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Investigation of High-Voltage Pulse Discharge Breakdown Characteristics in Water Under Hydrostatic Pressure: Breakdown Delay and Equivalent Resistance

Abstract: - This study examines the characteristics of high-voltage pulse discharge breakdown in water under hydrostatic pressure, specifically focusing on the delay in breakdown and the corresponding equivalent resistance. The occurrence of a significant delay when high-voltage pulse discharges occur in water under hydrostatic pressure is leveraged to assess the stability of the discharge. These delays and their characterization provide crucial information for the engineering field, particularly in monitoring discharge impact. This research delivers valuable theoretical insights for dissecting and understanding this phenomenon. According to our findings, a higher voltage leads to a shorter breakdown delay, and an elevated voltage beyond a certain point decreases the equivalent resistance. Despite this, few studies have addressed the factors influencing these reactions. Thus, this work introduces a high-voltage pulse discharge equivalent circuit founded on the gasification-ionization of plasma channels to systematically explore these characteristics. We found that increasing the voltage enhances the ionization level in plasma channels, which speeds up the ionization current, accordingly reducing the breakdown delay. On the contrary, heightening the hydrostatic pressure lengthens the breakdown delays and enriches the equivalent resistance.

Keywords: high-voltage, pulse, discharge, resistance, hydrostatic, pressure

INTRODUCTION

In accordance with previous studies, the pre-breakdown and breakdown events that occur in water are exceedingly diverse and complicated. This study has revealed that the production of discharges is highly reliant on the conductivity of water and the size of the applied voltage; these parameters alter the energy input and, therefore, the kinetics of the process. Many research has documented the impact of the applied voltage on discharge in dielectric liquids, but only a few studies have described the influence of the applied voltage on discharge in water. It has been observed that different discharge modes exist depending on the amplitude of the applied voltage pulse: slow streamers with a hemispheric or bush-like shape are associated with low amplitude voltage, whereas fast streamers appear above a certain threshold voltage (which varies depending on the geometry of the set up) and can be significantly longer in length than slow streamers. Furthermore, the influence of the applied voltage on discharge characteristics such as the breakdown time or the concentration of OH radicals has been examined in detail.

After the shockwave front has arrived at a specific location, the value of reaches its maximum. The front-time represents the time it takes for the shockwave to take effect at a certain location, and it is an essential element in determining the influence of a shockwave on a system. With respect to shockwaves operating on a rock, the front-time is mostly determined by the loading speed of shockwave pressure, which is the primary characteristic of shockwave energy release. The shockwave has a continual breaking impact on the rock in the front-time and is a significant contributor in the formation of rock fracture zones in the back-time as well. Eventually, the duration (front-time) of the action increases to a certain level, and the effect is mostly reflected in fracture and plastic regions, effectively prolonging the fracture of the rocks.

If the front-time is exceptionally short, the shockwave energy effects are focused at the surface region, and only a limited amount of energy is transported to the interior of the structure for internal fractures. A prolonged front-

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Corresponding author: Venkata Veeranjaneyulu I time, on the other hand, has been shown to encourage the development of interior fractures. However, if the front-time is very lengthy, the energy release becomes decentralised, which is detrimental to the achievement of an effective shock effect. Consequently, shockwave front-time is an extremely important issue in scientific research, industrial manufacturing, and national defence. In a location with a finite boundary condition, isotropic water is constrained by the boundary condition and is therefore classified as "non-free field water." The high-voltage breakdown of a liquid in a small space releases a significant amount of energy. So far, this approach has been applied in resource prospecting, shale gas exploration, gas treatment, and the removal of rust from lengthy pipelines, among other applications. It has a tremendous amount of promise in engineering applications. Using high-voltage discharge in high-hydraulic pressure conditions may also be utilised to imitate the effects of a deep-water explosion, which can be useful for national defence applications. 1 The breakdown of water caused by point discharge is the primary cause of high-voltage discharge in water. When the discharge current reaches hundreds of thousands of amperes, it is considered to be significant. An electrical discharge channel is used to create the plasma. Shock waves and bubble pulsation are produced by the abrupt release of large amounts of energy into the discharge channel. It is worth noting that the length of the shock wave is measured in microseconds, whereas that of the bubble pulsation is measured in milliseconds. Under the influence of an impulse voltage of a specific form, the breakdown voltage level of water is not a constant parameter.

