Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 14, No. 2, 2025

Advances in the Study of High-voltage Pulsed Discharges in Water

Changpeng Li, Jing Tao

China; School of Sichuan University of Science & Engineering, Yibin 643000, China

Abstract: This paper provides a basic overview of the process of high-voltage impulse discharge in water, and summarizes the theoretical explanation of the breakdown mechanism of high-voltage discharge medium in water; at the same time, it summarizes the research on the characteristics of impulse discharge in water, and high-voltage impulse discharge in water can be divided into three categories: corona discharge, spark discharge and arc discharge, and the arc discharge process can be divided into two phases of pre-breakdown and high-current discharge; and it also summarizes the research on the characteristics of surge wave in water, which clarifies the mechanism of generating surge wave and summarizes the factors affecting the peak value of surge wave; finally, it summarizes the applied research on high-voltage impulse discharge in water. In the process of summarizing the research on the characteristics of surge, the mechanism of surge generation is clarified, and the various factors affecting the peak value of the surge are summarized; finally, the article summarizes the research on the application of high-voltage pulsed discharge in water.

Keywords: High-voltage pulse discharges under water; breakdown mechanism; Applied Research.

1. Introduction

High-voltage pulse discharge in water refers to the high-voltage electrical energy stored in capacitors or other storage devices in advance, in the liquid medium for rapid, instantaneous release of a physical process. When the high-voltage electrical energy in the liquid release of the moment, will trigger a series of significant physical phenomena, including the generation of high-intensity shock waves, intense light radiation and loud sound, etc., people will be this phenomenon as the liquid power effect[1]. B.R. Locke and other scholars classified the impulse discharge in water into corona discharge and arc discharge according to the size of energy deposited in the discharge system. With the continuous deepening and expansion of the research work, Sun Bing and other researchers on the type of impulse discharge in the water for more detailed division, it is divided into corona discharge, spark discharge and arc discharge three categories, and clearly pointed out that the main difference between spark discharge and arc discharge is the discharge process of high current exists for a different period of time, and when the energy storage equipment in the power is sufficient enough to spark discharge can be further developed to arc discharge. Arc discharge[2,3,4]. Since 1955, the Soviet scientist Yutkin after a long time of research found that high-voltage discharge in water can produce a huge mechanical effect, the prospects for the application of high-voltage discharge in water began to be generally recognized. By 1980, the physical phenomenon produced by high-voltage discharge in water, began to be applied to engineering practice, and began in the United States and Japan and other developed countries in many fields to achieve substantial application of research[5,6]. With the deepening and expanding of the research, the discharge device of high-voltage pulse discharge in liquid is gradually diversified; the study of discharge mechanism is gradually deepened; the characteristics of discharge are gradually clarified; the various physical and chemical phenomena produced in the discharge process are gradually clarified; and the application of high-voltage discharge in water is also more widely used.

