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Experimental Study on the Discharging Characteristics of Pulsed High-voltage Discharge Technology in Oil Plug Removal

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Abstract

Oil plugging of the downhole during oilfield development leads to a decline in well yield. A new plug removal method based on pulsed high-voltage discharge technology was proposed in this paper to solve this plugging problem. A low-carbon steel high-pressure sealed drum was developed to simulate a downhole operating environment with high static pressure. Four sealed contact pins were designed on the drum cover. These pins were used to insert the high-voltage cable into the drum body while ensuring the drum is leakproof. The maximum static pressure borne by the drum was 40 MPa. An experimental system of pulsed high-voltage discharge was designed based on the drum. A platform for the discharging experiment was established according to the system principle diagram. The effects of variation in static pressure on discharging voltage, discharging current, critical breakdown field strength, discharging time and its data discretization, and other parameters were determined with water and crude oil as the discharging media. Experimental results indicate that increasing static pressure increases discharging time, enhances pulsed discharging randomness, reduces the strength of impact waves generated in the discharging media, and weakens the fracture-generating effect on the cement tube. Increasing the working voltage achieves better plug removal. However, the requirements for size, texture, and insulativity of plug removal equipment are elevated accordingly. This study provides a basis for the application of pulsed high-voltage discharge technology in oil reservoir plug removal.

Keywords: Plug Removal Technology; Pulsed High-Voltage Discharge; Static Pressure; Discharging Characteristic

1. Introduction

Well drilling, well completion, and fracturing usually cause water-sensitive minerals in the stratum to expand during oilfield development. These minerals do not fuse with the oil-water layer, leading to precipitation, extraction of wax, and pitch in crude oil as well as intrusion and breeding of bacteria. These phenomena constrict the oil seepage channel, resulting in hole plugging, reduced oil layer permeability, and decline in well yield. Conventional plug removal technology removes plugging through chemical agents [1, 2]. However, this technology will lead to the corrosion of the tubular column and will generate secondary pollution of the oil layer. Ultrasonic wave plug removal technology can prevent oil layer pollution caused by chemical agents. This technology involves a vehicle-mounted high-power ultrasonic wave transmitter on the ground that transforms electric power into high-frequency electric signals which will be transmitted to a downhole transducer through a transmission cable. These signals are transformed into ultrasonic mechanical oscillation. The oscillation will act on the oil-containing stratum, depolymerize macromolecular matters, and then remove the well hole plug [3, 4]. However, this process has limitations. For example, ultrasonic wave plug removal requires a well depth not exceeding 3,300 m and well deviation not exceeding 200 cm at the oil layer. Various countries involved in oil production have studied ways to achieve environmentally-friendly and effective removal of a downhole oil layer plug, sustainable well yield growth, and enhanced benefits of oilfield development.

A new plug removal method based on pulsed high-voltage discharge technology is proposed in this paper. A high-pressure sealed drum (HPSD) was developed to successfully apply this technology in a downhole high static-pressure operating environment. The drum was used to design an experimental system of pulsed high-voltage discharge. Then,

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an experimental platform was set up according to the system principle diagram, and pulsed discharging characteristics under high static pressure were evaluated with water and crude oil as media.

2. State of the art

As early as the 1970s, several early-stage test studies of applied pulsed high-voltage discharge technology in plug removal during oil production were implemented in various locations across the world. The single energy of electric pulse oil extraction equipment adopted by Russia was 1.5 kJ, whereas the single-pulse energy of downhole pulse output increasing equipment developed by Ukraine was 1 kJ. The equipment showed varied experimental results. Henan Oil Field Logging Company in China adopted a self-developed low-frequency impulse oscillation plug removal instrument to conduct an experiment in a Henan oilfield with single-pulse energy of 3 kJ. The experimental results indicated that the instrument achieved an efficiency level of 90% [5, 6]. In oil-layer plug removal, the single-pulse energy of the aforementioned equipment is low, and multiple discharges are needed for plug removal. This phenomenon shortens the service life of discharging electrodes. The single discharging energy of a transmission-type electric spark source developed by the Institute of Electrical Engineering of the Chinese Academy of Science reached 20 kJ. However, this equipment is not applicable for narrow downhole operation because of its heavy weight. Hence, studying the parameters of pulsed high-voltage discharge technology and discharging characteristics is key to the successful application of this technology.

