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Electrical Energy Conversion Characteristics based on Underwater High-voltage Pulse Discharge

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Abstract

Underwater high-voltage (HV) pulse discharge mainly involves the process of HV discharge, breaking down water and releasing huge amounts of electrical energy, which is then rapidly converted into plasma. The plasma expands and creates shock waves and bubble pulsation effects. These effects are the main ways in which electrical energy transfers into mechanical energy. A breakdown process analysis model and an experimental method are proposed with a view to revealing the energy conversion characteristics during underwater pulse discharge and to understand the basic physical process. A plasma channel model was established in combination with the existing fundamentals of electricity and theoretical analysis. In addition, the discharge process was analyzed, along with shock wave and bubble pulsation action characteristics, on the basis of an underwater pulse discharge experiment. Meanwhile, theoretical analysis revealed the basic physical process involved in the electrical energy conversion effect. The results demonstrate the following: (1) The "vaporization-ionization" breakdown model divides the breakdown process into three stages (i.e., heating effect, breakdown detonation and mechanical energy effect stages); (2) the heating effect stage is a phase prior to breakdown, which possesses significant heating characteristics and generates initial plasma; (3) a large electric current (10^4A) during the breakdown process heats the plasma channel to a high-temperature, where it becomes dense; this condition is followed by an instant decrease in channel resistance; the breakdown current peak depends on the residual voltage at the moment of breakdown; (4) during the breakdown detonation stage, discharge breakdown occurs, along with electric arc detonation. After the heating gasification process, when the electrical field intensity is sufficient, the high-temperature HV plasma rapidly expands outward, resulting in a rapid conversion from electrical energy to mechanical energy. Thus, shock waves are formed, followed by bubble pulsation. The proposed method provides a good prospect for the application of underwater HV pulse discharge technology in the field of engineering.

Keywords: Underwater Pulse Discharge, Electrical Energy Conversion, Breakdown Process, Thermal Effect, Mechanical Effect

1 Introduction

Pulsed high-voltage discharge in water produces enormous instantaneous energy. High-energy plasma is naturally generated, and electrical energy transfer occurs during the discharge process [1, 2]. It has vast engineering potential in the fields of resource exploitation and sewage purification. However, low extraction efficiency and incomplete extraction are currently the main bottlenecks in nonconventional natural gas extraction.

Consequently, scholars have proposed a large number of coalbed methane and shale gas mining studies [3]. However, problems, such as slow fracturing loading and low peak pressure, still exist. In addition, the cracks only extend along the weak native plane, and the degree of crack penetration is small. Thus, improving the permeability of the rock stratum becomes difficult. When using the existing hydraulic fracturing technology, the application of pulsed discharge technology increases the specific mechanical energy within the hydraulic fracturing process, and pulse vibration effects occur at the tip of the rock fracture [4]. Consequently, a large number of new fractures appear, thereby clearing the fracture channel, mitigating the blockages, and forming a stable flow channel. These mechanical energy effects are useful in fracturing permeability enhancement. The United States has significantly improved extraction efficiency by injecting water into underground oil fields and switching to high-voltage discharge technology. This method also has broad possibilities in the extraction of coalbed methane and unconventional natural gas. Therefore, a study on effectively improving the efficiency of unconventional natural gas extraction and exploration of related technologies is urgently required.

The present study aims to investigate pulsed high-voltage discharge in water by building an electrical energy conversion model, facilitating analysis of the thermal effects of pulsed discharge in water. We also aim to improve understanding of pulse energy conversion and provide references for the application and development of underwater pulsed high-voltage discharge in the field of unconventional natural gas extraction.

2 State of art

Pulsed discharge in water has been extensively studied. Touya [5] obtained the relevant mechanical parameters of underwater pulsed discharge by experimental study. He consequently proposed the theory of underwater shock waves and the empirical formula of shock wave peak pressure. However, only three experimental data collection points are available, and the data should be supplemented by adding more observation points. Chen and Olivier [6] conducted experiments on shock wave fracturing specimens generated by arc discharge and suggested that underwater pulsed discharge technology could be an effective method to replace hydraulic fracturing permeability enhancement in low-permeability oil and gas reservoirs. However, the mechanical energy effects of underwater pulsed discharge have been inadequately explored. Ushakov [7], Bruggeman [8] et al. illustrated the breakdown of water medium by pulsed high-voltage discharge. This unique physical plasma phenomenon was combined with various physical processes, such as mechanics, thermology, and electricity; however, relevant details of the mechanical characteristics were limited. Ahmad [9, 10] investigated the basic physical phenomenon that low-heat plasma is generated by pulsed discharge under standard atmospheric pressure. The discharge electrical and optical characteristics were monitored using probes and ultra high-speed imaging, respectively. Despite ample experimental study, mechanical analysis of pulse discharge plasma was still limited. Rond [11] investigated the pulse plasma discharge in water using the needle electrode configuration to study this phenomenon before and after the breakdown and measured the electrical parameters. Robert [12] used a continuously flowing liquid film reactor driven by a variable nanosecond pulsed power supply, where plasma channels generated in argon propagate along the water film, to assess the effects of the output voltage setting. However, related physical and mechanical properties should still be explored.