2. Principle of High Voltage Pulse Discharge under Water

2.1. Overview of High Voltage Pulsed Discharge in Water

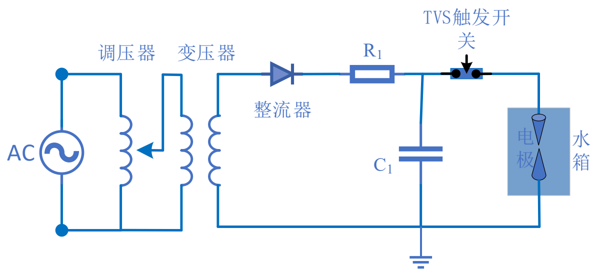

Figure 1. Underwater High Voltage Pulse Discharge Base Unit

The basic device of high-voltage pulse discharge in water is shown in Figure 1, which is mainly composed of regulator, transformer, rectifier, current limiting resistor R1, high-voltage pulse capacitor C1, high-voltage on-off switch, discharge electrode and water tank. In the working process, AC power in the regulator, transformer and rectifier under the action of the conversion to high-voltage DC power to high-voltage pulse capacitor C1 charging, charging is completed to control the TVS switch conduction, switch conduction capacitance C1 in the electrical energy is instantly loaded to the two electrodes of the water gap between the electrodes, the electrodes between the water gap is broken to form a discharge channel (discharge time of about 10 μs-1ms), the temperature of the discharge channel The temperature in the discharge channel can reach 104-105 K, the energy density reaches 108-109 J/m^3, and the pressure inside the discharge channel rises to 1 GPa. At this time, there is a huge temperature and pressure gradient between the inside of the discharge channel and the external liquid, which makes the discharge channel expand rapidly and realize the conversion from electrical energy to mechanical energy[7]. The surrounding liquid is rapidly compressed under the rapid expansion of the discharge channel, thus forming a strong shock wave, the shock wave generated by the cylindrical or spherical outward expansion of the discharge channel will propagate in all directions at a speed greater than the speed of the underwater sound velocity, and the peak shock wave pressure can reach 102-104Mpa[6,8].

2.2. Liquid media breakdown mechanism

In the process of high-voltage pulsed discharge of liquids, a plasma discharge channel is formed when the medium between the two electrodes is punctured. The breakdown of the liquid-phase medium between the two discharge electrodes is the beginning of the subsequent generation of strong shock waves. Since the 1950s, many scholars at home and abroad have carried out a large number of theoretical and experimental studies on the breakdown mechanism of the liquid-phase medium. However, a systematic theoretical system has not yet been formed for the breakdown mechanism and characteristics of liquid under the action of high-voltage pulse. At present, regarding the breakdown mechanism of liquid medium, there are two main views in the academic community. One viewpoint is that the pulse discharge in the liquid essentially belongs to the gas discharge, and the ionization process of the liquid medium is closely related to the existence of gas bubbles in the liquid. Another viewpoint is that the impulse discharge in the liquid is essentially a direct breakdown of the liquid-phase medium[9,10]. he theories supporting high-pressure pulsed discharges in liquids as gas discharges mainly include the microbubble theory[11,12], the electrothermal breakdown theory[13,14,15], the electrostriction theory[16,18] and the field emission theory[19,20,21], and the theories supporting the direct breakdown of the liquid-phase medium are mainly the direct ionization theory[22,23]. For the application conditions of various theories domestic scholars Liu Siwei summarized them, and their total results are shown in Table 1[10].

Table 1. Conditions of application of different discharge theories[10]

typology	doctrinal	Conditions of use
gas discharge theory	microbubble theory	Pre-existing microbubbles on or around the electrode surface: (1) Larger pulse duration (2) Smaller static pressure
	the theory of electrothermal breakdown	Larger conduction currents lead to a Joule heating effect in the vicinity of the electrodes: (1)Larger pulse duration, >100 microseconds (2) Larger deposition energy, >100 J
	electrostriction theory	The rapidly changing electric field causes the liquid to rupture under tension: (1) Very high electric field (2) Small pulse rise time, <10 ns (3) Smaller electrode radius, <10 μs
	field emission theory	Electron spillage at the electrode surface leads to a localized electrical explosion: (1) Very high electric field, 1 MV/cm to 5 MV/cm (2) Small electrode radius, 1μm～10μm
Liquid Discharge Theory	direct ionization theory	Direct ionization of liquids at very high field strengths: (1) Very high electric field, >10MV/cm (2) Smaller electrode radius, <100μs Smaller flow injection current

3. Summary of Studies on The Characterization of Pulsed Discharges in Water

3.1. Overview of discharge types and processes

B.R.Locke et al. found that according to the size of the energy deposited in the discharge system will be divided into corona discharge and arc discharge two types of pulse discharge in the water, domestic scholars Sun Bing et al.[4] based on this in the research process to further put forward between the two another type of discharge between the discharge type of spark discharge, the difference between the spark discharge and the arc discharge is that the presence of large currents of different times. Spark and arc discharges form a discharge channel connecting the two discharge electrodes during the discharge process, whereas corona discharges cannot form such a discharge channel, but only generate a discharge phenomenon in the region of high electric field intensity and at the electrode tips[1]. According to the study, it was found that the impulse discharge process in which plasma discharge channels can be formed can be divided into two phases: pre-breakdown and high-current discharge, and the high-current discharge phase can be subdivided into the main discharge phase and the attenuation oscillation phase[24.25].

