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Study on Breakdown Delay Characteristics Based on High-voltage Pulse Discharge in Water with Hydrostatic Pressure

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Abstract

Significant breakdown delay occurs during high-voltage pulse discharge in water with hydrostatic pressure; this phenomenon contributes to an assessment of the stability of discharge. Monitoring discharge effect is also an important approach in engineering. However, only a few studies have reported related influencing factors. This study established an equivalent circuit of a high-voltage pulse discharge based on gasification-ionization of plasma channels to study characteristics of high-voltage pulse discharge breakdown in water with high hydrostatic pressure. Simulation calculation of channel resistance was conducted using experimental data under different hydrostatic pressure and voltage conditions. The discussions in this paper center on the influencing mechanisms of hydrostatic pressure and voltage in breakdown delay. The results show that higher voltage leads to shorter breakdown delay. Equivalent resistance decreases with increasing voltage. High voltage can enhance the degree of ionization in plasma channels, which accelerates the velocity of the ionization current, shortening breakdown delay. Higher hydrostatic pressure results in longer breakdown delay. Equivalent resistance increases with increasing hydrostatic pressure. High hydrostatic pressure inhibits section areas of the plasma channel, slowing down the velocity of the ionization current and prolonging breakdown delay. This study provides theoretical guidance for monitoring analysis of high-voltage pulse discharge in engineering and studies on breakdown delay characteristics in pulse discharges.

Keywords: High-voltage pulse discharge; Breakdown delay; Equivalent resistance; Voltage; Hydrostatic pressure

1. Introduction

Water breakdown in high-voltage pulse discharges is a unique plasma physics phenomenon. Multiple physical processes, including mechanics, thermology, and electricity, accompany this breakdown; these processes were discussed by Bruggeman [3] and Okun [22] et al. Application of high-voltage pulse discharge in water has potential in rock fracturing. Unlike the conventional fracturing method by explosive explosion, high-voltage pulse discharge in water features many advantages, such as energy controllability, high fracturing precision, suitable repeatability, safety, and reliability. Therefore, high-voltage pulse discharge in water has attracted much attention in rock fracturing, especially in energy exploitation.

At present, hydraulic fracturing technology [1] is generally combined with high-voltage pulse discharge technology in exploiting petroleum, coal bed gas, and shale gas. Therefore, studies should consider pulse discharge characteristics in environments with high hydrostatic pressure. The following problems are frequently encountered in exploitation of coal bed gas: difficulty arises from accurate assessment of down-hole discharge conditions during discharge on the ground. Thus, discharge is sometimes blindly continued even when working with damaged down-hole working electrodes. Work efficiency is largely affected due to the lack of monitoring analysis of discharge. However, high-voltage pulse discharge techniques are still at the initial stages of research. Most previous studies mainly focused on experiments in environments with low or no hydrostatic pressure, and only action characteristics of electrohydraulic effect were mainly discussed [6]. Research rarely involved pulse discharge in water with high hydrostatic pressure.

Current studies on breakdown simulation of pulse discharge in water mainly include numerical and circuit simulations based on theoretical analyses [33]. However, based on theoretical analysis, numerical simulations require many boundary conditions and uncertain parameters. Many existing inconvenient factors [33] are also unsuitable for engineering applications. In circuit simulation, pulse discharge circuits can be considered specific RC oscillator circuits to effectively simplify discharge and to obtain resistance char-

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acteristics before and after breakdown. Discharge effects can then be monitored and analyzed [34] by combining delay characteristics of discharge breakdown, which significantly affects subsequent electrohydraulic effects [18]. Therefore, the influence of hydrostatic pressure and voltage on discharge breakdown delay should be first analyzed based on experiments, theory, and circuit simulation calculations to monitor and analyze pulse discharges.

The current study focuses on breakdown delay characteristics of pulse discharges in water with high hydrostatic pressure. Theoretical analysis was used to obtain an equivalent circuit of water gap in high-voltage pulse discharges. Experimental data under different hydrostatic pressure and voltage conditions were used for simulation calculations to obtain equivalent resistance of water gap in breakdown delay. Equivalent resistance was analyzed, and investigations were conducted to determine mechanisms influencing hydrostatic pressure and voltage in breakdown delay.

2. State of the art

High-temperature and dense discharge plasma channel can be formed in high-voltage pulse discharge breakdown in water [2]. This type of breakdown phenomenon has been studied by many researchers for a long time. Huang reported the latest progress and achievements in breakdown theory about liquid dielectric [12]. Merits and demerits of different theories were compared and discussed. A peculiar property of the breakdown mechanism of liquid was also specified.

Zhu [36] reported on the influence of electrons on heating and gasification of water dielectric. Gasified water molecules were ionized under continuous influence of electrons. Ionized electrons continually affected boundary water dielectric under the effect of continuous field strength, forming a gasification-ionization cycle that extended toward another electrode end. When gasification-ionization cycle arrived at another electrode end, a bright plasma channel was formed and led to breakdown. Zhu described in detail the entire breakdown based on gasification and ionization models. However, the breakdown delay issue was not clearly explained.

During extension of gasification-ionization, a gasification-ionization cycle called a streamer occurs in the plasma [17]. The streamer extends and develops toward another electrode in the gasification-ionization cycle. The arrival of the streamer at another electrode forms a cut-through. This part of the cut-through streamer is called the plasma channel [7]. Unlike the analysis of the entire discharge breakdown by Zhu, Kolb [17] focused on streamer formation and cut-through in two electrodes. Kolb observed delay characteristics prior to breakdown, thus further promoting studies on discharge breakdown delay. However, the mechanism of breakdown delay was not analyzed.

Lu [20] investigated electric exploding wires in water. A plasma channel model of discharge in water was established in theoretical research. Influencing factors in the plasma state equation were mainly studied in the said model. Effects of bubble expansion were also analyzed.

Sun [19] and Zuo [10] investigated experiments and industrial applications of pulsed corona discharge in water. Shock waveforms of arc discharge were obtained. The relationship between peak pressure of shock waves and electrode gap was confirmed to some extent. Several explanations were also reported for breakdown delay characteristics, but no detailed experiment research was conducted.

Ushakov [27] determined that when water temperature did not meet breakdown requirements, breakdown failed to occur even when a streamer connected two electrodes. Boundary water dielectric is heated by plasma channels and breakdown is achieved when the water temperature meets requirements. Buogo [4, 5] studied pulse discharges in water and proposed an original model in practical engineering. Touya [26] believed that heating delay before breakdown reaches 100 µs, and at least 200 J of energy is required between electrode gaps. Touya's research results indicated that sufficient gasification energy is required for boundary water dielectric in plasma channels, causing breakdown delay. No breakover current was observed in delay, and breakdown delay reached 100 µs. However, factors affecting breakdown delay were not discussed. Charging voltage and hydrostatic pressure were hardly introduced into their experiments.

Tan [25] investigated discharge characteristics under different voltage and solution conductivity conditions based on a simulation model of streamers in water. Development velocity of streamers in channels increased with increasing voltage and solution conductivity, whereas breakdown delay decreased simultaneously. However, the said study focused mainly on simulations and lacked experiments. Analyses did not consider the effects of hydrostatic pressure on breakdown delay. Huang [13] discussed electrode voltage and current waveform under different discharge voltages and established that breakdown delay features a certain randomness.