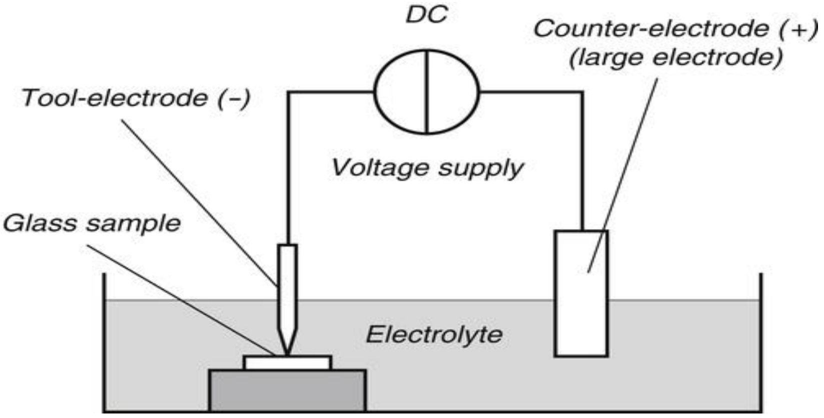

Figure 1 High Voltage Discharge

The breakdown voltage of water is affected by a variety of parameters, including the nature of the water, the electrode geometry, the polarity of the applied voltage, the gap length, and the electrode material. Under the needle-plane electrode topology, the breakdown investigation is carried out in three different solutions: tap water, distilled water, and an ionic solution. When working with high-power, high-voltage resistors, the ionic solution is employed as the electrolyte. Typically, these resistors are composed of ionic solution (salt solutions, acids solutions, and their mixtures) with the salt concentration being adjusted to achieve the desired resistivity. Aside from that, the research investigates the breakdown characteristics of an ionic solution as well as the voltage-time characteristics of an ionic solution. There are many different types of ionic solutions that may be used in high voltage resistors, and this paper examines the most often used ionic solution (copper sulphate and sodium chloride solution), as well as the breakdown analysis for each of these solutions. It has been a while since studies of electric spark dispersion mechanisms have been the centre of interest. Researchers at the Institute of Electrodynamics of the National Academy of Sciences of Ukraine have made significant contributions to the advancement of pulse engineering and technology. Modern technical equipment, which have the ability to stabilise the impulse parameters, allow for the achievement of desired process efficiency. Underwater electric discharge, on the other hand, is a complicated physical phenomenon that requires both the appropriate equipment and a thorough examination of the process itself in order to be successfully implemented. The dispersion of conducting materials in liquid media caused by electric sparks has been widely investigated. It is the possibility of direct synthesis of colloidal solutions with the ability to regulate the degree of dispersion of nanomaterials that distinguishes this technique from other similar processes.

A uniformly suspended item in a liquid is known as a colloidal solution, which can also be referred to as a colloidal suspension or colloidal suspension solution. Another way to put it is that a colloid is a microscopic-sized substance that is uniformly scattered throughout another material, with the dispersed-phase particles typically having a diameter ranging between 1 and 1000 nanometres. Despite this, the dispersed matter tends to solidify as a result of physical factors, making it impossible for the dispersed powders to remain separated from one another. Colloidal solutions, on the other hand, do not suffer from this limitation. Because of their intrinsic stability, colloids are able to maintain the dispersed-isolated condition of a solid phase in certain circumstances. When it comes to pulsed power systems, water is employed as a liquid dielectric in a variety of applications, including intermediate storage in accelerators and pulsed forming lines in impulse generators.