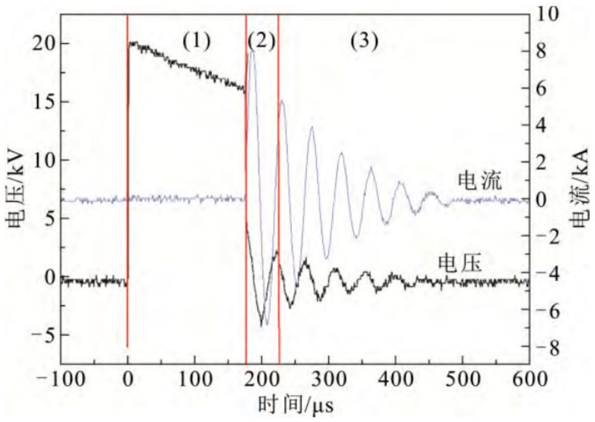

Figure 2. Typical arc discharge current-voltage diagram[25]

In order to more clearly illustrate the characteristics of different discharge stages in the arc discharge process, this paper draws on the typical arc discharge current-voltage graphs provided in the literature [25] to provide a detailed description of the various discharge stages in the process. From the typical arc discharge process presented in Fig. 2, it can be clearly divided into three parts (1), (2), and (3), which correspond to the pre-breakdown stage, the main discharge stage, and the decay oscillation stage, respectively. In the pre-breakdown stage, the voltage between the two discharge electrodes rapidly rises to 20 kV, and then after about 180 μs, the voltage decreases to 17 kV, at which time the water medium between the two discharge electrodes has not yet been penetrated, and the discharge channel connecting the two electrodes has not yet been formed. The main reason for the voltage drop is the small current leakage between the two discharge electrodes. Entering the main discharge stage, the water medium between the two discharge electrodes is broken through, thus forming a discharge channel connecting the two electrodes, and the discharge circuit is established. As the resistance of the discharge circuit is very small at this time, a high current discharge is generated between the two discharge gaps, and the electric energy in the storage device is instantly released, thus forming a high temperature and high voltage discharge channel. In the decay and oscillation stage, due to the presence of a certain amount of inductance in the discharge circuit, the circuit discharge begins to oscillate and decay phenomenon, and after a period of time to stop discharging[25].

3.2. Characterization of the pre-breakdown phase of arc discharge

In the pre-breakdown stage of the arc discharge can not form a discharge channel connecting the two discharge electrodes, but there will still be a weak discharge phenomenon, scholars at home and abroad with the "flow", "pilot" and "corona" and other terms to describe this phenomenon, in the following description of this paper uses the term "flow" to describe this phenomenon. Scholars at home and abroad have used terms such as "flow injection", "pilot" and "corona" to describe this phenomenon, and in the following description, this paper adopts the term "flow injection" to describe this phenomenon[10].

During the arc discharge study using the needle-plate discharge electrode shown in Fig. 3, the arc discharge can be categorized into two types, positive and negative, based on the difference between the positive and negative polarities of the voltage applied to the needle electrode. Accordingly, the flow injection formed in the arc discharge process can also be differentiated into positive polarity flow injection and negative polarity flow injection. According to the different development modes of the flow injection, the flow injection can be subdivided into supersonic flow injection and subsonic flow injection. Domestic scholars Zhou Guyue found that, when using needle-plate discharge electrodes for arc discharge, the anodic flow injection shows bubble cluster characteristics in the overall morphology, and its center part of the brightness is higher; while the cathodic flow injection shows more dendritic bifurcation, and its external profile is more dispersed, and the part of the brightness is concentrated in the dendritic part. In addition, it was found that the breakdown voltage of the negatively polarized subsonic flow injection was slightly higher than that of the positively polarized subsonic flow injection. Moreover, when the gap between the needle-plate was increased to a certain extent, the positive polarity flow injection only penetrated in supersonic mode[26].