Lu [13, 14, 15] conducted a large number of experimental studies on plasma and thoroughly explored its related physical properties. In particular, useful underwater pulsed high-voltage discharge experimental results were obtained and the characteristics of pulse discharge plasma under atmospheric pressure were discussed. Sun [16, 17, 18] introduced the principle and development of a pulse discharge source that can achieve arc and corona discharge to investigate discharge characteristics under different conditions. In addition, application of the electro-hydraulic effect and possible development of it were studied. Zhou [19], based on three discharge loads, namely, water gap, electrical wire, and energetic material loads, briefly introduced the discharge processes and analyzed the characteristics of the associated shock waves. Yan [20] studied shock wave generation under hydrostatic pressure and the law of shock wave attenuation via underwater pulsed discharge experiments. Although some mechanical properties were explored, relevant theoretical analysis is limited.

The above results were mainly obtained using pulsed discharge technology, but the characteristics of its electrical energy conversion have rarely been studied. In this study, on the basis of a mechanical analysis model and experiments, an electrical energy conversion effect model was built to explore the characteristics of this form of mechanical energy and to explain the basic physical process. The process and characteristics of the discharge thermal effect of underwater pulsed discharge were analyzed, and the basic physical process of electrical energy conversion was obtained through theoretical analysis. The results provide a reliable reference for the application of underwater pulsed high-voltage discharge technology in the field of mining engineering.

The remainder of this study is organized as follows. Section 3 describes the content of the experiment and establishes the analysis model. Section 4 analyzes the characteristics of the conversion of electrical energy into mechanical energy through experimental and theoretical means, explores the mechanism, and illustrates the entire physical process. Section 5 summarizes the conclusions.

3 Methodology

3.1 Experiment

The experimental set up (Figure 1) consists of an underwater pulsed discharge device and a precision measurement system. The pulse power supply provides 6–15 KV DC high voltage, the rated charging capacity is 60 µF, and the energy storage upper limit is 7000 J. The actual electrical power unit with high-voltage pulse is shown in Figure 2. The structure and electrode are displayed in Figure 3. The electrode is a steel pipe-copper rod, and the distance between positive and negative electrodes is 5 mm. The electrode is placed at the head of a pipe with an inner diameter of 100 mm and a length of 4 m. The hydrostatic pressure is provided by a pressure pump.

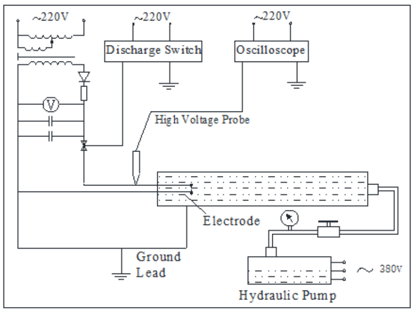

Figure 1: Diagram of the underwater pulsed discharge experimental system

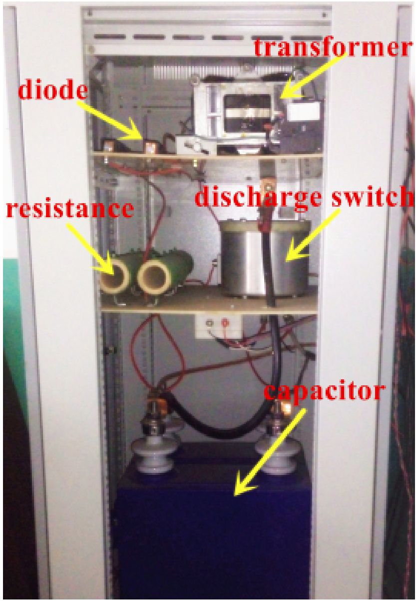

Figure 2: Actual electrical power unit with high-voltage pulse

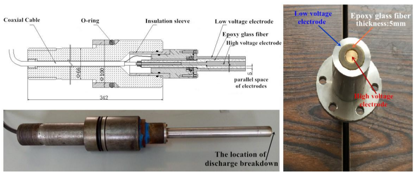

Figure 3: Electrode and its structural diagram

A P6015A high-voltage probe and DSO6014A digital oscilloscope were used to measure the transient pulse voltage waveform. The P6015A high-voltage probe was produced by *Tektronix* . The voltage was below 40 kV, with an attenuation ratio of 1000 X, a compensation range of 7–49 pF, and a bandwidth of 75 MHz. The instantaneous pulse voltage was above 2.5 kV. A current measurement coil, also known as the Rogowski coil, was used to measure the transient current. The Rogowski coil was constructed based on the electromagnetic induction principle and the law of total current and was developed by the Institute of Electrical Engineering, Chinese Academy of Sciences.