Gurovich theoretically analyzed electrical resistivity of discharge plasma channels [11]. A time-varying model of resistance was discussed for a preliminary understanding of resistance of plasma channels. Zhang [35] studied circuit models and the circuit equation of pulse discharges in water. Voltage waveform characteristics were analyzed to determine the relationship between resistance and voltage waveform.

Several studies were conducted on breakdown delay in high-voltage pulse discharges but lacked experiments on specific pulse discharge with hydrostatic pressure and mechanism analysis of breakdown delay. Therefore, the present study experimentally and theoretically studied breakdown delay characteristics of high-voltage pulse discharges in water with hydrostatic pressure to address deficiencies in other studies. Experimental data were obtained through an equivalent circuit of a pulse discharge under different hydrostatic pressure and voltage conditions for simulation calculations. Equivalent resistance of electrode gaps was analyzed, and examinations determined the influencing mechanism of hy-

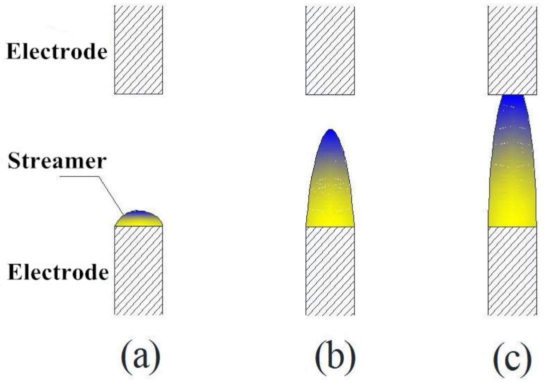

Figure 1: Schematic of streamer formation and connection

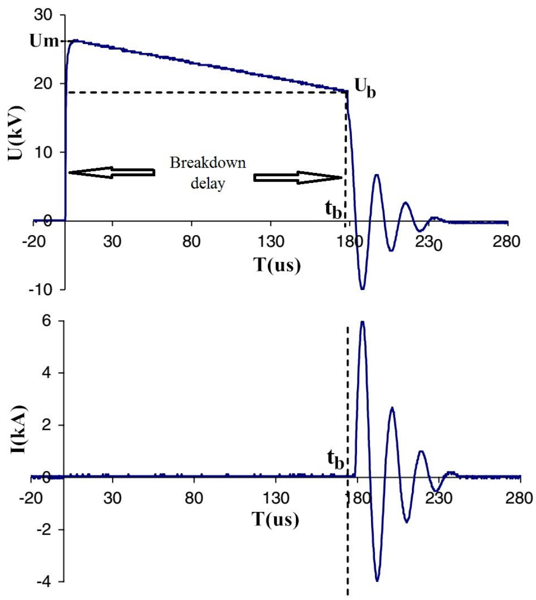

Figure 2: Breakdown delay phenomenon determined by Touya

drostatic pressure and voltage on breakdown delay.

The remaining parts of this paper are organized as follows: Section 3 presents an analysis of equivalent heating in breakdown delay and simulation model of equivalent circuit in a pulse discharge; Section 4 focuses on pulse discharge experiments under different voltage and hydrostatic pressure conditions, and effects of voltage and hydrostatic pressure are analyzed by simulation calculation; Section 5 summarizes conclusions.

3. Methodology

3.1. Equivalent heating in pulse discharges

Breakdown delay mainly occurs at two stages, namely, the streamer formation and connection stage and the pre-breakdown heating stage. Heating is involved in both stages, which are collectively referred to as the heating effect phase [29]. Fig. 1 presents a schematic diagram of streamer

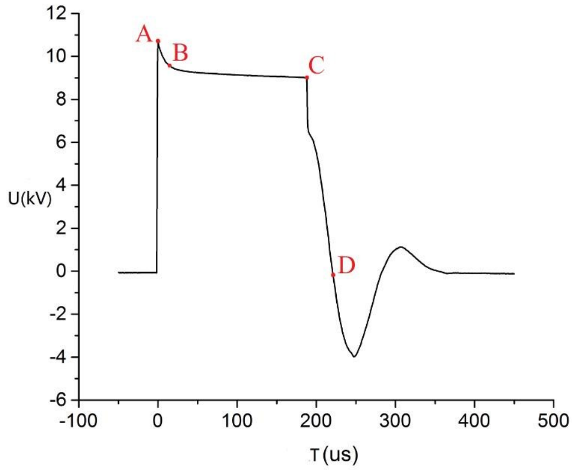

Figure 3: Time-history curve of voltage

formation and connection. Boundary water dielectric of the plasma channel in the heating effect phase was heated to a certain temperature to achieve breakdown [8]. Breakdown delay can be considered the time for heating water dielectric. Fig. 2 presents the breakdown delay determined by Touya [26].

In this process, the plasma channel is similar to a heating resistor that heats boundary water dielectric. For certain boundary water dielectrics, the electrical energy required to heat boundary water dielectric of the plasma channel to a certain temperature equaled that which is required to heat the same water dielectric while directly utilizing the resistor. Therefore, when electric energy and time (breakdown delay) for heating are the same, the final heating result of the heating effect phase can be equivalently expressed with one resistor (i.e., equivalent resistance of plasma channel). Equivalent resistance of the channel can be expressed by changes in voltage curves. Fig. 3 presents the time-history curve of voltage measured in experiments.

The time-history curve of transient voltage in Fig. 3 is divided into three parts by four points (A, B, C, and D): AB segment represents the streamer formation and connection stage, BC segment corresponds to the pre-breakdown stage, and CD segment refers to the discharge breakdown stage.

AB and BC segments are in the heating effect phase. Resistance change in the plasma channel can be evaluated utilizing the slope of the voltage curve. The absolute value of the curve slope in AB segment is extremely large, indicating extremely small equivalent resistance at this stage. Streamer formation and connection are completed within a short period (20 µs). Gasification-ionization is mainly involved in this part. Electron collision and ionization mainly occur in a streamer with suitable conductivity. Voltage decrease is rapid. Thus, resistance in this segment is extremely small. The absolute value of the curve slope gradually decreases with decreasing voltage, indicating a gradual increase in resistance.

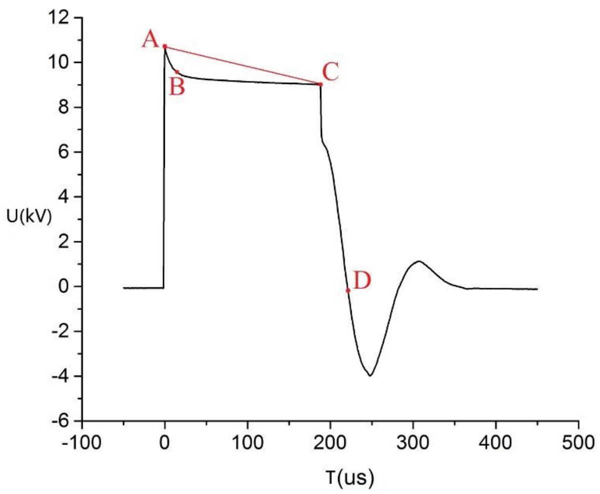

Figure 4: Equivalent diagram of time-history curve of voltage

The curve slope in BC segment features an extremely small absolute value, and the slope is smooth, suggesting that equivalent resistance at this stage is a large value that eventually stabilizes. The plasma channel was formed after two electrodes are connected by the streamer. Particle density in the plasma was at an extremely low level, based on weak expansion characteristics of the channel [21]. Therefore, a sufficient electron number is required in channels to achieve discharge breakdown. As shown in BC segment, particle number in the channel increased by heating and gasifying boundary water dielectric of the plasma channel.