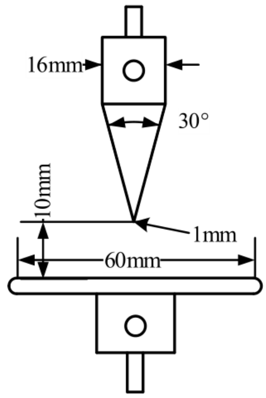

Figure 3. Needle-plate discharge electrode diagrams[26]

3.3. Characterization of the high-current discharge phase of arc discharge

As shown in Figure 2 typical arc discharge current-voltage diagram, the voltage and current in the circuit of the high-current discharge stage of the arc discharge are periodically oscillating and decaying, which can be known as under-damped form of discharge. The entire discharge circuit can be formed by the circuit can be approximated equivalent to the RLC second-order circuit, circuit diagram shown in Figure 4. Figure 4, C for the energy storage capacitance, L1 and R1 on behalf of the circuit capacitance, wire, switch inductance and resistance of the sum, and respectively, L2 and R2 on behalf of the equivalent inductance and equivalent resistance of the plasma discharge channel. Considering L as the total inductance of the circuit shown in Fig. 4, the following equation can be listed according to Kirchhoff's voltage law:

$$L\frac{di(t)}{dt} + (R_1 + R_2)\, i(t) + \frac{1}{C}\int i(t)\,dt = 0 \quad (1)$$

Differentiating Eq. (1) with respect to time t yields the following second order constant coefficient chi-square differential equation:

$$L\frac{d^2i(t)}{dt^2}+(R_1+R_2)\ \frac{di(t)}{dt}+\frac{1}{C}i(t)=0 \qquad (2)$$

Combining the initial condition $i(0_+)=0$ $\frac{di}{dt}|_{t=0_+}=\frac{U_0}{L}$ with the current waveform graph during the discharge process can be solved the expression for the change of the relationship change of the current i:

$$i(t)=\frac{U_0}{\omega l}e^{-t/\tau}\sin(\omega t) \qquad (3)$$

And;

$$\tau=\frac{2L}{R_1+R_2} \qquad (4)$$

$$\omega=(\frac{1}{LC}+\frac{1}{\tau^2})^{1/2} \qquad (5)$$

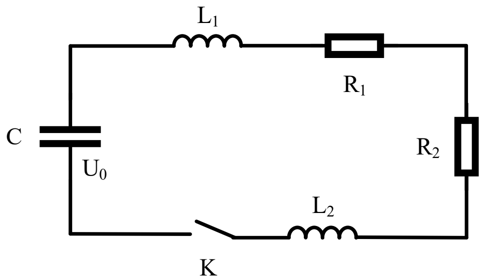

Figure 4. Equivalent circuit

The results of the study by Liu Yi et al. show that after the formation of a plasma channel, the impedance value inside the channel can be regarded as a constant. The impedance value of the channel can be solved by combining the current waveform obtained by short-circuit discharge of the circuit, the current waveform obtained by pulse discharge, and equations (4) and (5). The energy deposited into the discharge channel can then be analyzed and calculated with the help of the current variation relation. However, the factors affecting the amount of energy deposited into the discharge channel are complex and diverse, including the voltage of the storage capacitor, the spacing between the two discharge electrodes, the conductivity of the liquid, the electrode material, and the structure of the two electrodes, etc., which all have different degrees of influence on the size of the deposited energy[4,24].