In the experiment, the whole pipeline was filled with tap water. The conductivity of the water was approximately 1.25 S/m, and the charging voltages U_m are 9, 11, 13, and 15 kV. The data under different charging voltages and hydrostatic pressures can be obtained experimentally and were combined with theoretical model analysis to explore the characteristics and mechanism of the conversion of electrical energy into mechanical energy.

3.2 Physical model of underwater pulsed discharge breakdown

Pulsed high-voltage discharge in water is a point discharge breakdown process, where the current instantaneously reaches 10^5A. The plasma breakdown instantly releases a large amount of energy, thereby producing evident mechanical energy effects. During the entire discharge breakdown process, the electrical energy is not immediately converted into mechanical energy, and a delay state is obtained [21]. The breakdown delay mainly exists within the streamer generation and connection stage, and the pre-breakdown heating stage, both of which undergo a heating process. Figure 4 shows the streamer generation and connection process. The water medium is heated at the plasma channel boundary to a certain temperature to achieve breakdown [22]. The breakdown delay is the time required to heat the water medium. Figure 5 shows the breakdown delay observed by Touya [5] in the experiment.

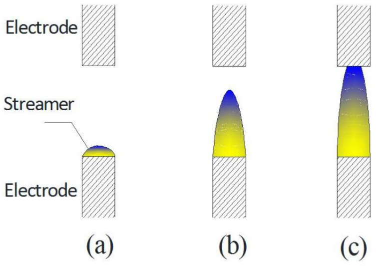

Figure 4: Schematic diagram of the streamer generation and connection process

The initial plasma channel was constructed as a cylin-

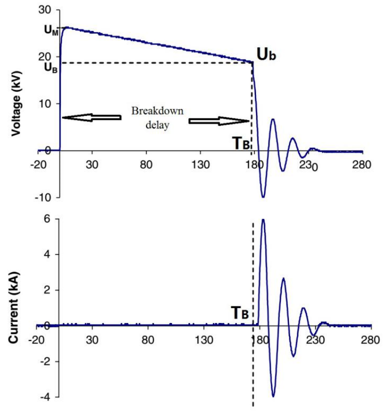

Figure 5: Breakdown delay phenomenon discovered by Touya in the experiment

drical model, as shown in Figure 6, to obtain an intuitive pre-breakdown process of the heating stage and facilitate accurate and concise analysis.

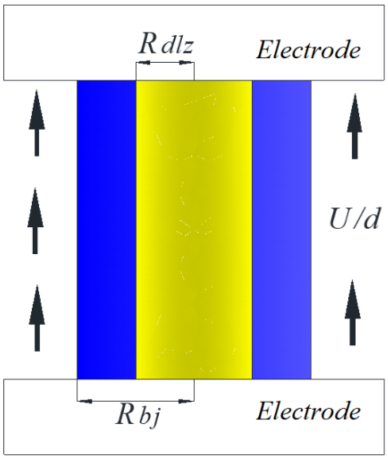

Figure 6: Schematic diagram of the initial plasma channel model

As shown in Figure 6, in the gap between the two electrodes, the yellow part is the initial plasma channel, and the blue part is the water medium at the initial channel boundary. This part of the blue water body is heated and vaporized during the breakdown process for ionization. U is the voltage between the two electrodes, d is the electrode spacing, R_{dlz} is the radius of the initial plasma channel, and R_{bj} is the distance from the center of the initial channel to the external part of the water medium at the boundary. The initial plasma channel heats the surrounding water at the boundary through thermal radiation and ion current. In the cylindrical model, heat conduction and the water characteristics were disregarded. The water at the boundary was considered to have certain axisymmetric characteristics.

3.3 Analysis model for mechanical energy of pulsed discharge in water

During high-voltage discharge, the wave head pressure of the disturbance medium is immediately transformed into strong pressure waves in the water, and the pressure experiences a sudden state change. Subsequently, it decays according to an approximate exponential function change, and the decay time is at a microsecond level. After the disturbance is generated, it propagates radially in the water in the form of compression waves, and the waves with steep peaks are significant shock waves [23]. It is usually simplified into a triangular waveform to facilitate analysis and to obtain a typical waveform model, as shown in Figure 7.

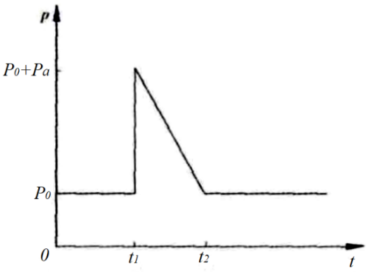

Figure 7: Schematic diagram of the triangular pulse wave model

The construction of the shock wave pressure field is complicated, and the establishment of a triangular waveform to simulate the underwater pulse shock wave pressure field waveform is important in the subsequent study of underwater electric pulse pressure fields.