In the heating effect phase from time A (power-on) to time C (discharge breakdown), channel resistance gradually increased and eventually stabilized. The electrical energy required to heat boundary water dielectric of the channel was assumed to be constant in this process (i.e., mass and the heating temperature of this part of the water is definite). Therefore, we can consider that as long as the heating gasification energy for boundary water dielectric within the same time is the same, the plasma channel can be equivalently simplified as constant resistance. Not only was water temperature elevated, but power in the heating effect phase was also consistent in this equivalent simplification. Residual voltage at time C (discharge breakdown) remained unaffected. Therefore, reasonable simplification and calculation can be conducted without loss of accuracy for the simulation circuit.

Line AC in Fig. 4 presents a variation in voltage for equivalent resistance of the channel. Gradually varying power heating (Curve ABC) was equivalent to constant power heating (Line AC). Equivalent resistance of channel is defined as Z_{dx}. CD segment represents the discharge breakdown stage: voltage decreases rapidly, a large pulse current occurs in an electric arc, the entire circuit is at an underdamping state, and arc resistance approximates an extremely small value [32]. Discharge heating delay was simplified as equivalent heating of resistance by introducing equivalent resistance values of channel and arc.

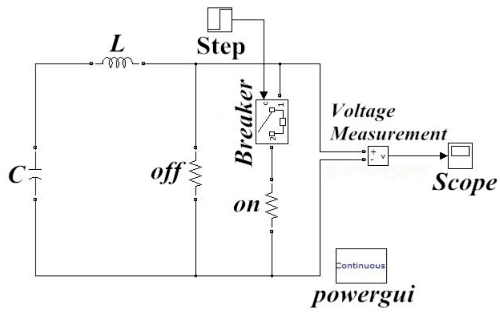

Figure 5: Schematic for equivalent circuit of pulse discharge in water

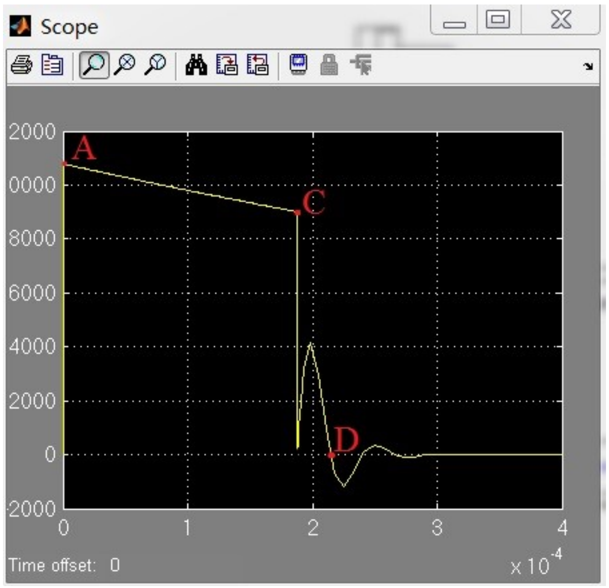

Figure 6: Simulation diagram of equivalent circuit

3.2. Simulating calculation of equivalent circuit

The plasma channel (with small radius and without expansion property) was instantaneously changed to a discharge arc channel (with large radius and rapid expansion property) after a certain delay time. Initial equivalent resistance of the channel featured a large value that rapidly decreased to an extremely small one after a certain delay. Capacitor discharge was achieved through large pulse currents in the arc. Therefore, a complex discharge circuit was simplified in studies of equivalent resistance and breakdown delay to investigate the effects of hydrostatic pressure and voltage on breakdown delay. Fig. 5 shows the equivalent circuit of pulse discharge in water.

C in Fig. 5 represents the capacitor, and an external power source (not shown in the circuit diagram) was adopted for charging; L corresponds to inductance of the discharge circuit; *off* refers to equivalent resistance of the heating effect phase of the plasma channel; *on* stands for equivalent resistance of the arc; *Step and Breaker* represent the breakdown delay control system; *Voltage Measurement and Scope* correspond to the voltage acquisition system of the discharge water gap; and *powergui* is the setting for debugging and operating. Simulation programming of the equivalent circuit for high-voltage pulse discharge in water was run in *Matlab* calculation software. Simulation was written by utilizing *Simulink* extensions of *Matlab*, which models and programs dynamic systems that combine block diagrams, interfaces, and interactive simulation functions. The required system model was established by programming the setting and connection of the module for simulation analysis [28]. The simulation was written with the *SimPower* Systems module. Simulation of the equivalent circuit was conducted through experimental results in Fig. 4, and the simulation results are shown in Fig. 6.

Slope of line AC, breakdown delay, time of CD segment, and curve fluctuation after time D were all relatively close according to the simulation diagram of the equivalent circuit (Fig. 6) and equivalent diagram of the time-history curve of measured voltage (Fig. 4). Discharge powers at AC and CD segments agreed with those of experimental conditions. Simulation effectively reflected the underdamping fluctuation of circuits at heating effect, breakdown, and post-discharge phases. Equivalent resistance of the plasma channel obtained by simulating calculation measured $Z_{dx} = 17.35\,\Omega$, whereas equivalent resistance of the breakdown arc reached $0.096\,\Omega$. Rough ranges were commonly provided for gap resistance in previous studies, whereas equivalent resistance values of the channel and arc were accurately quantified in the present study. Discharge characteristics were intuitively and quantitatively reflected. Equivalent resistance of the plasma channel was emphatically discussed. The results provide reliable bases for mechanism analysis of primary factors influencing the breakdown delay of pulse discharge in water with hydrostatic pressure.

3.3. Experimental

In this study, the experimental setup comprised pulse discharge devices and a measurement system. Fig. 7 shows a schematic diagram of the pulse discharge experiment system in water. Pulsed power supply can provide 6 kV to 15 kV (DC), rated charging capacitance was 60 μF, and the energy storage limit was 7 kJ. Fig. 8 displays an image of the actual electrical power unit with high voltage pulses. The electrode was made of a coaxial steel tube-copper bar. Fig. 9 shows the actual electrode and its structural diagram. The distance between positive and negative electrodes measured 5 mm. The electrodes were located at the tube head with an inner diameter of 100 mm and length of 4 m. Hydrostatic pressure in the tube was supplied utilizing a hydraulic pump. A P6015A high-voltage probe and a DSO6014A oscilloscope were combined to measure transient pulse voltage waveforms; the equipment is manufactured by *Tektronix* and is generally employed to measure transient pulse voltages measuring less than 40 kV. The attenuation ratio was 1,000X, compensation range reached 7–49 pF, and frequency band measured 75 MHz. Thus far, the P6015A high-voltage probe is the preferred industrial device for measuring transient pulse voltages higher than 2.5 kV.