4. Summary of the Study on The Excitation Characteristics of Pulsed Arc Discharge in Water

In the process of pulsed arc discharge, the pressure inside the discharge channel formed will be much higher than the pressure of the external liquid. Under the action of this pressure difference, the discharge channel will be rapid expansion, and in the expansion process to generate shock waves. In a study using a high-speed camera to film an arc in water, Chung found that the discharge channel always expands outward in a cylindrical shape at the initial stage, but after about 10 μs, its shape gradually transitions to a spherical shape[27]. During the pulsed discharge process, the generation of excitation waves occurs in three main stages: the flow injection generation stage, the arc channel expansion stage, and the large bubble pulsation stage. Among them, the peak value of the excitation wave generated in the arc expansion stage is significantly higher than that generated in the other two stages. Scholar Caulfield found in his study that there is a linear relationship between the peak current and the peak surge value of pulsed arc discharge. In addition, Guman found a linear relationship between the peak surge value and the breakdown voltage and the deposition of the peak current in the arc discharge process in his study of the peak surge value generated by arc discharge under different circuit parameters[28,29]. Further, in a more in-depth study, scholar Zingerman gave an empirical formula for the peak surge Pm[30,31].

$$P_m=\beta\sqrt{\frac{\rho_0 w}{\tau T_a}} \qquad (6)$$

Where P_m is the peak value of the excitation wave, β is a constant, generally taken in water 0.7-0.75, ρ0 is the density of water, Ta is the pulse duration, τ is the wave front time, W is the energy per unit length of the arc discharge channel. Scholar Chapman found that the peak value of the excitation wave Pm and the energy E deposited in the discharge channel can be fitted in the course of research, and the fitting formula is shown below[32];

$$P_m=kE^b \qquad (7)$$

where: k and b are the fitting coefficients, while E is the energy deposited in the discharge channel.

In the subsequent research process, it is found that in addition to the internal factors of the discharge circuit will have an impact on the peak value of the excitation wave, the external factors of the arc discharge will also have an impact on the peak value of the excitation wave, in order to ensure that the variables are single, scholars Liang Mengmeng investigated the different electrode forms and electrode spacing, which are the two external factors on the peak value of the excitation wave, and found that in the measurements of a number of sensors using the conical rod discharge electrode for arc discharge, the highest average peak value was measured[4]. It was found that the highest average peak excitation value was measured when the arc discharge was carried out with conical-head rod discharge electrodes under multiple sensors; and it was found that the peak excitation value increased and then decreased with the increase of the spacing length in the discharge studies with different electrode spacings, which indicated that there was an optimal discharge gap[7].

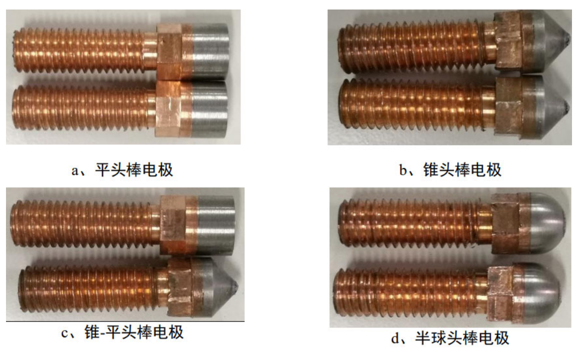

Figure 5. Different discharge electrodes[4]

5. An Applied Study of Pulsed Discharges in Water

With the continuous development of underwater pulsed discharge technology, it has been widely used in many fields such as industry, medicine and environmental protection. In this paper, the application of underwater pulse discharge is systematically summarized according to domestic and international literature:

(1) Wastewater treatment: In the process of high-voltage pulse discharge, hydroxyl radical (-OH), hydrogen peroxide (H_2O_2), ozone (O_3) and so on with strong oxidizing property can be produced. These strong oxides can effectively oxidize and degrade most of the organic matter in the sewage. In addition, the ultraviolet light generated during the discharge process can not only decompose the organic matter, but also has a sterilizing effect. At the same time, the high temperature and huge shock wave generated by the pulse discharge also promote the decomposition of organic matter to a certain extent[33].

