect on the electrode structure [16]. We designed a buffer structure on the electrode head to alleviate the effect of shock wave. The two sets of buffer structures are respectively made of metal cone type head (type-I electrode) and polytetrafluoroethylene (PTFE) cone type head (type-II electrode). The dimensions and structure of the components are the same, the former adopts the same stainless steel as the electrode, which is equivalent to artificially increasing the contact area between the metal anode and water, the latter adopts PTFE material to ensure the insulation effect between the anode and the water, as shown in Figure 3 and Figure 4. The anode heads of the two electrode groups are all hemispheres with a radius of 2 mm. It ensures that the discharge gap structure of the electrodes are the same when the voltage is applied to the electrodes, and the electric field between the electrodes are basically consistent. In both structures, the electrode rods are wrapped in polytetrafluoroethylene to prevent contact from the aqueous medium.

![Figure 3. type-I electrode.](image)

![Figure 4. type-II electrode.](image)

The cathodes of the two sets of electrodes are all hemisphere made of stainless steel with a radius of 2 mm. During the experiment, the electrode gap was fixed at 2 mm, the initial voltage was adjustable from 14 to 20 kV, and the capacitance was 1 μF. In order to illustrate the response of loop current and voltage to the variety of conductivity of aqueous medium under the same electrode structure conditions, water with different conductivity is used as the discharge medium, which are 300 μS/cm and 8200 μS/cm, respectively. The conductivity is controlled by the amount of NaCl in deionized water.

3. Experimental results and analysis
The current and voltage waveforms are illustrated in Figure 5 and Figure 6 when the type-I electrode discharged in water with conductivity of 300 μS/cm and 8200 μS/cm respectively, under the condition of 18 kV initial voltage.

![Figure 5. Current and voltage waveforms of type-I electrode discharge in 300 μS/cm water conductivity.](image)

![Figure 6. Current and voltage waveforms of type-I electrode discharge in 8200 μS/cm water conductivity.](image)
As the water is electrically conductive, when the voltage is applied to the gap in the water, the energy on the electrode is inevitably dissipated through the metal anode to the water around the electrode, and the cathode is grounded to form a leakage current. Based on Figure 5 and Figure 6, following results were observed:

1. For aqueous medium with conductivity of 300 $\mu$S/cm, the residual voltage at the time of breakdown is 15.1 kV, the pre-breakdown time is 619.3 $\mu$s as shown in Figure 5. When the conductivity of the aqueous medium is increased to 8200 $\mu$S/cm, the pre-breakdown time is significantly reduced to 7.7 $\mu$s approximately, while the residual voltage drops sharply to 9.8 kV as shown in Figure 6.

2. For aqueous medium with conductivity of 8200 $\mu$S/cm, during the discharge pre-breakdown stage, it is evident that the current in the loop passes with the maximum current is approximately at 800 A. When the conductivity is reduced to 300 $\mu$S/cm, the current in the loop is dropped to 10 A approximately.

From the perspective of the structure, comparing to the type-Ⅱ electrode group, the contact area of the type-I electrode group between the anode and the water is much larger. Therefore, for the type-I electrode group, more electric energy was dissipated between the contact surface of the electrode and the water into the surrounding aqueous medium, which was then transmitted to the cathode in the pre-breakdown phase. The energy in the storage capacitor, the voltage at the anode head and the electric field intensity between the electrodes decreased with the dissipation of electric energy increasing in the type-I electrode group, resulting in a slower rate of streamer generation and development in the pre-breakdown phase, which was required to bridge the two electrode channels, and it eventually led to an increase in pre-breakdown time. With the pre-breakdown time increasing, the amount of dissipated electric energy rose during the period. Therefore, a positive feedback loop was formed until the conduction path was generated. The electric energy dissipated from the contact surface might reach a considerable amount to produce a serious impact on the residual voltage during severe discharge, eventually the breakdown might even not complete. When the dissipated electric energy reached a certain amount, even if the entire discharge process was completed normally, the accompanying optical, physical, chemical, and mechanical effects would be evidently weakened.