Timoshkin designed a plasma channel drilling system which directly applied pulsed discharging energy onto rocks and could crush 3.5–15 cm rocks [7]. Wilson analyzed the energy cost of pulsed high-voltage discharge equipment in crushing stainless steel and experimentally measured the impact waves generated by pulsed high-voltage discharge [8]. Rongyao developed a set of high-energy arc fracturing devices and implemented a rock sample fracturing experiment. The results show that the higher the single pulse discharge voltage is, the greater the single energy storage and the better the high-energy arc fracturing effect will be [9]. Tang studied a high-energy density capacitor which could meet the demands of large capacity and small volume of downhole equipment [10]. Kovalchuk successfully designed a high-voltage pulse generator which consisted of a low-voltage part, high-voltage part, coaxial transmission line, breakstone chamber, and a control system. Moreover, system parameters were provided [11]. These studies focused on the pulsed high-voltage discharge system and its parameters, but an in-depth analysis of the discharge characteristics of this system has not yet been performed. Gutsol studied the variation in the surface attribute characteristics of liquids, such as water and crude oil, under a high-intensity current. The results show that a change in the crude oil components sometimes completely alters the plasma kinetic characteristics [12]. Moreover, Given stated that a pulsed discharging circuit could be equivalent to one underdamped RLC circuit. Dynamic characteristics of the resistance and inductance in the circuit were obtained by evaluating the characteristics of the variation in the discharging current [13]. Rassweiler controlled the full width at half maximum (FWHM) and other parameters that generate impact waves by regulating discharging parameters. The results show that the FWHM of impact waves should be small enough for these waves to acquire megawatt-level pulse power [14]. However, these studies on pulsed high-voltage discharge characteristics did not consider an actual downhole operating environment. Moreover, the influence of downhole high static pressure [15, 16] on discharging characteristics was rarely investigated. High static pressure is one of the key factors for determining whether pulsed high-voltage discharge technology could be effectively applied to increase oilfield output. Hence, this study was performed to investigate the influence of high static pressure on pulsed discharging characteristics.

The rest of this study is arranged as follows. The development of an HPSD was described in section three. An experimental system of pulsed high-voltage discharge was designed based on this HPSD. An experimental platform was set up according to the system principle diagram, and experimental parameters were set. The results were analyzed in section four according to the discharging voltage, discharging current, discharging time, and other experimental data. The results from a cement tube impact test were also provided. This paper was summarized in the final section, and relevant conclusions were drawn.

3. Methodology

3.1. Experimental Principle

The new pulsed high-voltage discharge technology uses the electrohydraulic effect [17] to generate mechanical action. The electrohydraulic effect refers to the generated physical effects in heat, light, force, and acoustics when pulsed high voltage and high current are discharged in a liquid medium. The effect essentially rapidly transforms electric energy in a capacitor into mechanical energy in impact waves. This principle has been extensively applied to medical extracorporeal lithotripsy, water treatment, electrohydraulic forming, rock crushing, plasma source, etc.

A storage capacitor with high working voltage is used in oil layer plug removal to rapidly discharge in water or an oil-water mixture. In this process, a discharging channel with high temperature, high density, and high conductivity is formed. An enormous amount of energy is instantly released inside a discharge channel, transforming electric energy into impact waves which then act on an oil layer. Impact waves have extremely strong penetrating power. Thus, these waves bombard plugging substances and pollutants near the wellbore zone, resulting in the oscillation and crushing of these blockages. Then, the cavitation effect and the pressure of the oil layer itself are used to suck and push these crushed blockages. Finally, the oil layer plug is removed, and permeability characteristics near the wellbore zone at the oil layer

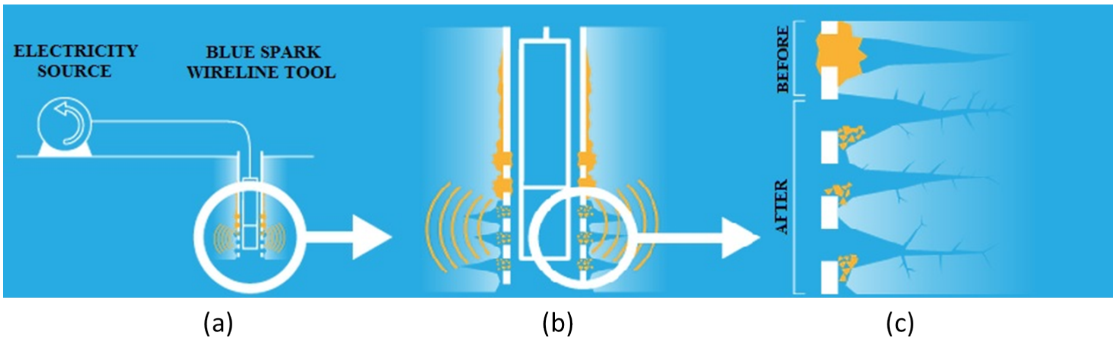

Figure 1: Schematic diagram of an application of pulsed high-voltage discharge technology: (a) Structure of pulsed high-voltage discharge system; (b) Electrohydraulic effect generated by downhole discharge; (c) Dredge oil pipe