The bubble pulsation analysis model is as follows: after the discharge circuit is connected, the water medium is broken down by the high-energy current. Immense heat is instantly released, and the area of liquid around the electrode vaporizes rapidly. As a result, there is a drastic pressure rise and hydrostatic pressure gradually forms large bubbles. Subsequently, three processes occur: a bubble pulsation process, irregular attenuation process, and disappearing process, as shown in Figure 8. The regular pulsation stage ends in the form of several successive attenuation pulse forms [24].

The discharge product gradually diffuses into the water, and the volume and energy of the bubbles reduce significantly. As the pulsation effect on the surrounding water medium gradually becomes unstable, the

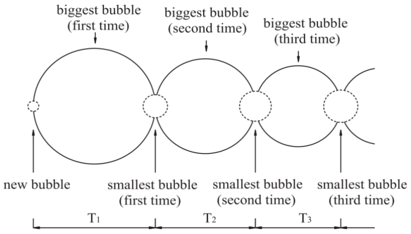

Figure 8: *Schematic diagram of the underwater bubble pulsation model* [24]

bubbles can only expand and contract in a minor and unstable manner, the energy decays irregularly, and the gas diffuses into its surroundings.

When the irregular minor pulsation cannot be maintained continuously, with further bubble diffusion and energy attenuation, single large bubbles disintegrate into several small bubbles, which move radially under the action of the surrounding water and lose their pulsation characteristics.

4 Result Analysis and Discussion

4.1 Analysis of the thermal effect in the electrical energy conversion process

Figure 9 shows the curve of voltage time history measured in the experiment.

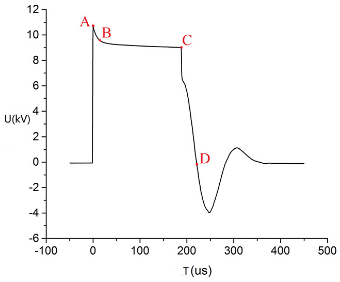

Figure 9: Voltage time history curve of underwater pulsed discharge experiment

The period from moment A when the power circuit is turned on to moment C when the breakdown starts is mainly reflected in the heating effect. The resistance of the channel gradually increases from a small value to a large and stable resistance value. The electrical energy required for the heating of the water medium at the boundary of the channel is considered a fixed value. Accordingly, as long as equivalent heating energy is consistently provided to the water medium at the boundary, the water can be heated and the heating power remains constant. Therefore, the residual voltage at the time of discharge breakdown C will be unaffected, and a reasonable simplified analysis can be achieved.

The entire breakdown process can be divided into three successive stages according to their characteristics, as follows: (1) heating effect stage, (2) breakdown detonation stage, and (3) mechanical energy effect stage. Figure 10 shows the "three-stage" analysis diagram of pulsed discharge breakdown in water.

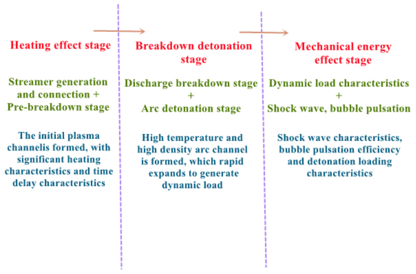

Figure 10: Analysis of the three stages of pulsed discharge breakdown in water

(1) First, the heating effect stage was analyzed. This stage refers to the heating process prior to breakdown, with significant heating characteristics. The plasma in the heating effect stage is called the initial plasma, without expansion shock effect due to low density. A large amount of thermal radiation appears in the initial plasma channel to heat the surrounding water, and under the action of an external high conductivity electric field in water, an ion current will be generated around the initial plasma heating channel. When the water at the boundary of the initial channel is heated to a certain temperature, the water molecules break the restriction of the hydrogen bonds and vaporize, leading to avalanche ionization in the channel.

The streamer generation and connection stage is the first part of the heating effect stage. The local field emission current on the surface of the electrode heats the water, which vaporizes to generate small bubbles, thereby enhancing the local breakdown effect of the electric field. The resulting high-temperature charged particles then accelerate to strike the water near the electrode surface, under the action of the electric field. The water is heated and vaporized by the impact of electrons, and the vaporized water molecules are ionized by the continuous impact. The ionized electrons continue to strike the water medium at the boundary under the action of continuous field strength, thereby producing a "vaporization–ionization" cycle, which extends to the other electrode. This stage has multiple heating processes.

The pre-breakdown stage is the second part of the heating effect stage. This stage occurs after the streamer is connected to the two poles and before the discharge splits the water; thus, it is called the pre-breakdown stage. After the streamer is connected to the two poles, the entire circuit is regarded as being in a conducting state, and the voltage on the capacitor is loaded to both ends of the streamer. The streamer plasma channel under high voltage requires a high temperature. The main feature of this stage is that the water at the boundary of the initial plasma channel is heated to gradually reach the temperature required for vaporization. Particle density is thereby increased when entering the initial channel.