Excessive contact area between the electrode and the aqueous medium leads to unnecessary consumption of energy. This area is defined as the energy dissipation area in this paper where the dissipative current is generated. The dissipative current is also referred to be generated by the water, regarded as the large resistance conductor, between the electrodes during the pre-breakdown.

The current and voltage waveforms are illustrated in Figure 7 and Figure 8 when the type-Ⅱ electrode discharged in water with conductivity of 300 $\mu$S/cm and 8200 $\mu$S/cm respectively, under the condition of 18 kV initial voltage.

**Figure 7.** Current and voltage waveforms of type-Ⅱ electrode discharge in 300 $\mu$S/cm water conductivity.

**Figure 8.** Current and voltage waveforms of type-Ⅱ electrode discharge in 8200 $\mu$S/cm water conductivity.
As depicted in Figure 4, the anode of the type-II electrode group is almost completely enclosed in the insulating cover, so that the dissipation area is sufficiently reduced. Compared with the type-I electrode group, the pre-breakdown time is shortened in these two conductivity aqueous media. Especially in water with conductivity of 300 μS/cm, the pre-breakdown time is substantially reduced to 12.1 μs, the residual voltage at the time of breakdown is 18.1 kV. In the water with conductivity of 8200 μS/cm, the reduction of pre-breakdown time is 4.7 μs which is not so exaggerated, the loss voltage is significantly cut down and the residual voltage is 12.3 kV. It could also be observed from Figure 7 and Figure 8 that increasing the conductivity has the effect of shortening the pre-breakdown time, but the reduction is relatively small. At the same time, for the case of 8200 μS/cm conductivity, it is observed that the amplitude of the dissipation current in the loop increases as time flows.

From the above experimental results, the phenomenon when the type-II electrode group is discharged is obviously different from that of the type-I electrode group. Comparing to the type-I electrode group, the energy dissipation area of the electrode is smaller, the energy dissipation and the voltage drop in the pre-breakdown process get lower, and the electric field intensity between the electrodes is almost immune to the energy dissipation in the type-II electrode group. The pre-breakdown period develops to make the breakdown occur in a short period of time, which ensures the working stability of the underwater plasma discharge to a certain extent. Therefore, in various applications of underwater plasma discharge, under the premise of ensuring the structure of the discharge electrode, reducing the contact area between the electrode and the working medium could effectively increase the utilization rate of the electric energy and improve the working stability of the system.

For the same conductivity, the contact area of the anode with water in the type-I electrode group is much larger than that of the type-II, in other words, the energy dissipation area of the electric energy is larger. In the water with a conductivity of 300 μS/cm, the type-I electrode has a much longer pre-breakdown time than that of the type-II electrode, and the dissipation voltage is also bigger. In the water with a conductivity of 8200 μS/cm, the pre-breakdown time of the two electrode groups are of the same magnitude, but the type-I electrode has a much larger dissipation voltage than that of the type-II electrode. Therefore, we could get the point that an increase in the contact area of the electrode with water might cause a significant increase in the effect of energy dissipation on the pre-breakdown time.

4. Summary
In this paper, experiments on the pre-breakdown process in underwater plasma discharge were carried out. We proposed two kinds of electrode groups through the theoretical analysis and precise control of the experimental parameters. The two sets of buffer structures are respectively made of metal cone head (type-I electrode) and polytetrafluoroethylene cone head (type-II electrode). Under the condition of initial voltage of 18 kV, the current and voltage waveforms of type-I and type-II electrodes in water with conductivity of 300 μS/cm and 8200 μS/cm were plotted, and the detailed analysis and summary were carried out. Based on the above study, we obtained the following conclusions. First, reducing the contact area between the electrode and the working medium, especially the conductive working medium, could effectively increase the utilization rate of the electric energy and improve the working stability of the system under the premise of ensuring the structure of the discharge electrode. Second, raising the initial voltage helps to shorten the pre-breakdown time, reduce the dissipation voltage, and increase the residual voltage at the time of breakdown. This is independent of the electrode structure and the conductivity of the aqueous medium. Finally, after significantly reducing the energy dissipation area, the randomness of the pre-breakdown time is greatly reduced, the influence of the conductivity of the aqueous medium is also weakened. In general, based on the research in this paper, it will be helpful for the application of plasma discharge in the treatment of water environment.
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