Figure 2: External structure of the high-pressure sealed drum (HPSD)

Figure 3: Arrangement of sealed contact pins

are improved. Meanwhile, sound energy, electromagnetic fields, and other parameters generated by the explosion of electric sparks are transmitted to the deep part of an oil layer to improve the oil-water interface and increase the oil-water transport speed. Thus, this process increases the liquid production capacity of the oil well (Fig. 1).

3.2. Development of HPSD

An HPSD was developed based on the majority of downhole static pressure data in China to simulate a downhole static pressure operating environment. The structure of the HSPD is shown in Fig. 2. The drum body was a cylindrical barrel with a diameter of 350 mm and a height of 1,500 mm (height of the inner edge was 1,200 mm). Four sealed contact pins were designed on the cover of the drum (Fig. 3). These pins were used to insert the high-voltage cable in the drum body while ensuring leakproofness. This sealed drum was made of low-carbon steel and could bear a maximum static pressure of 40 MPa.

3.3. Design of Experimental System

An experimental system of pulsed high-voltage discharge was designed based on the HPSD to study the influence of downhole high static pressure on the discharging characteristics and establish a better application of pulsed high-voltage discharge technology for oil layer plug removal (Fig. 4). This system mainly consisted of a power supply, charging and controlling part, pulsed high-voltage power supply part, pulsed discharge part, and measuring equipment. The power supply used was 220 V and 50 Hz. The charging and controlling part consisted of a boost-up device and a rectifier. The former included a voltage regulator and a high-voltage transformer with output voltage adjustable within 0–50 kV. The pulsed high-voltage power supply included a high-voltage capacitor and a triggered vacuum switch and its control circuit. The pulsed discharge part consisted of the HPSD and electrode assembly. The measuring equipment included a P6015A high-voltage measuring probe to measure the voltage at the two ends of the electrode, a PEM super-current measuring probe to measure the cur-

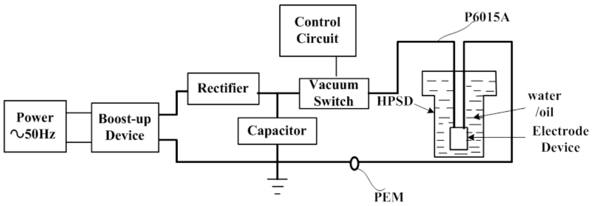

Figure 4: Schematic diagram of the experimental system of pulsed high-voltage discharge

Figure 5: Structure of the discharging electrode

rent in the discharge circuit, and one TDS2022 oscilloscope to record the voltage and current waveforms.

The discharging electrodes of a pulsed high-voltage discharge system can have different forms, such as needle-needle, bar-bar, and needle-plate structures. Similar to air breakdown under atmospheric pressure, breakdown of liquid media (such as water) under pulsed voltage also has a polar effect. A stainless steel electrode with a bar-bar structure was used in this paper to bear high voltage and facilitate the generation of a discharging channel. The electrode device shown in Fig. 5 had a total height of 300 mm, and its electrode space could be regulated according to the discharging channel. The electrode device was placed in the drum through a plastic rod and 280 mm away from the drum bottom. The anode of the center electrode was connected to the high-voltage leads, while its cathode was connected to the electrode shell under earthed backflow. The high-voltage and ground leads were attached to the drum body by the sealed contact pins (Fig. 6).