(2) The breakdown detonation stage is a transient physical process that occurs after the heating effect stage. This process involves the discharge breakdown stage and the arc detonation stage. Due to the extremely short time required for breakdown and detonation, and the complexity of the process, it is difficult to accurately separate discharge breakdown from arc detonation for independent study using existing technology. The research team believes that when breakdown is achieved, the process of injecting electrical energy into the plasma channel also contains certain detonation phenomena. Therefore, the discharge breakdown stage and the arc detonation stage are collectively referred to as the breakdown detonation stage.

The discharge breakdown phase of the breakdown detonation stage occurs when the heating and vaporization at the pre-breakdown stage are complete. When the boundary temperature reaches the rated value, and the average electric field strength in the water gap is sufficient, a large number of electrons generated by the ionization avalanche penetrate the two poles of the electrode in the channel to achieve an actual closed circuit. The total energy of the power supply capacitor will then be rapidly released through the initial plasma channel, producing a discharge breakdown effect. In this case, the plasma channel in the discharge breakdown process becomes a high-temperature dense plasma channel under the action of large current, i.e., an electric arc.

The largest difference between the initial plasma channel and the discharge breakdown plasma channel (arc) lies in the particle density within the channel. The particle density in the arc channel is much higher than in the initial plasma channel. The arc detonation phase of the breakdown detonation stage can be described as follows: a high-temperature and high-density arc channel is formed during the discharge breakdown stage. During the continuous injection of external electric energy, the large pressure gradient caused by high internal pressure and the temperature gradient at the plasma boundary results in the rapid outward expansion of the plasma channel boundary. This condition causes the high-speed transfer of electrical energy into mechanical energy. The mechanical energy in the water is mainly released in the form of waves owing to the weak compressibility of the water medium around the plasma channel. This type of high-energy dynamic load is the shock wave, which is also the main part of the electric water hammer effect.

To achieve breakdown detonation in the heating effect stage, the water at the boundary of the initial plasma channel needs to be heated and vaporized. The average electric field strength in the water gap should maintain the vaporization–ionization cycle simultaneously in the channel. These factors are crucial and are features of static breakdown that distinguish it from other breakdown methods.

4.2 Analysis of the characteristics of breakdown detonation stage

The discharge breakdown stage occurs when the heating and vaporization at the heating effect stage is complete, the temperature of the water at the boundary reaches a certain value, and the average electric field strength in the water gap is sufficient. A large number of electrons generated by an ionization avalanche penetrate the electrode poles in the channel to achieve a conducting circuit, and all the energy of the power supply capacitor is rapidly released through the plasma channel, producing a discharge breakdown effect. The discharge breakdown stage is mainly a physical process, in which electrical energy is rapidly injected into the plasma channel, and a high-temperature dense arc is formed during the injection process.

During the arc detonation stage, the high temperature and high pressure in the channel lead to a large pressure gradient and temperature gradient on the plasma boundary, causing the rapid outward expansion of the plasma channel boundary. As a result, the high-speed conversion of electrical energy into mechanical energy is realized. The mechanical energy in the water medium is mainly released in the form of waves due to the weak compressibility of the water medium around the plasma channel. This type of high-energy wave is a shock wave, which is the main part of the electro-hydraulic effect and is also the focus of the study on the breakdown detonation stage.

The discharge breakdown stage has complex physical, chemical, electrical, heat, and mechanical processes, involving the transformation of water gap plasma from medium to high temperature, weak to high ionization, and low to high density. The formation of the dense plasma in the breakdown stage can be roughly divided into three phases, as follows: 1) the effect of electrons on the molecules, 2) ionization caused by electron collision, and 3) the relationship between injection and output power.

1) The effect of electrons on molecule phase: because free electrons are much smaller than molecules and atoms and ions within a certain range, electrons can obtain more energy from the external electric field because they are light. In addition, the electrons can be redistributed by an external electric field, and the dynamic equation of distribution function over time can accurately describe the electron distribution.

Water molecules and atoms struggle to achieve rapid distributed movement by an external electric field, owing to a large mass. They are also relatively poor at obtaining electrical energy from the electric field. Their energy changes with temperature variation. Molecule and ion temperature changes are mainly caused by the transfer of kinetic energy due to the elastic scattering of electrons and molecules, and the loss of thermal radiation.

Electrons can obtain more energy than ions from an external electric field due to the large difference in mass between electrons and ions. After the prebreakdown stage, the heated and vaporized water molecules enter the plasma channel. The mixture consists of a small number of electrons with a temperature of 10^4 K order and a large number of water molecules with a temperature of 10^2 K order. During this phase, the temperature of a small number of electrons is insufficient to stimulate the ionization of the collided water molecules. The reason is that the potential energy required for the ionization of water molecules is approximately 13 eV, and the corresponding temperature required for "thermal ionization" is over the order of 10^5 K. This condition, coupled with thermal radiation loss, makes it difficult to reach the temperature for thermal ionization. In addition, the ionization of water molecules in the plasma channel slightly affects the thermal effect ionization. Moreover, only when the incident kinetic energy of electrons exceeds the ionization potential of water molecules 13 eV will collision ionization develop rapidly and effectively. The avalanche ionization in the early stage of discharge breakdown does not occur immediately due to the low incident kinetic energy of the electrons and requires a short time.