The tube was filled with tap water (conductivity measured 1.2 S/m) in experiments. Hydrostatic pressure was classified in seven gradients, namely, 0, 1, 2, 3, 4, 6, and 8 MPa. Charging voltage was classified in four gradients, namely, 9, 11, 13, and 15 kV. Experiments were conducted to determine the time-history curves of voltage under different charging voltages and hydrostatic pressure conditions. Breakdown delay characteristics and mechanism were analyzed by combining theoretical analysis and simulation calculations.

4. Result Analysis and Discussion

4.1. Effect of charging voltage on breakdown delay

Charging voltage (U_m), residual voltage at breakdown (U_b) , and breakdown delay (t_b) are labeled in Fig. 10.

Figures 10 and 2 show coinciding label and waveform characteristics. General experiments in previous reports showed that the relationship between residual voltage (U_b) at breakdown, charging voltage (U_m), and breakdown delay (t_b) can be expressed in Formula 1 [23]:

$$U_b = U_m e^{-\frac{t_b}{RC}} \tag{1}$$

where R corresponds to resistance, and C represents capacitance. Peak current in the circuit increased with increasing charging voltage. Discharge tip field strength and tip voltage of electrodes in experiments followed the relationship below [23]:

$$E_s \approx U_m r ln \frac{2l}{r} \tag{2}$$

where r represents tip radius of curvature; U_m corresponds to charging voltage; l refers to gas distance; and E_s is tip field strength. Field strength increased with increasing charging voltage. For breakdown time, the empirical formula and qualitative theory for breakdown field strength of water dielectric can be similarly analyzed as follows [9]:

$$E_c = \frac{K}{A^\alpha t^\beta} \tag{3}$$

where E_c represents breakdown field strength; A refers to effective area of electrode; t corresponds to breakdown time; and α, β, and K are relevant constants in discharge (i.e. α, β, K, >0). When voltage reaches breakdown conditions of water dielectric, $E_s = E_c$. The following formula can then be derived based on Formulas 2 and 3:

$$t_b = \sqrt[\beta]{\frac{K}{A^\alpha U_m r ln \frac{2l}{r}}} \tag{4}$$

When other variables are constants, increase in charging voltage theoretically lowers breakdown delay (t_b) according

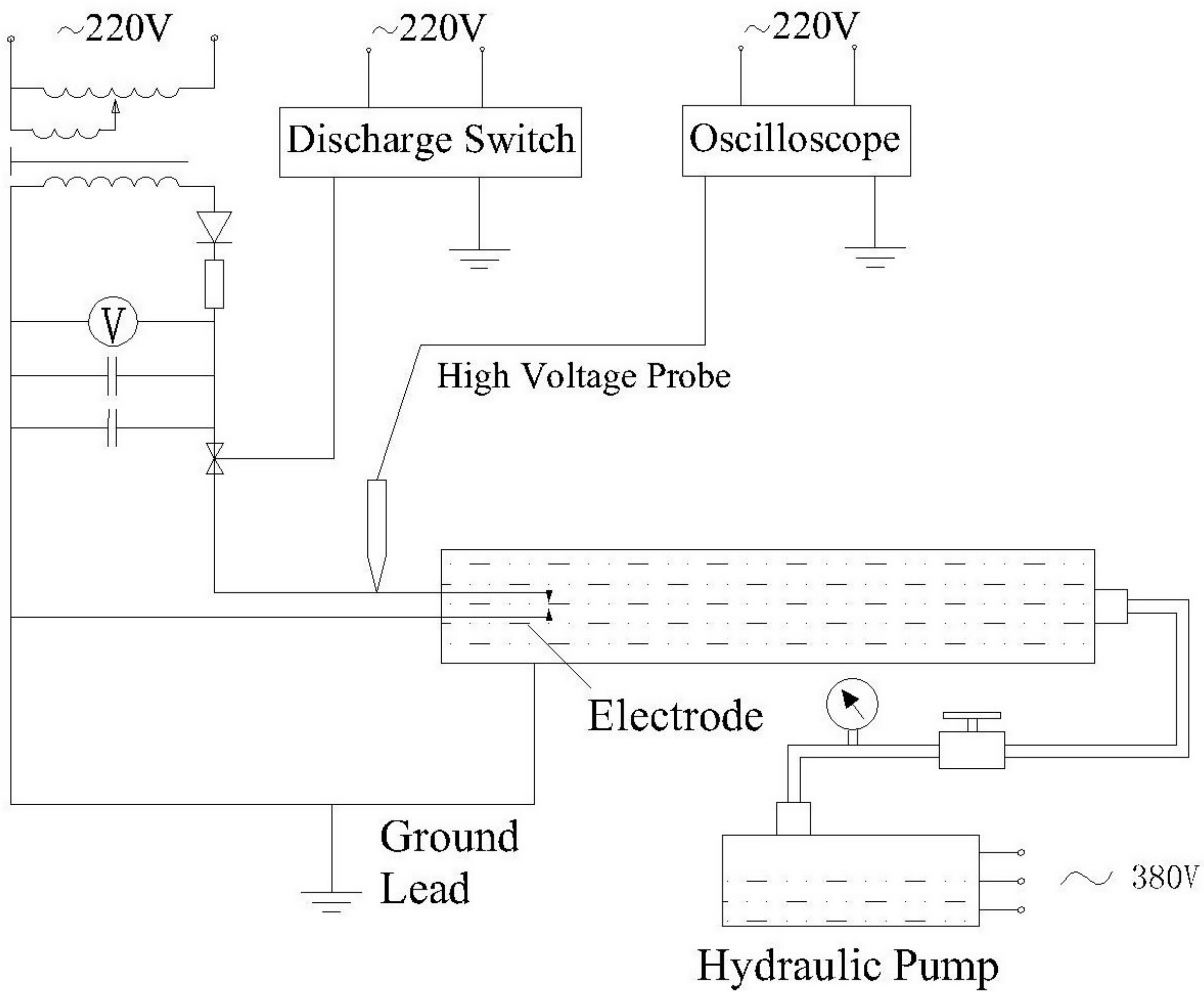

Figure 7: Schematic of the experimental device for pulse discharge in water

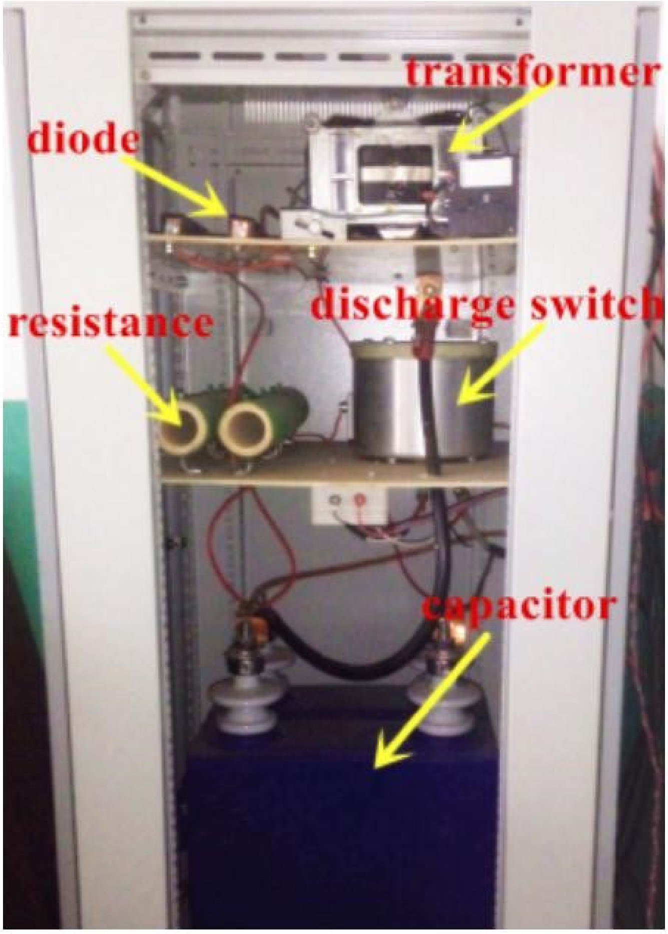

Figure 8: Photograph of the actual electrical power unit with high voltage pulses employed in this study