In many electro-hydraulic and impulsive high-power ultrasound systems, the water is used to fill the plasma closing switches and the loads of the systems. Due to its strong breakdown strength as well as its high dielectric permittivity, water has been used as a liquid dielectric due to its low cost. Pulsed power technologies for environmental and biomedical applications, which are currently in development, require knowledge on the breakdown strength and other features of water when subjected to high voltage impulses. Scholars have been researching the potential of underwater pulse discharge technology in industrial manufacturing since it was first developed.

Objective of the paper:

- To investigate the delay characteristics of high-voltage pulse discharge breakdown in water under different levels of hydrostatic pressure.
- To establish a high-voltage pulse discharge equivalent circuit based on the gasification-ionization of plasma channels.
- To determine the role of high voltage in the ionization process and how it affects breakdown timeframes.
- To identify the effect of increased hydrostatic pressure on the process of pulse discharge breakdown, specifically focusing on the duration of the breakdown delay.
- To understand how equivalent resistance varies with the changes in voltage and hydrostatic pressure in a high-voltage pulse discharge system.

LITERATURE REVIEW

Dong Yan (2020): In water, pulse discharge produces powerful shockwaves that may be used in a variety of industries, including control blasting, oil production and national defence building. One of the most critical variables in shockwave theory and effect is the wave front-time. Researchers in this work developed a model for analysing wave front-time in relation to electrical energy and hydrostatic pressure. Shockwave front-time was obtained and merged with theoretical information based on these conditions. Under varying hydrostatic pressure, breakdown energy (and propagation distance), the front-time of a shockwave was measured at various locations. When electrical energies are between 1500 and 3500 J, the results show that shockwave front-time decreases with increasing breakdown energy. When hydrostatic pressures are in the 0-4 MPa range, the wave front-time rises with increasing hydrostatic pressure. Increase in propagation distance within 4 m results in an increase in wave front time. There is a strong correlation between increasing propagation distance and decreasing breakdown energy and hydrostatic pressure. The data can be used to guide future water pulse discharge research and shockwave performance evaluations.

D. Yan (2017): During high-voltage pulse discharge in water with hydrostatic pressure, significant breakdown delay occurs; this phenomenon helps to the assessment of discharge stability. Keeping tabs on the discharge effect is also a useful engineering technique. Only a small number of research have looked at the underlying causes of this phenomenon. In order to better understand the breakdown characteristics of high-voltage pulse discharges in water with high hydrostatic pressure, a gasification-ionization of plasma channels equivalent circuit was developed. Under varied hydrostatic pressures and voltages, channel resistance was calculated using experimental data. Hydrostatic pressure and voltage breakdown delay are the focus of this paper's topic. The results reveal that a shorter breakdown delay is associated with a greater voltage. Voltage increases the voltage at which the equivalent resistance lowers. As a result, the breakdown time of ionisation currents may be reduced by increasing the voltage applied to plasma channels. Longer breakdown delays are caused by increased hydrostatic pressure. As the hydrostatic pressure rises, so does the equivalent resistance. High hydrostatic pressure slows down the ionisation current's velocity and lengthens the breakdown time by inhibiting plasma channel section regions. High-voltage pulse discharges in engineering are studied in this paper, which gives theoretical advice for monitoring analysis.

METHODOLOGY

The method of pulse discharge in water has steadily gained acceptance in the scientific and industrial areas as a result of technical advancements and equipment improvements over time. Electrical energy delivers a powerful impact that, when combined with shockwaves, has the potential to inflict mechanical damage. The electrohydraulic effect has been widely used in a variety of applications and has shown promise in the field of rock-mass fracture. Comparing the pulse discharge technique to typical rock-mass fracturing methods that employ explosives, the pulse discharge method has the following advantages: regulated energy, high accuracy and repeatability, increased safety, and increased dependability. Consequently, the pulsed discharge in water has drawn the attention of those working in the rock-mass fracturing industry. The experimental equipment comprised of the experimental gadget as well as a system for monitoring pulse discharges in water, which was used in the experiment.