The collision ionization between electrons and molecules is mainly dominated by elastic collisions due to the small intermolecular distance in the plasma channel, and elastic scattering occurs during most electron collisions. The temperature of water molecules and atoms rises after electron collision, and the temperature difference between electrons gradually narrows, the elastic collision scattering becomes more intense, and the ionization effect is significantly improved.

2) The ionization phase is caused by the collisions between water molecules and electrons. During post-impact, the temperature of the molecules gradually rises and various ionization reactions occur. Wang [25] briefly described the three major ionization reactions, as follows:

$$e\,(13.2eV) + H_2O \rightarrow 2e + H_2O^{+}$$

$$e\,(18.3eV) + H_2O \rightarrow 2e + H + OH^{+}$$

$$e\,(19.7eV) + H_2O \rightarrow 2e + H^{+} + OH$$

In the reaction formulas, e indicates free electrons, the kinetic energy carried by the electrons is expressed within(e), and the kinetic energy carried by the free electron e largely determines the ionization reaction of water. In a complex ionization reaction, various ions appear, with which electrons experience a neutralization reaction. After the ionized water molecules are neutralized with free electrons, they form highly excited molecules, whose molecular energy is much larger than the original OH bond energy. Moreover, the water molecules rapidly decompose in a highly excited state. The process is as follows:

$$e + e + H_2O^{+} \rightarrow e^{'} + H_2O^{*} \;\; \rightarrow e^{'} + OH^{*} \rightarrow H$$

where e is the electron in the initial low temperature state, $e^{'}$ is the high-temperature electron after the neutralization reaction, and H_2O^{*} is the water molecule in a highly excited state (*denotes that the particle is in a highly excited state, indicating that the particle carries large energy, and the * in the following content has the same definition). The highly excited water molecules rapidly decompose into highly excited OH groups and H atoms. OH and OH^{*} can also be ionized by the collision of e to generate OH^{+}. The neutralization reaction between OH^{+} and electrons also has a rapid decomposition phenomenon, similar to the ionization reaction between water molecules and ions. However, most of the ionization during the neutralization reaction exists within the molecule itself; thus, it is inappropriate to consider the neutralization reaction between electrons and ions as the reverse process of an ionization reaction. Ionization and neutralization are two independent processes. In the simultaneous rapid reaction of ionization and neutralization, large volume water molecules no longer exist in the plasma channel at the discharge breakdown stage, and $H2O$ is decomposed into single ions or atoms (H^+, O^+, H^*,O^*, H, and O). For OH and OH^*, the temperature of the plasma channel can reach the order of 10^4–10^5 K, which exceeds the energy of the OH bonds; thus, obtaining OH groups in the channel is difficult.

3) The relationship between injection and output power. In the early phase of the discharge breakdown stage, the plasma channel does not have a strong ability to scatter energy externally due to its small density and the poor expansion capacity. However, at this stage the avalanche ionization in the channel has only just begun, and high voltage between the two poles of the water gap is generated instantly. The power injected into the plasma channel during this process is much greater than the output power transferred to the external environment [26]. A dense channel is formed as the number of particles in the plasma increases dramatically in a very short time. This process is a discharge breakdown stage dominated by injected power, and the plasma channel does not have a strong mechanical expansion output.

The particle density in the arc channel formed in the middle of the discharge breakdown stage is stable, and the temperature does not rise indefinitely. A predictable temperature range allows an equivalent power to be injected into the plasma channel as the power lost externally. The ionization degree also reflects the stable reaction stage of the ionization and neutralization process. The ionization and neutralization reaction rates are in a balanced state, and the degree of plasma channel ionization is also stable. This process is a balanced discharge breakdown stage, where the characteristics of rapid external arc expansion gradually become prominent. At this point, the high-temperature, high-density arc has a strong mechanical expansion ability. This process is the discharge breakdown stage dominated by output power, where the characteristics of the arc detonation are fully reflected. The detonation enables the high-speed output of mechanical energy to the exterior, forming high-energy shock waves and achieving an electric water hammer effect.

4.3 Pulse current analysis at the breakdown stage

The breakdown detonation stage occurs when the heating and vaporization at the heating effect stage is complete, the temperature of the water medium at the boundary reaches the threshold, and the average electric field strength in the water gap is sufficient. A large number of electrons generated by the ionization avalanche penetrate the electrode poles in the channel to form a closed circuit, and all the energy of the power supply capacitor is rapidly released through the initial plasma channel, thereby producing a discharge breakdown effect. The plasma channel in the breakdown process becomes a high-temperature dense plasma channel under the action of large current (with the order of 10^4A), i.e., an electric arc. The electrical energy injected into the arc largely determines the energy of arc detonation, and it is a vital part of the study on shock wave characteristics during the breakdown detonation stage.