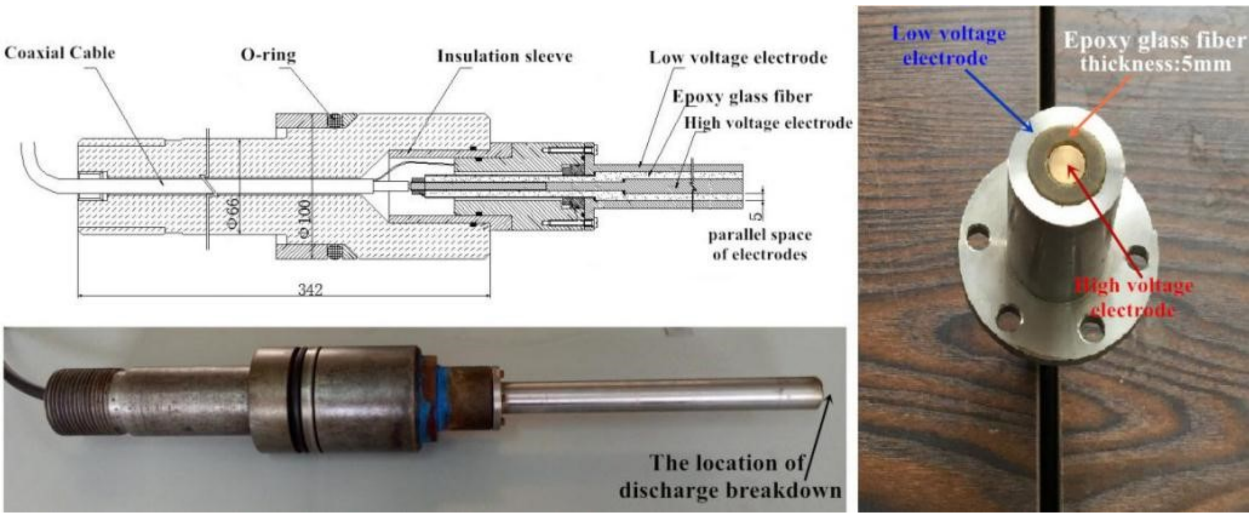

Figure 9: Image of actual electrode and its structural diagram

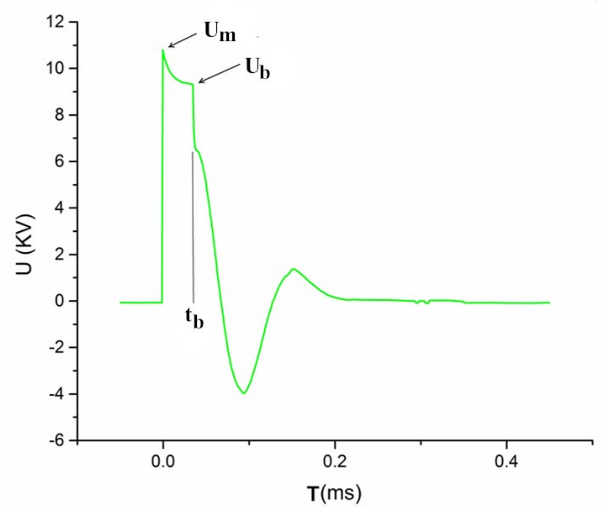

Figure 10: Schematic with labeled voltages (U) and breakdown delay (t_b)

to Formula 4. Several experiments were conducted, and results were analyzed to verify the relationship between charging voltage and breakdown delay and to further explain the formation mechanism. Different hydrostatic pressures (P_w = 0, 2, 4, 6 MPa) and charging voltages (U_m = 9-15 kV) were tested. Experimental results are shown in Fig. 11.

Fig. 11 shows that hydrostatic pressure (P_w) was only adopted as different discharging environments but not as study factors and to analyze the relationship between charging voltage and breakdown delay. The following trend was observed under different hydrostatic pressure values: breakdown delay decreased significantly with increasing charging voltage. Although Formula 4 can also explain the said condition through theoretical derivation, the root cause from mechanism did not explain the decreasing breakdown delay. Therefore, the mechanism was analyzed in this study in two aspects.

The first aspect was the heating of ionic current (or ionic current). The influencing mechanism of charging voltage on breakdown delay was investigated based on the streamer propagation theory proposed by Yang [31] and the thermal breakdown theory proposed by Ushakov et al. [10]. Breakover current was absent in delay after connecting electrodes with the streamer (Fig. 2 in experiment results of Touya [26]), and currents appeared upon completion of prebreakdown stage. However, an evident decrease in voltage was observed in the heating effect phase, as shown in Figures 2 and 3. Voltage decrease led to energy release. Electric energy released in the heating effect phase was mainly employed for the gasification-ionization cycle, which was equivalent to the formation of ionic current and flow in the plasma channel [24]. As the total flow of ionic current reached a certain level, sufficient energy was provided to heat boundary water dielectric to threshold temperature, which achieved breakdown. When the external environment is the same, higher charging voltage results in higher flow velocity of ionic current and shorter time required to reach total flow. Therefore, breakdown delay decreased with increasing charging voltage.

The second aspect was that the flow velocity of ionic current also represented the degree of ionization in the plasma channel. When external field strength was strong, electrons (e) acquired the kinetic energy required for impact ionization within a short time. A more rapid gasification-ionization cycle leads to a shorter time to achieve discharge breakdown. This condition can be intuitively described by flow velocity of ionic current. The flow velocity of ionic current in electrical characteristics can be indirectly reflected by equivalent resistance characteristics of the channel. The relationship between equivalent resistance of the channel and ionic current was similar to that between resistance and current in the circuit with a constant voltage DC resistance. Higher equivalent resistance of channel (Z_{dx}) resulted in smaller corresponding ionic current and higher breakdown delay. Experimental results in Fig. 11 were utilized to simulate the calculation of equivalent circuit. Equivalent resistance of channel was obtained under different charging voltage conditions. Calculation results are shown in Fig. 12.

Fig. 12 shows that equivalent resistance of the channel gradually decreased with increasing charging voltage when hydrostatic pressure was constant. This scenario indirectly indicates that ionic current increased with increasing charging voltage. Thus, the total flow required for heating arrived rapidly, leading to a decrease in breakdown delay (i.e., variation in $U_m - Z_{dx} - t_b$ under hydrostatic pressures ranging from 0 MPa to 6 MPa was uniform). Ionic current theory can be reasonably proved in variation analysis of $U_m + Z_{dx} - t_b$. Two possibilities for decrease in equivalent resistance of the channel (i.e., gas distance between electrodes was constant) are considered: (1) the degree of ionization in the channel of equivalent resistance of channel increased (similar to components that changed into pure resistance). Changes in the degree of ionization in the channel with increasing charging voltage were described in the velocity analysis of the ionic current. Specifically, the degree of ionization in the channel significantly improved with increasing charging voltage. (2) A cross section of equivalent resistance of the channel increased significantly, showing a similarity to the increase in the cross section of pure resistance. Only influences of charging voltage on the cross section of channel was analyzed at this point.