(2) Rock fragmentation: utilizing the high permeability shock wave generated during the high-voltage pulse discharge, the rock can be rapidly cracked. Alternatively, the electrodes are directly applied to the rock to cause a breakdown of the rock surface, which in turn forms a discharge channel inside the rock, causing the rock to be destroyed by the rapid expansion of the discharge channel[8,34].

(3) Electro-hydraulic molding: The shock wave generated during the high-voltage pulse discharge is rapidly transmitted to the material to be stamped and molded under the action of a water medium, causing the material to be stamped into the desired shape. This method is commonly used in the press molding of metal materials, and has the advantages of strong controllability, stable molding, high safety, and good repeatability[7].

(4) Electrospark vibration source: Shock waves formed during high-voltage pulse discharges can be received by geophones after passing through liquid and geological layers. Researchers can analyze the geological layer according to the received waveform data, so as to obtain relevant information about the geological structure[1,35]

(5) Shock wave extracorporeal lithotripsy: Shock waves generated by high-voltage pulsed discharges in the presence of external equipment can be collected inside the body. The stones near the focal point break up under the strong vibration of the shock wave, thus achieving the purpose of removing stones from the human body[36].

(6) Sand and dirt removal: When the shock wave generated by the high-voltage pulsed discharge is applied to the object attached with mud or dirt, it will make the attached object and the attached crop vibrate with different frequencies. This vibration produces a tensile force within the attached object, which in turn causes the attached object to break up and fall off[1].

(7) Oil field extraction and coal bed methane extraction: during oil field extraction, crude oil extraction becomes difficult due to various physical or chemical clogging phenomena. In order to solve this problem, clogging in oil wells needs to be cleaned. The strong physical shock wave and cavitation phenomenon generated during high-voltage pulse discharge can effectively clean the clogging in oil wells. And in the process of coalbed methane mining, in order to increase the production of coalbed methane, it is necessary to increase the cracks in the coalbed reservoir. The liquid electric effect produced during the high-voltage pulse discharge can realize effective fracturing effect on the coal bed[9,37].

(8) Bird repellent: Pecking of crops by birds is one of the important causes of crop yield reduction. Therefore, birds need to be repelled during crop cultivation. The loud popping sound produced during high-voltage pulse discharge can be an effective repellent for birds in many scenarios [6].

(9) Waste circuit board crushing: When a high-voltage pulse discharge is applied to an insulating solid, discharge channels are created from within it. The rapid expansion of the discharge channel will lead to the fragmentation of the insulating solid, which will lead to the crushing of the insulating solid. At the same time, the solid material around the discharge channel will also be shattered by the strong shock wave [38].

6. Summary

This paper systematically summarizes and outlines the current status of research on high-voltage pulse discharge in water at home and abroad. With the unremitting efforts of many scholars at home and abroad, the conditions and related equipment required for high-voltage pulse discharge in water have become clearer. At the same time, the current research results have also made the physical and chemical phenomena generated during the discharge process clearer and easier to understand. However, in spite of certain research progress, a set of systematic theoretical explanation on the breakdown process and characteristics of liquid during high-voltage pulse discharge has not been formed so far, which is still an important issue to be further studied in this field. In addition, domestic and foreign scholars in the study of high-voltage pulse discharge, the characteristics of the discharge and the characteristics of the surge generated in the discharge process have been thoroughly studied and analyzed. Through a series of experiments and theoretical discussions, the factors affecting the discharge characteristics and surge characteristics have been clarified to a certain extent, which provides an important theoretical basis and reference for the subsequent research. Finally, this paper also systematically summarizes the applied research on high-voltage pulse discharge in water. By combing and analyzing the existing research results, the potential and practical application of underwater high-voltage pulsed discharge in different fields are further demonstrated, which provides a strong support for the further popularization and application of this technology.