The influence of the charging voltage on the pulse current in the breakdown detonation stage was experimentally determined. Figure 11 shows the results of the breakdown current under a charging voltage of 9–15 kV. The heating effect stage has no breakdown and no current fluctuations. Therefore, the non-breakdown stage, where the current is 0, is omitted, and only the current time history data of the breakdown stage is retained, with the moment of breakdown as the timing starting point.

Figure 11 shows that as the charging voltage increases, the breakdown current peak rises accordingly. The resistance of the arc channel drops instantaneously and approaches zero as the arc has a highly ionized state and sharply expands outward during discharge breakdown. At this time, the circuit is in an under-damped state, and the magnitude of the peak breakdown current mainly depends on the residual voltage U_b at the moment of breakdown; it is the voltage at time C in Figure 9. However, the heating energy of the water medium at the initial channel boundary is insignificantly different under a charging voltage of 9–15 kV. Thus, the larger charging voltage U_m indicates greater remaining voltage U_b at the corresponding time of breakdown, and the peak breakdown current increases accordingly.

In terms of the current release process in the arc channel with a charging voltage of 9–15 kV, except for the evident difference in the magnitude of the current peak value, the waveform and pulse period are similar, the current pulse waveform is close to a sinusoidal curve, and the pulse period is approximately 110 µs.

This analysis demonstrated that, after the breakdown, the charging voltage only significantly affects the residual voltage U_b and the current peak value. The electrical characteristics of the arc channel remain stable (the arc equivalent resistance is low and the range of change is insignificant), and the charging voltage slightly influences the pulse output during the discharge breakdown process. This finding indicates

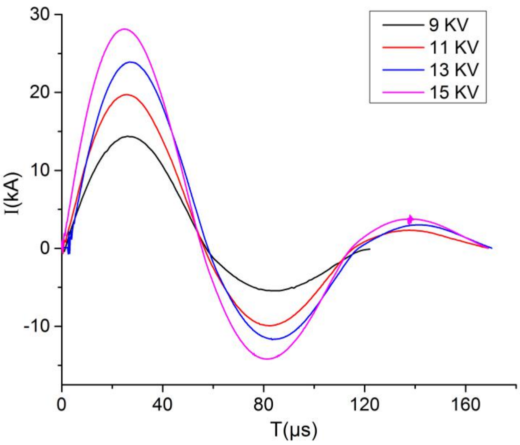

Figure 11: Experimental results of discharge breakdown current

that the breakdown output under charging voltages of 9–15 kV is highly consistent, and the discharge process in the arc is similar. At this stage, the charging voltage has no impact on the pulsed discharge process in the arc, and only the current peak value is different.

4.4 Analysis of the mechanical energy effect stage

Figure 12 shows the experimentally measured time history curve of shock wave and bubble pulsation pressure.

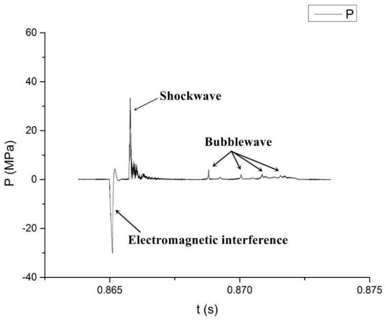

Figure 12: *Time history curve of shock wave and bubble pulsation pressure* [24]

If water is deemed as a uniform fluid without tangential stress, the change in the volume of the medium is determined by the displacement of its boundary fluid. In addition, the pressure variation acting on a certain range of fluid causes changes in the water volume [24]. The compressibility of water can be understood as follows: the pressure acting on the water medium is transmitted to the surrounding medium in the form of high-speed and limited fluctuation, which causes local pressure changes within the water and the movement of the medium. If the pressure is low, the wave transmission is unaffected. However, as pulsed discharge in water instantly releases vast electrical energy, a high-temperature, high-pressure plasma cluster is formed. Evidently, the pressure largely determines the speed of the wave. The disturbance of high-speed waves changes the water significantly, and the water motion state is adjusted equally; thus, other complex problems created by the waves can be disregarded. At this time, the water can be considered an incompressible medium that instantaneously disturbs all particles distributed over the fluid. The motion of the medium formed by this assumption of incompressibility plays an important role in simplifying the study of the plasma expansion process [20].

The water pressure around the electrode increases drastically during the instantaneous phase of pulsed discharge in water, causing vigorous oscillation and fluctuations of the surrounding water. Shock waves can propagate in the water through discontinuous peaks, leading to dramatic changes in water properties, such as pressure, temperature, and density. The shock waves impact from the center of the electrode to the surrounding medium at a supersonic speed, with great destructive power and evident single-propagation characteristics, without recurring shocks.