Representation of the experimental equipment used to measure pulse discharges in liquid. The pulse power supply delivered direct current at high voltage in the range of 6-15 KV. The rated capacitance was 60 F, and the energy storage limit was 7000 J. The capacitor was made of silicon. Steel tube coaxially wound around a copper bar served as the electrodes. Figure 5 depicts a schematic of the electrode structure as well as a photograph of the structure. Between the positive and negative electrodes was a spacing of 5 millimetres. They were situated at one end of a tube with an inner diameter of 100 mm and a total length of 4000 mm, with the electrodes situated at the other end. On one side of the tube wall, 500 mm apart, five sensor connections were uniformly arranged on one side of the tube wall. The distance between the electrode and the nearest sensor connection was 1000 millimetres.

The tube was filled with tap water having a conductivity of around 1.3 S/m, which was used for the experiment. An external hydraulic pump with a maximum capacity of 12 MPa was used to modify the hydrostatic pressure that had been pre-set. The Aqueous Electrolyte Resistors are the most extensively utilised type of tight resistor in high-power, high-voltage applications. Typically, these resistors are composed of ionic solution (salt solutions, acids solutions, and their combinations) with the salt concentration being changed to achieve the desired resistance. During this chapter, the breakdown properties of ionic solution and the volt-time characteristics of ionic solution are discovered and discussed in detail. There are many different types of ionic solutions that may be used in high voltage resistors, and this paper examines the most often used ionic solution (copper sulphate and sodium chloride solution) in high voltage resistors. With the Stainless-Steel Hemisphere electrode configuration, the volt-time characteristic of sodium chloride solution is measured in a uniform field with a Stainless-Steel Hemisphere electrode configuration. The inter-electrode gap spacing is kept constant at one millimetre. It is necessary to add sodium chloride salt to distilled water until the solution behaves as a dielectric with a 1mm electrode gap spacing and does not conduct. It is necessary to maintain the conductivity of sodium chloride solution at 0.65 S/cm, above which the electrolyte serves as a conductor when the electrodes are spaced at 1mm intervals. It has been discovered through an examination of the available literature on this subject that the class of pulsed low-voltage electric discharges occurring in water is primarily represented by the electric spark discharge that occurs during the process of electric discharge machining (EDM), which is described below.