Figure 6: Connection mode of the discharging electrode inside the HPSD

3.4. Establishment of Experimental Platform and Parameter Setting

An experimental platform according to the system principle diagram was set up in the downhole monitoring laboratory in Xi'an Shiyou University, with the experimental parameter settings shown in Table 1. The working voltage was the charging voltage of capacitor C. Theoretically, increasing the working voltage would result in higher voltage loading at the two ends of the discharging electrodes, leading to an enhanced plug removal effect. However, the volume of the pulsed high-voltage power supply would rise as voltage is increased, and insulation requirement for the equipment would also increase remarkably. In this study, the working voltage in the experiment was set to 10–25 kV, considering an actual

Table 1: Basic physical parameters of experimental coal samples

Parameter	Value range
50 Hz supply voltage, V	220
Working voltage, kV	10–25
Capacitor C, μF	12
Electrode type	Bar–bar
Gap distance of electrodes, mm	1.8
Static pressure, MPa	0–30

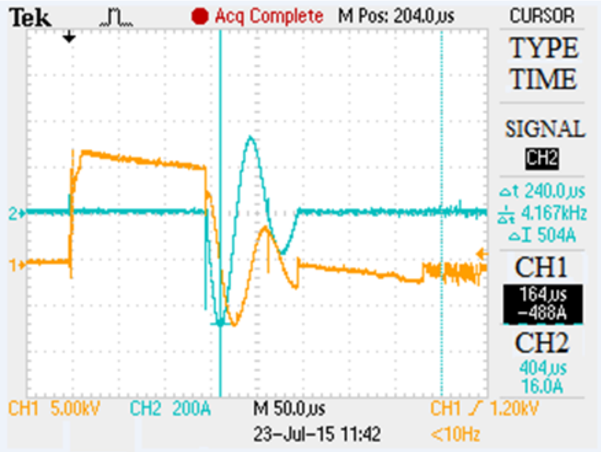

Figure 7: Voltage and current oscillographs under discharging breakdown in water

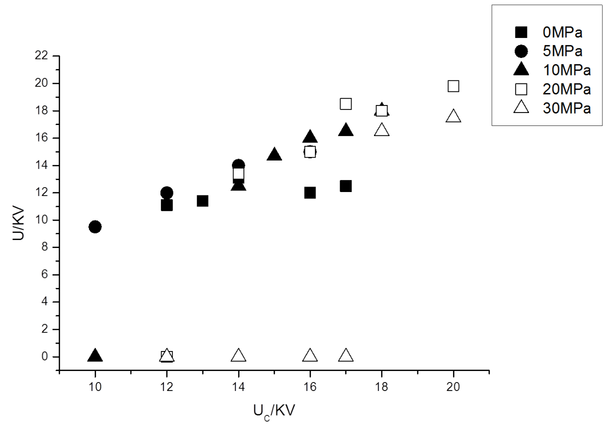

Figure 8: Influence of static pressure on the discharging voltage with water as the discharging medium

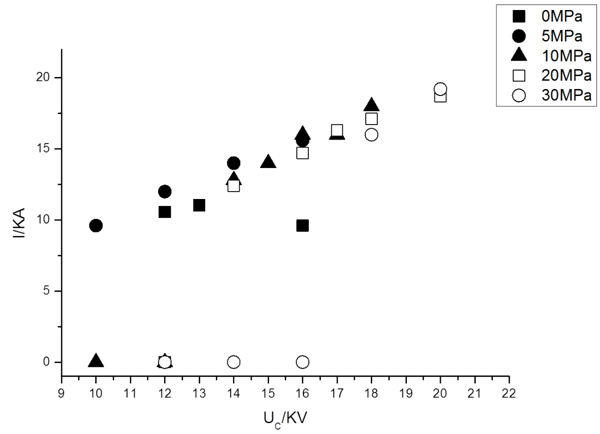

Figure 9: Influence of static pressure on the discharging current with water as the discharging medium

oil well operating environment.

4. Result Analysis and Discussion

4.1. Discharging Voltage and Current Waveform Analysis

The measured pulsed discharging voltage and current when the discharging medium was water and the working voltage was 12 kV are shown in Fig. 7. Channel 1 was the voltage oscillograph, which illustrated that the discharging voltage was 10 kV and the discharging time was 141 μs. Channel 2 was the current oscillograph, and the peak current under breakdown was 9.76 kA.

When the arc discharge was started, the high voltage inside the capacitor was directly loaded to the two ends of the electrode. Additionally, the discharging medium did not immediately experience a breakdown. The discharging voltage slowly decreased and the discharging current was nearly zero. The medium breakdown field strength was strong at the early discharging stage, but its insulating strength was not high. Thus, a weak discharging channel was formed between the two electrodes, and voltage slightly decreased. Meanwhile, Joule heat of the extra electric field and the leakage current accelerated the electrons to obtain enough energy for ionization and stimulation of water molecules. After a period, the voltage suddenly decreased, whereas the current abruptly increased. A plasma channel was established between the two electrodes, and the channel setting time, also known as discharging time, was 141 μs. Afterward, the medium broke down, forming a discharging loop, and the whole loop could be equivalent to an underdamped RLC oscillating loop. The existence of the loop inductance L resulted in the current in the loop presenting a damping oscillation form. The loop inductance basically ended after no more than two oscillations. The whole discharge process took approximately 250 μs.