The channel cross-section was analyzed as follows. Weak expansion characteristics of the plasma channel at the heating effect phase showed that internal pressure of the channel featured no significant difference with external water pressure. Initial plasma temperature was almost the same. Voltage measuring 9 kV to 15 kV presented extremely limited effects on particle number in the initial channel. We assumed that corresponding plasma volumes (V) at 9 kV to 15 kV voltages varied in a small range based on $pV = nkT$ in a constant-temperature process. The gap distance between electrodes was fixed in this study. Thus, 9 kV to 15 kV charging voltages posed extremely limited influence on the cross section of plasma channel.

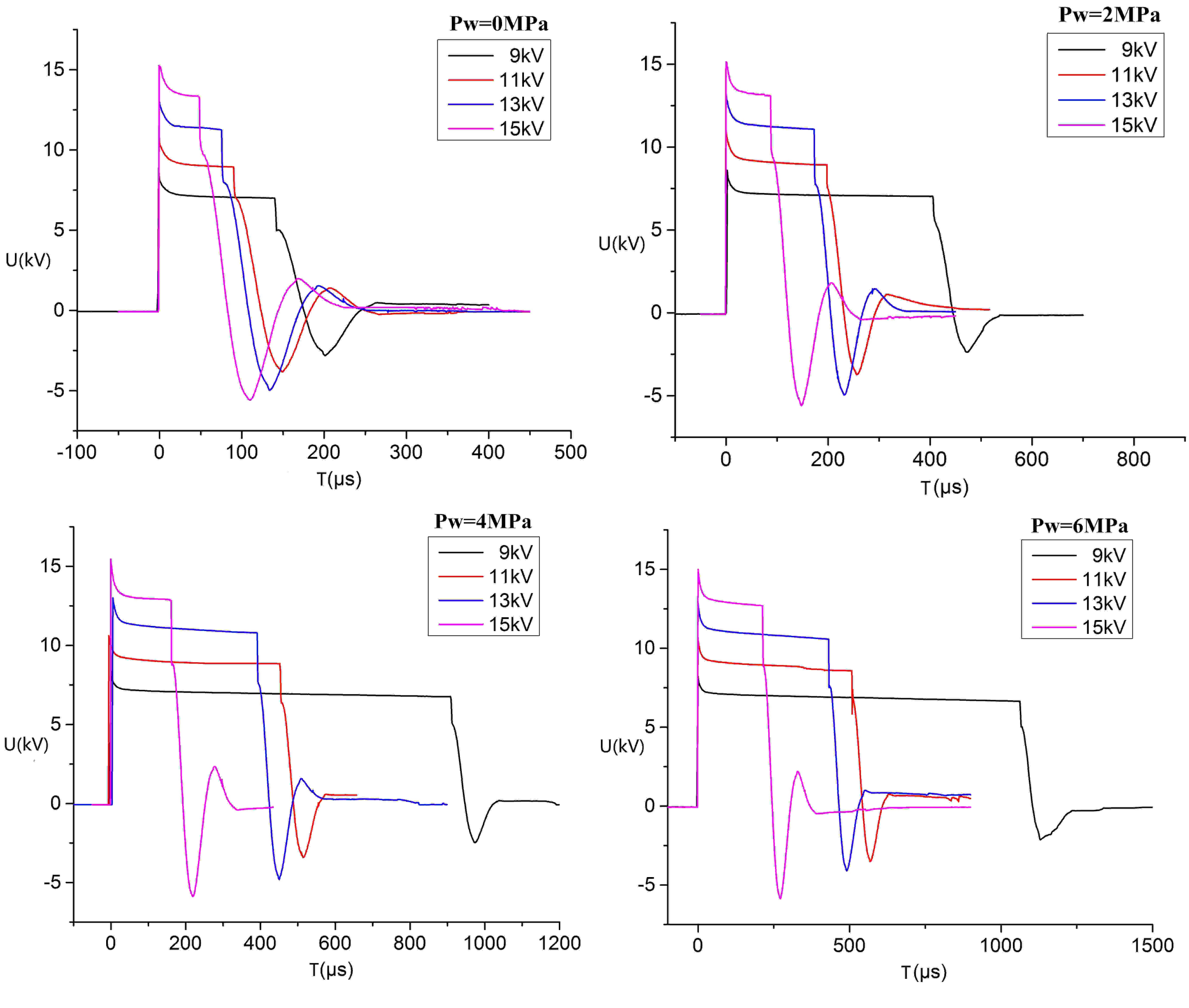

Figure 11: Experimental results of the relationship between charging voltage (U_m) and t_b (P_w = 0, 2, 4, 6 MPa)

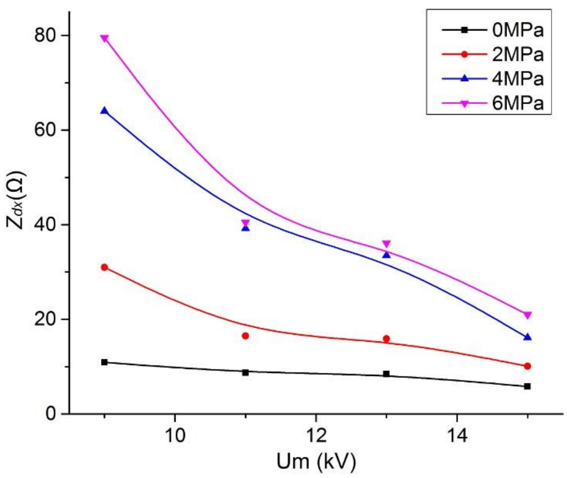

Figure 12: Equivalent resistance of channel (Z_{dx}) under different U_m

The degree of ionization in the plasma channel enhances increasing charging voltage, primarily causing the decrease in breakdown delay. The corresponding cross-section of plasma was close, with charging voltage in the 9 kV to 15 kV range. Increase in external electric field accelerated ionization in channel. Thus, a higher degree of ionization leads to higher flow velocity of ionic current and shorter breakdown delay. Influence of charging voltage on the cross-section of channel was extremely low; this influence is considered a secondary cause.

4.2. Influence of hydrostatic pressure on breakdown delay

The gasification breakdown model of a water dielectric proposed by Jones et al. [15] shows that hydrostatic pressure largely affects breakdown field strength. The kinetic equation for deformation of gasified bubbles in high-voltage pulse discharge in water can be described as follows:

$$R^2\frac{d^2r}{dt^2}+\frac{3}{2}\left(\frac{dr}{dt}\right)^2+\frac{4\eta}{\rho R}\frac{dr}{dt}+\frac{2\sigma}{\rho r}= \\ =\frac{1}{p}\left[P_{pd}(t)-P_w+P_s(T)\right] \tag{5}$$

where R corresponds to initial bubble radius; r represents radius of bubble channel; η refers to liquid viscosity; σ stands for surface tension of bubble; T is temperature; ρ indicates liquid density; P_{pd} corresponds to pressure on bubble surface due to Coulomb interaction of charge caused by bubble discharge in water; P_w represents pressure of water dielectric outside the bubble; and P_s is vapor pressure of liquid.