The shock wave model generated by pulsed discharge in water and similar to an explosion state was analyzed under simplified boundary conditions. From a physical perspective, the shock wave is limited by measurable depth. The depth reflects the relaxation process of the transition from one water particle equilibrium state to another. A shock wave has a sizeable depth, but its internal structure is extremely complicated; it is closely correlated with physical quantities, such as internal viscosity and heat conduction. Under normal circumstances, shock waves can be regarded as discontinuous jump surfaces, and the relationship between the parameter changes on both sides of the wave front causes the shock wave to form.

The charging voltage *Um* corresponds to the breakdown energy E_b and increases correspondingly, and the shock wave peak pressure rises accordingly. Increasing the charging voltage *Um* reduces the breakdown time and decreases the energy leakage from discharge to breakdown. Thus, the energy injected into the plasma channel is increased, and the shock wave peak pressure increases. The charging voltage is 9–15 kV, the corresponding breakdown energy E_b is 2087, 3079, 4524, and 5906 J, the peak pressure of the shock wave at a distance of 0.5 m from the electrode is 20–40 MPa, and the corresponding peak pressure of the shock wave is 20.1, 24.7, 25.8, and 27.9 MPa.

Bubbles are formed during the final stage of the discharge process. After the energy penetration, the bubble expansion continues, and the bubble pressure exceeds the hydrostatic pressure, forcing the water body to move; the internal pressure of the bubbles is equal to the static pressure of the water medium. The inertia of the previous compression of the water by the bubble expansion causes the bubble expansion to continue. The bubble expansion process is complete when the kinetic energy is completely transferred into an expansion potential energy. However, at this time, the internal pressure within the bubbles is much less than the external hydrostatic pressure. Thus, the water medium produces a flow of reverse compressed bubbles, and the bubble potential energy gradually becomes water kinetic. When the bubble volume reduces to a minimal value, its internal pressure increases sharply, producing a reverse movement pushing forward the water medium.

The high-temperature, high-pressure plasma channel appears during the pulsed discharge breakdown, and large temperature and pressure gradients appear in the bubbles. This condition triggers rapid outward expansion, and the boundary water medium becomes incompressible. The macroscopic physical quantities of the water medium change rapidly and a sudden interface is formed due to the rapid bubble expansion. The mechanical energy of the bubbles in the water medium propagates outward as pulses. The peak pressure of bubble pulsation is below 10 MPa, and the bubble pulsation pressure in this experiment is 2–8MPa. The initial bubble pulsation pressure peak is the highest and then gradually drops; the bubble expansion energy decay rate is maintained at 40%–60%. Finally, the bubble breaks down and the pulsation pressure falls to zero.

The duration of the shock wave phase is in microseconds, and the bubble pulsation phase is generally in milliseconds. The shock wave causes a drastic change in the macroscopic parameters during the fluctuation of the water medium and an instantaneous impact on the surrounding medium results. The bubble pulsation lasts for a comparatively long time and produces a structurally damaging secondary vibration effect on the target. Underwater pulsed discharge technology plays a particularly prominent role in resource extraction. The United States has greatly increased extraction rates by injecting water into underground oil fields and using high-voltage discharge technology. It also has wide ranging potential in the extraction of coalbed methane and unconventional natural gas. Therefore, underwater pulsed discharge justifies significant study.

5 Conclusion

The thermal effect, breakdown detonation stage characteristics and mechanical energy effect in the energy conversion process were analyzed to explore electrical energy conversion characteristics during underwater high-voltage pulsed discharge and reveal the energy conversion process and function characteristics of high-voltage pulsed discharge in water. This study was conducted based on the physical model of pulsed discharge breakdown in water, and a combination of experimental study and theoretical analysis was performed. The following conclusions may be drawn:

(1) Based on the “vaporization–ionization” breakdown model, the breakdown process is divided into three stages, namely, heating effect, breakdown detonation and mechanical energy effect stages.

(2) The heating effect stage is a heating process before the commencement of breakdown, with significant heating characteristics. The plasma in this stage is called the initial plasma.

(3) The plasma channel in the breakdown process changes to a high-temperature, dense plasma channel under the action of large current (10^4 A). Subsequently, the channel resistance instantly decreases and approaches zero. The peak value of the breakdown current mainly depends on the residual voltage at the moment of breakdown.

(4) At the breakdown detonation stage, when the heating and vaporization processes are complete, and the electric field strength is sufficient, the discharge breakdown ensues, accompanied by the arc detonation phenomenon. The high-temperature, high-pressure plasma rapidly expands, forcing the high-speed conversion of electrical energy into mechanical energy. Consequently, shock waves are formed, accompanied by bubble pulsation.

Experimental and theoretical methods are combined to develop a new understanding of the electrical energy conversion characteristics during pulsed high-voltage discharge in water. The constructed plasma model is simpler and more realistic, providing a reliable reference for the subsequent development of underwater pulsed discharge technology. However, this study is limited by the lack of plasma monitoring methods and insufficient data on high-temperature, high-pressure plasma. For future work, more advanced experimental equipment and experimental methods are required to conduct a study on the thermal effects and the laws of mechanical energy conversion during the breakdown process.

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