4.2. Influence of Static Pressure on Discharging Characteristics with Water as the Discharging Medium

With water as the discharging medium, static pressures inside the HPSD were set to 0, 5, 10, 20, and 30 MPa, while the working voltage was increased from 10 kV to 20 kV.

Altering the static pressure and working voltage resulted in variation in the discharging voltage and current under different static pressures (Figs. 8 and 9).

The discharging voltage and peak discharging current increased as working voltage increased under unchanged static pressure (Figs. 8 and 9). Increasing the working voltage indicated increasing discharging energy when static pressure remained unchanged, because the numerical value of the capacitor in the experiment was established. Thus, the forerunner breakdown would happen more easily, plasma density inside the discharging channel increased, and resis-

Table 2: Critical breakdown field strengths under different static pressures

Static pressure, MPa	10	20	30
Critical breakdown field strength, kV/cm	61.1	72.2	100

Table 3: Variable value of measuring circuit at static pressure of 15 MPa

Experiment times	Discharging voltage, kV	Discharging time, μs
1	19.9	10
2	20	15
3	22	30
4	22	10
5	22	10
6	21.8	10
7	20	9
8	22	10
9	22	10
10	22	9

Table 4: Variable value of measuring circuit at static pressure of 30 MPa

Experiment times	Discharging voltage, kV	Discharging time, μs
1	18.5	10
2	20	9
3	22	20
4	22	33
5	21	30
6	21	39
7	20	20
8	18	28
9	18	22
10	19	20

tance of the channel was reduced, consequently increasing the peak current. Under unchanged working voltage, static pressure increased from 0 MPa to 30 MPa, and breakdown probability declined. The critical breakdown field strengths of the different static pressures are shown in Table 2.

Table 2 shows that as static pressure increased, the critical breakdown field strength nonlinearly increased, indicating that the requirement for working voltage increased during discharge. This characteristic is due to the fact that as static pressure increases, the plasma density in the forerunner declines, propagation velocity of forerunner slows down, and discharging resistance increases. These phenomena increase the difficulty of breakdown. Hence, as static pressure increases, parameter requirement in the pulsed high-voltage discharge system also increases. This phenomenon amplifies the requirements for insulation and the size of a pulsed high-voltage discharge device.

The influence of static pressure on discharging characteristics was shown in the experiment. However, in reality, a downhole discharging medium was an oil–water mixture. Thus, further study on the influence of static pressure on discharging characteristics with crude oil as the discharging medium was performed.

4.3. Influence of Static Pressure on Discharging Characteristics with Crude Oil as the Discharging Medium

The depth of oil extraction in China is generally 2000–3000 m, with formation pressures varying in different areas, and pressure decreasing slightly after oil extraction has been underway for a certain period. For example, the original formation pressure of one normal-pressure low-penetrating oil well was 28.9 MPa, and the formation pressure value after oil extraction was 15.56 MPa. Thus, two static pressures, namely, 15 MPa and 30 MPa, were selected

Table 5: Influence of static pressure on the discharging time with crude oil as medium

Static pressure, MPa	Time delay, μs	η
15	12.56	6.4
30	23.10	9.07

for the experiment, working voltage was set to 22 kV, and discharge was implemented ten times under the two static pressures. Experimental data are shown in Tables 3 and 4.

The average discharging voltage was calculated from the values in Tables 3 and 4. The average discharging voltages were 21.70 and 19.33 kV when the static pressures were 15 MPa and 30 MPa, respectively. Experimental results indicate that when the discharging medium was crude oil, discharging voltage decreased as static pressure increased. This result is consistent with the results in the water medium.

The average values of discharging time and data dispersion were calculated to study the influence of static pressure on discharging time. The dispersion of experimental data is described by standard deviation and calculated using Equation ((1)). The results are shown in Table 5.

$$\eta = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{1}$$

where η is the dispersion of experimental data, x_i is the variable value of the ith experiment, and $\overline{x}$ is the average value of data obtained from the experiments implemented for n times.