Formula 5 indicates that three acting forces existed in discharge breakdown in water, namely, P_w, internal pressure of bubble (P_s), and pressure on inner wall of bubbles due to electric field action (P_{pd}). These forces collectively determined changes in channel radius (r). Internal pressure of bubble and electric field action belonged to expansion force of charge breakdown channel, whereas hydrostatic pressure corresponded to force that inhibited expansion deformation of the channel. Therefore, resultant force applied to bubble wall in the breakdown channel is as follows:

$$p_{sum}=\frac{p_w-p_s-3\varepsilon_0\varepsilon_1E^2}{2+\Delta p_e+\Delta p_\eta+\Delta p_{str}+p_\sigma} \tag{6}$$

t_b can be expressed as follows:

$$t_b=\frac{(2\varepsilon_r+1)\rho U}{6\varepsilon_0\varepsilon_r\mu E^4}\cdot \\ \cdot\left\{\left[\frac{9\varepsilon_0\varepsilon_rE^4}{(2\varepsilon_r+1)U}\left(r-\frac{(2\varepsilon_r+1)U}{6\varepsilon_rE}\right)\right]^{\frac{2}{3}}+\frac{2P_{sum}}{3\rho}\right\} \tag{7}$$

When other factors are constant, P_{sum} in Formula 6 breakdown delay increases with increasing P_w , resulting in increased t_b in Formula 7. The relationship between hydrostatic pressure and breakdown delay was verified by experiments and further explained from the mechanism based on simulation calculation. Different hydrostatic pressures (i.e., 0, 1, 2, 3, 4, 6, and 8 MPa) and charging voltages (i.e., 9-15 kV) were investigated in this study. The results are shown in Fig. 13.

Charging voltage was considered a fixed parameter in Fig. 13 to analyze the relationship between hydrostatic pressure and breakdown delay. The following phenomenon was observed under different charging voltage conditions: breakdown delay increased significantly with increasing hydrostatic pressure, agreeing with theoretical derivation result from Formula 7. This condition was divided into two aspects to analyze and explain the root cause of the influencing mechanism. The electrical energy released at the heating effect phase was mainly utilized for the gasification–ionization cycle, which was equivalent to the formation of ionic current and flow in the plasma channel. When total flow of ionic current reached a certain level, sufficient energy was provided to heat boundary water dielectric to the threshold temperature, achieving breakdown. Flow velocity of ionic current in electrical characteristics was reflected by equivalent resistance characteristics of the channel. Higher equivalent resistance of channel indicated smaller corresponding ionic current and higher breakdown delay. Experimental results in Fig. 13 were utilized to calculate the simulation. Equivalent resistances of the channel were obtained under different hydrostatic pressures. The calculation results are shown in Fig. 14.

Fig. 14 shows that equivalent resistance of the channel gradually increased with increasing hydrostatic pressure when charging voltage was constant. This scenario indirectly indicates that ionic current decreased with increasing hydrostatic pressure. Thus, the required time for total flow of heating increased accordingly and led to an increase in breakdown delay (i.e., variation in $P_w-Z_{dx}-t_b$ under different charging voltages in the range of 9 kV to 15 kV was uniform). Two possibilities for increase in Z_{dx} were considered: (1) ionization degree in equivalent resistance of the channel decreased; equivalent resistance was similar to components that changed pure resistance. Previous reports discussed

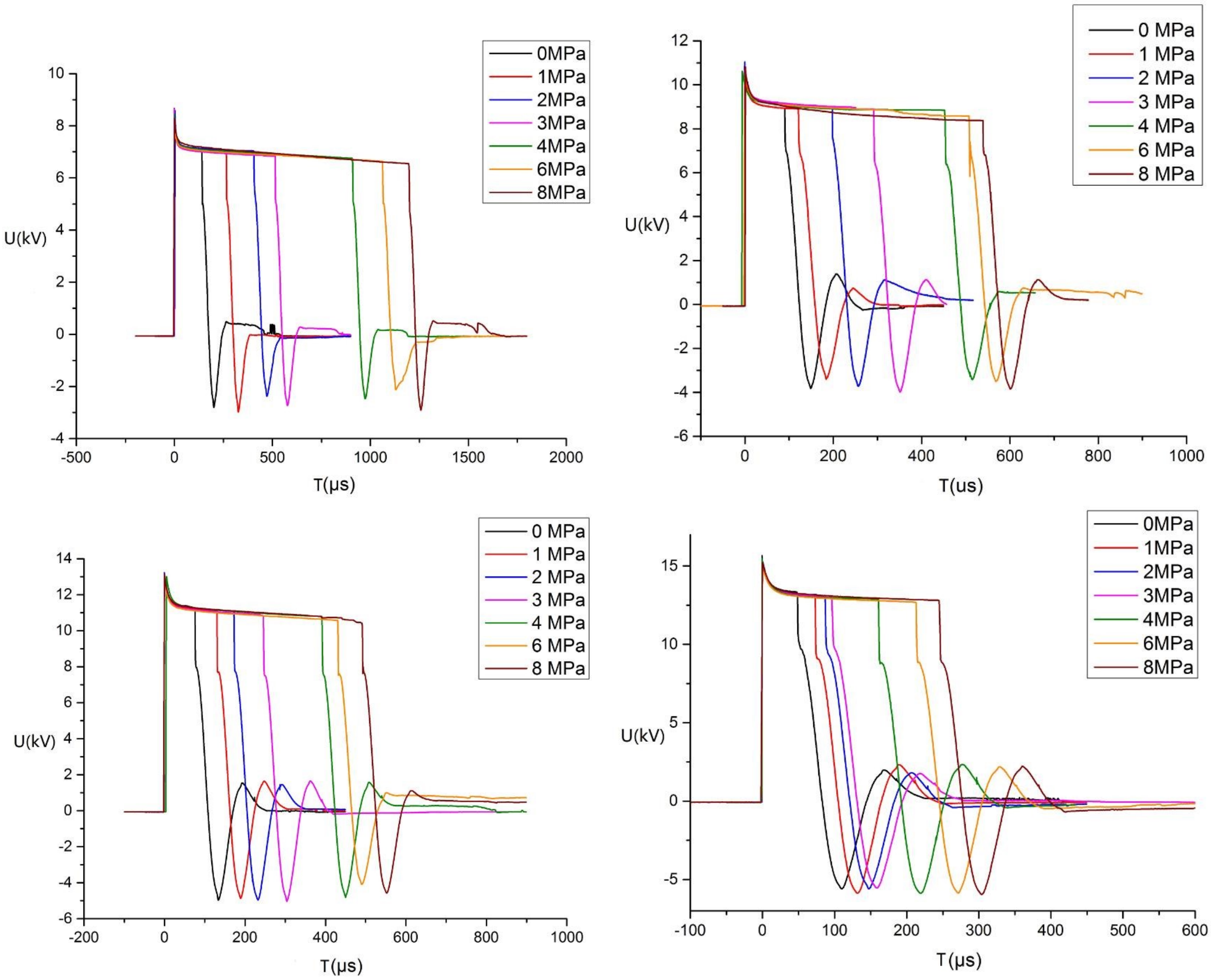

Figure 13: Relationship between hydrostatic pressure (P_w) and t_b (U_m = 9, 11, 13, 15 kV)