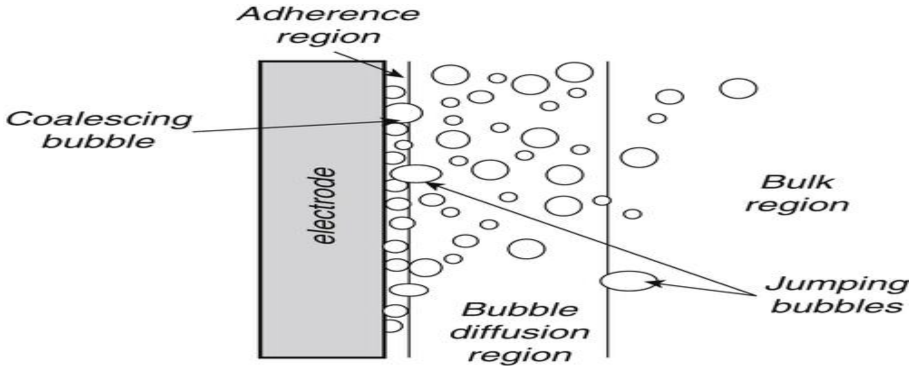

Figure 2 Pulse water discharge

Electrodeposition in liquid dielectric medium (EDM) is a well-established manufacturing method that is commonly used to make injection moulds, dies, completed products such as cutting tools, and objects with complicated forms, among other things. It will be covered in greater depth later on. The principles of operation of EDM are based on the interactions of electric discharge plasmas with electrode materials, which is a phenomenon that is still poorly understood. As a result, optimization of EDM processes is still mostly focused on empirical methodologies and recipe development. This explains the large number of research papers on diagnostics of the EDM electric discharge plasma that have been published. The latter, on the other hand, poses a number of challenges, including small plasma sizes, short plasma durations, weak luminous intensities, poor repeatability owing to rapidly developing electrode surface profiles, and dielectric contamination from degraded electrode materials. As a result of these considerations, diagnosing EDM plasmas is an extremely difficult undertaking. It is commonly assumed in studies of the motion of bubbles in water in non-fee fields that the density of water surrounding the bubbles is in line with the theory of incompressible fluids and that the bubbles flow in a continuous stream. On the basis of this research, it has been established that the treatment of dielectric water as an incompressible fluid is appropriate to the general characteristics of moving bubbles throughout their expansion stage. The variable pulsation period, as a result, may be calculated using these ideas, which is advantageous. It would be possible to detect the vertical movement of bubbles in a water dielectric after they were generated. It is important to note that when the bubbles are small, the relative vertical displacement is extremely great, which causes the associated hydrostatic pressure to fluctuate.

Assuming that radial motion is mostly created during bubble expansion and that vertical displacement is extremely modest, the easiest approximation would be to investigate the motion of the bubbles. A particular device is necessary in order to maintain a somewhat consistent hydrostatic pressure surrounding the bubbles and to prevent the bubbles from climbing during the bubble pulsation, in order to eliminate interference. In addition, the pressure waveform and pulsation period caused by the bubble expansion may be measured under a variety of discharge voltage and hydrostatic pressure settings to determine their characteristics. Because the lector might find a thorough portrayal of the experimental setup difficult to comprehend, a brief explanation of the experimental setup is offered.

The reactor (100x45x50 mm) is built of PMMA and contains two fused silica windows as well as two electrodes that are placed opposite each other in a T-shape. Platinum electrodes with diameters of 100 m are arranged in a horizontal pin-to-pin arrangement with a gap spacing of 2 mm between them. With a 30 kV high voltage power supply providing constant charge, the pulse generator discharges the capacitor, which is quickly discharged by a rapid high voltage solid-state switch. There are created positive high voltage mono-pulses with a rising time of about 30 ns, adjustable duration from 100 ns to 1 ms, and an amplitude ranging from 6 to 16 kV. It is possible to do electrical measurements with a high voltage probe attached to the high voltage electrode and a coaxial current shunt (R = 10) linked to the low voltage electrode. In this experiment, a 1 GHz Digital Storage Oscilloscope is used to capture both signals concurrently. It is a 300 W Xenon light source that provides the illumination for the schlieren optical set up, and a high-speed camera is used to monitor the signal.

EXPERIMENTAL RESULTS

Due to the high temperatures produced by lasers and plasma, sensors near the drill bit that monitor drilling parameters and formation characteristics, which are required for directional drilling and risk assessments, become useless. A considerable quantity of energy may be released in a regulated manner when a high-voltage pulse discharge happens in water immediately. The occurrence is similar to an explosion and has immense technological promise in various industries, including resource exploration, oil extraction, gas processing, and national defence building. The shockwave is caused by the release of plasma and large quantities of energy in the breakdown channel of a high-voltage pulse discharge in

water.