Acknowledgements

Study of a steady state propulsion device based on the hydroelectric effect(Y2023073)

References

[1] Liu Qiang. The Study of Pulsed Corona Discharge in water [D]. Beijing: Institute of Electrical Engineering Chinese Academy of Sciences,2006.

[2] Locke B R, Sato M, Sunka P, et al. Electrohydraulic discharge and nonthermal plasma for water treatment[J]. Industrial & engineering chemistry research, 2006, 45(3): 882-905.

[3] By Sun Bing.. Liquid phase discharge plasma and its applications [M]. Beijing:China Science Publishing&media Ltd.2013.

[4] Liang Mengmeng. Study on Pulsed Arc Discharge in Water and its Pressure Wave Characteristics [D]. Hubei : Huazhong University of Science and Technology,2017.

[5] Yutkin. Translated by J.S. Yu. Liquid electric effect. Beijing:China Science Publishing&media Ltd,1962.

[6] Zhang Xiao. Characteristic analysis of hydroelectric effect transducer and its application in bird repelling gun [D]. School of Computer Science Yangtze University,2023.

[7] Zhang Siyuan. Study of bubble motion and impact characteristics of high voltage pulse discharge in water [D]. liaoning: Dalian University of Technology,2022.

[8] Liu Ning. Study on Electro-hydraulic Impulse Water Jet Generator and Rock-Breaking [D]. Chongqing: Chongqing University,2008.

[9] Yin Zhiqiang. Study on the liquid-electric properties and coal fracturing effect of high-voltage pulse discharge in water [D]. Shanxi: Taiyuan University Of Technology,2016.

[10] LIU Siwei. A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy of Engineering [D]. Hubei : Huazhong University of Science and Technology,2020.

[11] BOUSSATON M P, COQUILLAT S, CHAUZY S, et al. Influence of water conductivity on microdischarges from raindrops in strong electric fields[J]. Atmospheric Research, 2005, 76(1–4): 330–345.

[12] JOSHI R P, QIAN J, ZHAO G, et al. Are microbubbles necessary for the breakdown of liquid water subjected to a submicrosecond pulse?[J]. Journal of Applied Physics, 2004, 96(9): 5129–5139.

[13] PANOV V A, VASILYAK L M, VETCHININ S P, et al. Slow 'thermal' and fast 'streamer-leader'breakdown modes in conductive water[J]. Journal of Physics D: Applied Physics, 2018, 51(35):354003.

[14] KUZNETSOVA N, LOPATIN V, BURKIN V, et al. Theoretical and experimental investigation of electro discharge destruction of non-conducting materials[C]. 2011 IEEE Pulsed Power Conference, Chicago, IL, USA: IEEE, 2011: 267–273.

[15] LISITSYN I V, NOMLYAMA H, KATSUKI S, et al. Thermal processes in a streamer discharge in water[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 1999, 6(3): 351–356.

[16] SEEPERSAD Y, PEKKER M, SHNEIDER M N, et al. Investigation of positive and negative modes of nanosecond pulsed discharge in water and electrostriction model of initiation[J]. Journal of Physics. D: Applied Physics, 2013, 46(35): 355201.

[17] SEEPERSAD Y, PEKKER M, SHNEIDER M N, et al. On the electrostrictive mechanism of nanosecond-pulsed breakdown in liquid phase[J]. Journal of Physics D: Applied Physics, 2013,46(16): 162001.

[18] MARINOV I, GUAITELLA O, ROUSSEAU A, et al. Cavitation in the vicinity of the high-voltage electrode as a key step of nanosecond breakdown in liquids[J]. Plasma Sources Science & Technology,2013, 22(4): 042001.

[19] HALPERN B, GOMER R. Field emission in liquids[J]. The Journal of Chemical Physics, 1969, 51(3):1031–1047.