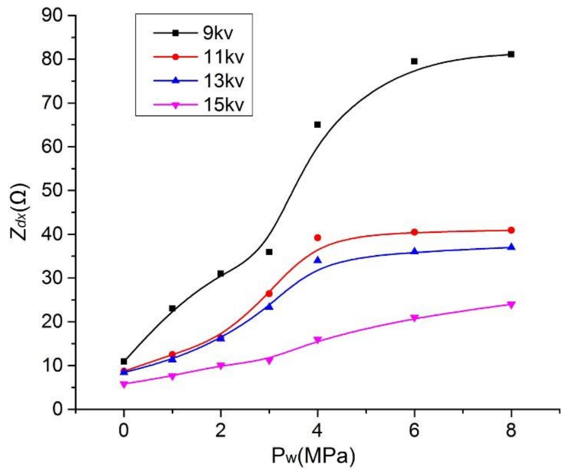

Figure 14: Z_{dx} under different P_w conditions

changes in ionic current in the corresponding ionization degree in the channel with varying charging voltage. Charging voltage mainly caused changes in ionization degree in the channel and was considered a fixed parameter in the study of effects of hydrostatic pressure on breakdown delay. Ionization degree in the initial channel was almost the same under different hydrostatic pressure conditions, indicating its similarity to components of pure resistance. Therefore, the effects of ionization degree in the channel can be ignored. (2) The cross-section of equivalent resistance of the channel decreased, coinciding with the decreasing cross-section of pure resistance. Only the effects of hydrostatic pressure on channel cross-section were analyzed at this point.

Weak expansion characteristics of the plasma channel show that its initial internal pressure featured no significant difference to the external hydrostatic pressure. The initial plasma temperature was also extremely close. When charging voltage was constant, ionization degree and particle number with different hydrostatic pressures were almost the same. We assumed that channel volume (V) with high hydrostatic pressure was smaller than that with low hydrostatic pressure when charging voltage was constant based on $pV = nkT$. Gap distance was constant in this study. Thus, the channel cross-section with high hydrostatic pressure was smaller than that with low hydrostatic pressure. The entire influencing process of hydrostatic pressure on breakdown delay can be described as follows: increase in hydrostatic pressure decreased channel cross-section (i.e., equivalent to the potential compressing effect that caused a decrease in the cross-section). Thus, the flow velocity of ionic current also decreased. Therefore, more time was required for total heating flow, and breakdown delay increased accordingly.

Cross-section of the channel was greatly affected by hydrostatic pressure, and breakdown delay evidently increased. Therefore, the effect of hydrostatic pressure on the cross-section of plasma channel primarily caused an increase in breakdown delay (i.e., an increase in equivalent resistance).

Experimental results in Fig. 13 show a significantly changed law on breakdown delay: breakdown delay was extremely close when hydrostatic pressure ranged from 0 MPa to 3 MPa. However, a remarkable span (i.e., abrupt increase) was observed in the range of 3 MPa to 4 MPa. An abrupt increase in breakdown delay indicated evident changes at the heating effect phase; this increase was mainly caused by inherent small bubbles in tap water [14]. Breakdown theory of high-voltage discharge in water was initially explained: the classical heating gasification breakdown theory was proposed by Ushakov [27] and Kao [16] et al. based on many experiments. The entire process can be described as follows: the Joule heating effect of ionic current at electrode tip led to a rapid increase in water temperature; water was gasified to small bubbles at high temperature; gaseous water molecules in bubbles were ionized at high temperatures and voltages; ionization occurred in bubbles, and the gasification-ionization cycle was induced; two electrodes were connected by a streamer, gradually resulting in discharge breakdown.

Tap water generally contains a certain amount of small bubbles. These bubbles are called original small bubbles and adhere to electrodes. The presence of many original small bubbles weakened the discharge heating gasification phase to some extent, thus decreasing the energy required for discharge heating gasification. Therefore, gases in original small bubbles were directly utilized for ionization to achieve breakdown. Heating delay decreased in this process [30]. Heating gasification and ionization were required for discharge breakdown of water dielectric without bubbles. When water dielectric contained original bubbles, breakdown mainly occurred in ionization. Time decreased due to saving of heating gasification.

Many original small bubbles were present in water when hydrostatic pressure ranged from 0 MPa to 3 MPa. These bubbles effectively participated in ionization breakdown, which saved time required for heating and lowered breakdown delay. When hydrostatic pressure increased to a certain value (between 3 and 4 MPa), original small bubbles were cracked and scattered and no longer participated in ionization breakdown. Hence, the time of the heating effect phase greatly increased, significantly increasing breakdown delay (i.e., the abrupt increase in breakdown delay in Fig. 12 when hydrostatic pressure was 4 MPa).

5. Conclusions

This study focused on delay characteristics and related influencing factors in pulse discharge breakdown. Pulse discharge experiments under different voltage and hydrostatic pressure conditions were conducted based on the simulation model of equivalent circuit of pulse discharges. The influencing mechanism of voltage and hydrostatic pressure on breakdown delay was analyzed by equivalent resistance. The following conclusions were then drawn:

1. The plasma channel was equivalently simplified to constant resistance. The same energy of heating gasifica-

tion was supplied for boundary water dielectric. Equivalent resistance effectively simplified breakdown delay analysis in the heating effect phase.

2. Higher charging voltage led to shorter breakdown delay. This mechanism can be described as follows: higher voltage enhanced the degree of ionization in the plasma channel; equivalent resistance then decreased, whereas the flow velocity of ionic current increased; thus, breakdown delay decreased under constant total flow of ionic current. The degree of ionization in the plasma channel improved with increasing charging voltage, which primarily decreased breakdown delay.
3. Higher hydrostatic pressure resulted in longer breakdown delay. High hydrostatic pressure inhibited the cross-section area of the plasma channel. Equivalent resistance then increased, whereas the flow velocity of ionic current decreased. Thus, breakdown delay increased under constant total flow of ionic current. The cross-section of the plasma channel significantly compressed with increasing hydrostatic pressure, prolonging breakdown delay.
4. Many original small bubbles were present in water when hydrostatic pressure measured 0 MPa to 3 MPa, and breakdown delay was short. When hydrostatic pressure exceeded 4 MPa, many original small bubbles were cracked and scattered. Therefore, the time of the heating effect phase greatly increased, leading to an abrupt increase in breakdown delay.

This study comprehensively analyzed the influencing law of voltage and hydrostatic pressure on breakdown delay. Accurate descriptions were provided for breakdown delay characteristics of pulse discharge in water with hydrostatic pressure. This study provides theoretical guidance for the monitoring of discharge effects in practical engineering. The present work also focuses on equivalent resistance characteristics of plasma channels. However, only a qualitative analysis was conducted for the cross-section radius of the channel, and this analysis placed certain limitations on quantitative research on the cross-section of plasma channels.

This study also determined that breakdown delay is also affected by other factors, such as water conductivity and the spacing of the discharge electrodes. Mechanism analysis of these influencing factors can be performed by sound experimental designs and accurate numerical simulation. These influencing factors should be considered in future studies.

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