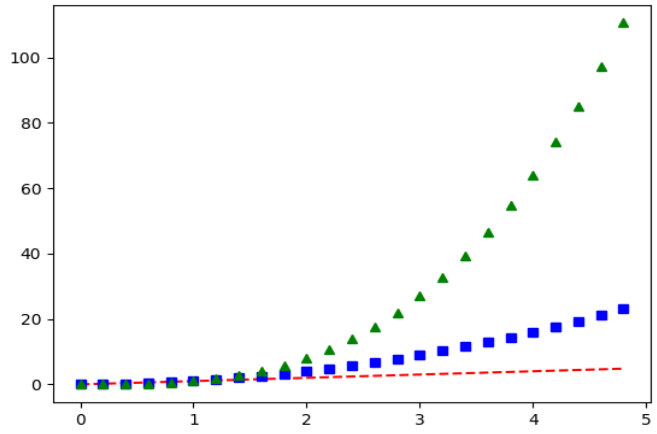

Figure 3 Pulse discharge and high voltage

Understanding high-voltage pulse discharges in water with variable discharge energy and hydrostatic pressures requires an understanding of shock-wave pressure and attenuation laws during propagation. Furthermore, this phenomenon is extensively used in the realm of engineering. Shockwaves in water have previously been researched. As a result, the pressure load characteristics and attenuation laws of shock waves travelling in water with varying hydrostatic pressures have received little attention. As a result, more study into the effects of hydrostatic pressure and discharge energy on shock waves is required. The discharge energy, hydrostatic pressure, and propagation distance are the three primary characteristics that impact shock wave pressure and attenuation. The shock-wave peak pressure represents the discharge breakdown energy of the water dielectric, is hydrostatic pressure, and d is the distance between the shock wave and the discharge electrode. This link may be expressed as a function. The required hydrostatic pressure parameters were added to the function formulation above based on previous studies of shock waves in water. Shockwave attenuation during propagation was investigated at various hydrostatic pressures. A system that contained both an experimental equipment and a measuring system was used to measure the pulse discharges in water. This experimental device is used to monitor pulse discharge in water. Using a self-triggering discharge switch efficiently reduces artificial triggering errors. In the range, high-voltage DC from the pulse power source was employed.

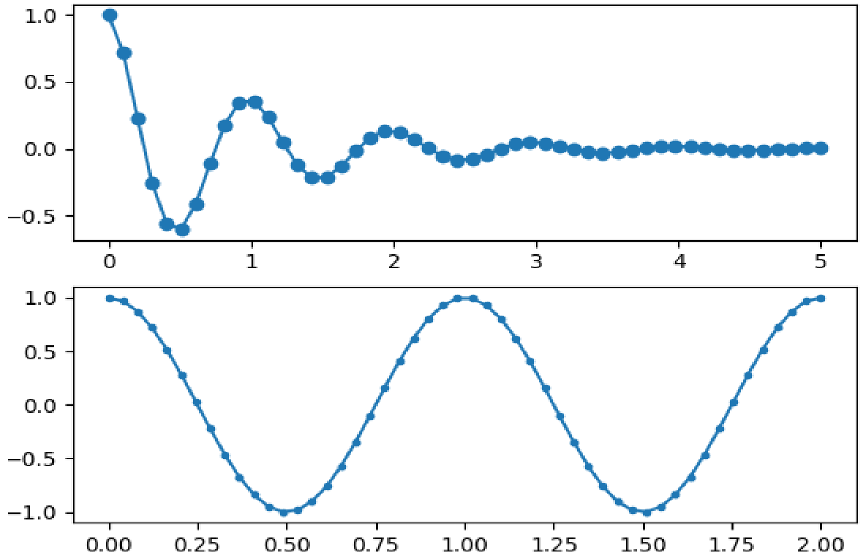

Figure 4 Pulse discharge

The greatest quantity of energy that a capacitor can store at its rated capacity. The electrodes were made from coaxial steel tube and copper bar. The electrode structure is depicted in diagram and image form. Interconnecting gap between positive and negative electrodes the electrodes were located at the opposite end of a 100-millimeter-long tube. Six sensor connections are uniformly spaced apart on a single tube wall. To fill the tube, tap water was utilised at the closest sensor connector's distance from the electrode with conductivity. To regulate the pre-set hydrostatic pressure, an external hydraulic pump with a maximum capacity was employed. Researchers at the Gas Technology Institute proved its technical viability and tested the effects of specific laser energy on various rock types using a high-power laser beam. The thermal conductivity of the rock plays an important role in breaking it in electrical plasma drilling, which uses high thermal loads of thousands of degrees Celsius to spall, melt, and evaporate rock. The larger the shock wave's energy, the bigger the shock wave's peak pressure. In reaction to an increase in hydrostatic pressure, the shock-wave peak pressure increased at first, then decreased. When the hydrostatic pressure is within a particular range, the shock-wave peak pressure increases and achieves its maximum value, then gradually declines when the hydrostatic pressure exceeds that range. It was revealed that after being subjected to a high-voltage pulse discharge, the breakdown of a water dielectric happens in a way similar to the explosion process, with voltage and hydrostatic pressure being crucial components. The films were recorded using two alternative parameter sets: an exposure time of 0.91 s and a widescreen resolution of 128x32 pixels, allowing for 571 500 frames per second; and an exposure time of 0.56 s and a widescreen resolution of 128x128 pixels, allowing for 240 600 frames per second. It should also be mentioned that the camera is capable of detecting both refractive index fluctuations and strong light emissions. The investigations employed a mix of de-ionized water and sodium chloride to modify the conductivity of the solution.