Table 5 shows that discharging time when static pressure was 30 MPa was longer by 10.54 s compared with that at 15 MPa, and the capacitor experienced a slow discharging process. This phenomenon is due to the fact that the genesis and development of the forerunner are hindered by static pressure as static pressure increases. This behavior increases the discharging time of the pre-breakdown phase. When static pressure was 30 MPa, the dispersion of 10 groups of data was greater by 2.67 compared with that at 15 MPa, indicating that the enhanced randomness of breakdown hampered the generation of the breakdown phenomenon.

4.4. Experimental Study of Plug Removal

A cement tube impact experiment was conducted to study the strength of impact waves generated by the pulsed high-voltage discharge under different static pressures and verify its plug removal effect. The cement tube was 600 mm in height, 200 mm in outer diameter, and 170 mm in inner diameter. The tube was placed inside the HPSD, and the electrode device was placed inside the tube. The cement tube was affected by the impact waves and then fractured when the discharging medium was water, the working voltage was 20 kV, and static pressures were 15 MPa and 30 MPa (Figs. 10 and 11).

Table 6 shows that the cement tube sustained more severe cracks when static pressure was 15 MPa than at 30 MPa.

Figure 10: Damaged cement tube at static pressure of 15 MPa

Table 6: Cement tube breakage under different static pressure conditions

Static pressure, MPa	Charging voltage, kV	Number of times of discharge	Number of cracks	Crack height, mm
15	20	5	3	600
30	20	5	1	600

This result indicates that when the working voltage was 20 kV, as static pressure increased, the impact waves generated in the discharging medium declined, and fracture formation in the cement tube weakened. Short discharging time and a large peak current value increased the energy of the impact waves and enhanced the plug removal effect. Hence, increasing the working voltage is beneficial for increasing the pressure of the impact waves. However, increasing the working pressure will hamper the development of the pulsed high-voltage discharge device to a certain degree.

4.5. Improvement of the Experimental Device

Electrode materials in this experiment were made of stainless steel, and discharge was implemented 150 times during the experiment. Experimental results indicated that the final height of the anode was reduced by 1 mm compared with that before the experiment, whereas the final height of the cathode was reduced by 2 mm. These results indicate relatively serious electrode erosion (Fig. 12).

Downhole equipment should have guaranteed long-term durability. Thus, pulsed high-voltage discharge electrodes

Figure 11: Damage of cement tube at static pressure of 30 MPa

should be made from materials with high erosion resistance, such as WCu alloys [18]. Improvement of electrodes should be considered in subsequent experiments.

5. Conclusions

An HPSD with low-carbon steel texture was developed to study whether pulsed high-voltage discharge technology could effectively remove plugs in a downhole operating environment with high static pressure. The device simulated a high static-pressure operating environment. An experimental system of pulsed high-voltage discharge was designed based on the HPSD. Then, the influences of static pressure on the discharging characteristics with water and crude oil as media were evaluated. The following conclusions could be drawn:

1. Calculated critical breakdown field strengths were 61.1, 72.2, and 100 kV/cm when the medium was water and static pressures were 10, 20, and 30 MPa, respectively. These results indicate that the critical breakdown field strength nonlinearly increases as static pressure increases. Thus, breakdown difficulty is enhanced, and parameter requirement of the whole pulsed high-voltage discharge system is also amplified.
2. With crude oil as the medium, discharging time at static pressure of 30 MPa was longer by 10.54 s compared with that at 15 MPa, and data dispersion increased by 2.67. These results indicate that as static pressure increases, the discharging process of the capacitor slows

Figure 12: Electrode erosion

down, discharging time of the pre-breakdown phase increases, and randomness of generating breakdown is enhanced.

3. A cement tube impact experiment was conducted with water as the medium. The fracturing degree of the cement tube at static pressure of 30 MPa was lower than that at 15 MPa. This result indicates that, as static pressure increases, the impact waves generated in the discharging medium decline and fracture formation in the cement tube weakens. A short discharging time and a high peak current would result in impact waves with higher energy and an enhanced plug removal effect. Hence, increasing working voltage is beneficial for improving the strength of impact waves.

4. Stainless steel discharging electrodes underwent severe erosion and therefore WCu alloys with high erosion resistance should be used.

In this study, pulsed high-voltage discharge technology was applied for plug removal in an oil layer. The designed experimental system of pulsed high-voltage discharge could simulate a downhole operating environment with high static pressure. The results provide a foundation for the development of a pulsed high-voltage discharging device. However, field tests were not performed. Thus, future studies will take into account the downhole high-temperature environment and factor the size and insulation of the discharging device into the developed experimental system. The system will be improved to achieve more accurate pulsed high-voltage discharge technology.

Acknowledgments

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