[20] BEROUAL A. Electronic and gaseous processes in the prebreakdown phenomena of dielectric liquids[J]. Journal of Applied Physics, 1993, 73(9): 4528–4533.

[21] JONES H M, KUNHARDT E E. Development of pulsed dielectric breakdown in liquids[J]. Journal of Physics D: Applied Physics, 1995, 28(1): 178.

[22] FUJITA H, KANAZAWA S, OHTANI K, et al. Initiation process and propagation mechanism of positive streamer discharge in water[J]. Journal of Applied Physics, 2014, 116(21): 213301.

[23] BONIFACI N, DENAT A, ATRAZHEV V. Ionization phenomenon in high-density gaseous and liquid argon in corona discharge experiments[J]. Journal of Physics D: Applied Physics, 1997, 30(19):2717–2725.

[24] LIU Yi, LI Zhiyuan, LI Xiando, et al. ffect Factors of the Characteristics of Shock Waves Induced by Underwater High Current Pulsed Discharge [J]. Proceedings of the CSEE, 2017, 37(9): 2741-2749.

[25] XING Zhengwei, WANG Zhiqiang, CAO Yunxiao, et al. Direct Impact Pressure Characteristics of Pulsed Arc Discharge Plasma Channel in Water [J]. High Voltage Engineering March 31, 2019 DOI: 10.13336/j.1003-6520.hve.20190226022,2019,45(03):832-838.

[26] Zhou Guyue A Thesis Submitted in Partial Fulfillment of the Requirements For the Degree of Master of Engineering [D]. Huazhong University of Science and Technology,2018.

[27] CHUNG K J, LEE S, HWANG Y S, et al. Modeling of pulsed spark discharge in water and its application to well cleaning[J]. Current Applied Physics, 2015, 15(9): 977–986.

[28] CAULFIELD D D. Predicting sonic pulse shapes of underwater spark discharges[C]. Deep Sea Research and Oceanographic Abstracts. Elsevier, 1962: 339–348.

[29] GUMAN W J, HUMPHREY Jr B G. Studies on an electric discharge underwater sound source[R].Fairchild Hiller Corp Farmingdale NV Republic Aviation Division, 1968.

[30] Chen Dan. Research of Discharge Mechanism of Underwater Plasma Acoustic Source [D]. National University of Defense Technology, 2016.

[31] Yibo Wang. heoretical and experimental study of the Underwater Plasma Acoustic Source [D]. Changsha: National University of Defense Technology, 2012.

[32] Chapman N R. Measurement of the waveform parameters of shallow explosive charges[J]. The Journal of the Acoustical Society of America, 1985, 78(2): 672-681.

[33] Zhao Haiyang. Experimental study of the feasibility of pulsed discharge plasma wastewater treatment [C]. Proceedings of the Lighting Science and Technology Forum of Municipalities directly under the Central Government, the Yangtze River Delta Lighting Science and Technology Forum and the 2008 Annual Meeting of the Shanghai Lighting Association.

[34] MA Ning,JIN Bo,ZHOU et al.. Simulation study on high voltage discharge rock breaking based on COMSOL [J]. Drilling Engineering, 2022, 49(6):62-70.

[35] QI Bin, WANG Xiangchun, ZHAO Qingxian . et al.Progress in seismic exploration of marine electric spark source seismic survey [J]. Geophysical and Geochemical Exploration, 2020, 44(1): 107-111.

[36] Qin Zengyan et al.. High-voltage intense pulsed discharges and their applications. Beijing: Beijing University of Technology Press Official Website，2000

[37] Lei Xiaolong. Experimental Study on Impulse Characteristics of Downhole Liquid Electric Pulse [D]. Shaanxi: Xi`an Shiyou University,2018.

[38] Diao Zhijun. Study on Mechanism of Fragmentation of Waste Printed Circuit Board by High Voltage Pulse [D]. Jiangsu: China University of Mining and Technology,2013.