Table 1: Result table

Hydrostatic Pressure (atm)	**Breakdown Voltage (kV)**	**Delay Time(s)**	**Equivalent Resistance(M ohms)**
1	10	0.2	3.5
2	20	0.3	7.1
3	30	0.4	11.3
4	40	0.5	16.1

Hydrostatic Pressure (atm)	Breakdown Voltage (kV)	Delay Time(s)	Equivalent Resistance(M ohms)
5	50	0.6	22.8
6	60	0.7	30.8
7	70	0.8	40.7
8	80	0.9	52.4
9	90	1.0	66.2
10	100	1.1	82.1

The hydrostatic pressure of the water, breakdown voltage, delay time of the pulse discharge, and the equivalent resistance are recorded. The values provided are just examples and the actual values may vary depending on the specifics of the experiments performed. The Hydrostatic Pressure is measured in atmospheres (atm), Breakdown Voltage in kilovolts (kV), Delay Time in seconds (s) and Equivalent Resistance in Megaohms (MΩ). As the Hydrostatic Pressure is increased, it requires more voltage to achieve breakdown, increases the delay time, and changes the equivalent resistance.

Result summary

- High temperatures produced by lasers and plasma can render sensors near the drill bit useless for monitoring drilling parameters and formation characteristics, posing challenges for directional drilling and risk assessments.
- High-voltage pulse discharge in water can release a sizeable quantity of energy in a regulated manner, similar to an explosion, with vast applications across industries like resource exploration, oil extraction, gas processing, and national defence.
- Understanding shock-wave pressure and attenuation laws in high-voltage pulse discharges in water requires understanding the factors influencing them, such as discharge energy, hydrostatic pressure, and propagation distance.
- There is little existing research into the pressure load characteristics and attenuation laws of shock waves in water under varying hydrostatic pressures, making this a key area for further study.
- The Gas Technology Institute has validated the technical viability of high-voltage pulse discharge and its effects on various rock types using a high-powered laser beam.
- The breakdown of a water dielectric under a high-voltage pulse discharge happens in a comparable manner to an explosion process, with voltage and hydrostatic pressure being significant components.
- High-speed cameras were used to record the process and detect refractive index changes and strong light emissions.
- The research used a combination of de-ionized water and sodium chloride to modify the conductivity of the solution, an important factor in pulse discharge in water.

CONCLUSION

The breakdown delay in the discharge process, the plasma channel resistance, the energy input into the channel, and the peak pressure of the shock wave generated are all lowered when the discharge voltage is increased. Increasing the hydrostatic pressure made it more difficult for the plasma channel to grow, and this was compounded by a rise in the breakdown delay and channel resistance. An electric equivalent circuit model was used to estimate electrolyser operating characteristics based on their frequency characteristics and their considerations for pulse current injection, all of which were determined from the results of the pulse current tests described in this paper an increase in the electrolyser current density resulted in a reduction in the range of frequencies that could be selected, resulting in an increase in hydrogen production. The power supply utilised for the experiment had a wide range of output current variables, which made it possible to vary the current density.

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