Experimental study on scale removal from special-shaped conduits through underwater electrical discharge

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Abstract. Underwater electrical discharge technology is an innovative technique that can be used to enhance the stress intensity of water and improve the load addition. The technique enlarges the section area and compresses the surrounding water using a high-powered shock wave, which is induced by an underwater electrical discharge. This paper investigates the effectiveness of scale removal for special-shaped conduits employing underwater electrical discharge. Experimental results show that the pressure wave generated by underwater electrical discharge is capable of eliminating scale in special-shaped conduits. The data indicates that when the capacitance of the parallel-pulsed capacitors was 4 μF, the high pulsed power voltage was 33 kV and the primary discharge gap was 48 mm, the result of scale removal was remarkable. In laboratory tests, the scale of special equipment was removed to a great extent by this method. Because of its effectiveness and low cost, this method improves the practice and extends the lifetime of such equipment, and thus has potential application and economic value.

1. Introduction
Underwater electrical discharge is a process of instantaneous strong current pulse discharge in a liquid medium. Additionally, this discharge of high voltage and large current is a kind of high-energy-density transient conversion process. It has characteristics such as high efficiency, strong shockwave pressure and low energy expense. Underwater electrical discharge technology (UEDT) has thus been widely used in scientific research and industrial application, such as machinery manufacturing, mining, environmental engineering and biotechnology [1–5].

In production processes and related areas of the petroleum chemical industry, heat-exchange equipment, reaction devices and chemical containers have differently shaped pipes. After a long period of operation, scale commonly becomes a problem in pipes and containers. Because of scaling, devices need to be stopped, replaced or cleaned after a few months. The removal of scale requires a lot of manpower and materials each year. Currently, the main cleaning methods are chemical corrosion, mechanical processing and hydraulic injection. However, actual surveys show that these methods are not satisfactory. Therefore, there is an urgent need for an effective solution.

2. Underwater electrical discharge system and components
An experimental system was designed to systematically generate high-voltage pulses under reproducible conditions. The system comprises a dc power supply with capacitive energy storage and

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a discharge source immersed in tap water at room temperature. A schematic diagram of the arrangement is shown in figure 1. The electrode system was located in the centre of a water tank with dimensions 800 mm (length) × 500 mm (width) × 500 mm (depth).

Figure 1. Schematic diagram of the experimental arrangement.

In figure 1, the coupling voltage regulator T1 (output voltage range of 0-280 V) receives external 220-V ac power, thus providing variable voltage for the high-voltage transformer T2. T2 and a silicon rectifier stack D constitute a high-voltage dc power supply (output voltage range of 0–50 kV); both T2 and D serve as a reserved capacitance charging power supply. The current-limiting resistance R limits the current charging loop and protects the high-voltage dc power supply. C1 and C2 each having capacitance of 2 μF withstand a voltage of 50 kV and provide total capacitance of 4 μF in a parallel manner. When the closure of J2 is triggered, the resultant short-circuit has a fast-fall-time step voltage. Owing to the charge stored in the capacitance, there is an electrical energy potential across the water-filled gap between the main electrodes J1. After a short delay time on the order of milliseconds, there is electrical breakdown of the water and the capacitor discharges through the plasma channel. The auxiliary discharge electrode J2 enhances the strength of the electrical discharge effect, and the gap J2 can be adjusted (adjustable range of 0–30 mm).

In this paper, the experimental subject was an ordinary steel tube with cement evenly spread on its inner wall. To study the mechanism of scale removal, the test model was constructed, simulating real conditions.

3. Experiment process, results and analysis

3.1. Experimental process

According to the structure of a "U-shaped" pipe and the actual working conditions of a sink, the experiment adopted indirect discharge. Indirect discharge is adopted (indirect discharge means external electrode discharges workpiece, instead of taking workpieces as discharge electrode). The main electrode is adjusted and moved both vertically and horizontally under water, 15 cm away from the upper outer wall of pipe fitting vertically. In the experiment, the main electrode discharge gap was set as Z = 48 mm. The tested common steel pipe fitting had an inner diameter of 25 mm, thickness of 2 mm, and length of 500 mm. To stimulate actual scale, the steel tube was bent in a U-shape, cut along its central axial, and uniformly coated with a 2-mm layer of cement along its inner walls. Because silicate cement is composed of silicates, its comprehensive mechanical and physical performance is similar to that of scale, but its adhesion to metal is stronger than that of scale. In this experiment, the applied cement is ordinary Portland cement, mode 300, and the proportion between cement and slurry is 1:3. After being mixed and tumbled with an appropriate quantity of water, the Portland cement was evenly smeared on the inner wall of the tube. The two halves of the pipe were then clamped and fixed.

3.2. Experiment results

The experimental results are given in tables 1 and 2. The tables show that for the same number of electrical discharges, electrical discharge energy increased and scale removal improved distinctly with an increase in the pulsed discharge voltage between the main electrodes; however, when the voltage of
storage capacitances remained stable, even with a greater number of discharges, the result of scale removal was inferior to that for the pulsed voltage step-up. In the tables, single-discharge energy was calculated using equation (1). The removal rate was the weight percentage removed relative to the total amount of cement.

| pulsed voltage (kV) | Single discharge energy (J) | Number of discharge | Removal rate |
|---------------------|-----------------------------|---------------------|--------------|
| 24                  | 1152                        | 20                  | 7.1%         |
| 27                  | 1458                        | 20                  | 34.2%        |
| 30                  | 1800                        | 20                  | 68.5%        |
| 33                  | 2178                        | 20                  | 97.3%        |
| 36                  | 2592                        | 20                  | 98.8%        |

Table 1. Experiment data of scale removal with increasing pulsed voltage.

| Pulsed voltage (kV) | Number of discharge | Removal rate |
|---------------------|---------------------|--------------|
| 20                  | 25                  | 6.8%         |
| 20                  | 30                  | 16.0%        |
| 20                  | 35                  | 31.5%        |
| 20                  | 50                  | 66.7%        |
| 20                  | 65                  | 81.3%        |

Table 2. Experiment data of scale removal with increasing number of discharges.

Figure 2 shows clear dependency of the scaling removal rate on the pulsed voltage and the discharge frequency. The trends of the two lines verify that increasing the pulsed voltage achieves a better result.

Figure 2. Descaling rate versus discharge voltage and number of discharges.

Figure 3 shows the part section of semi-tube that is daubed by cement, and figure 4 shows the result of inner wall descaling by increased pulsed discharge when its value is 36 kV. Although figure 4 shows that there is some residuum of the daubed cement not removed completely, its total descaling result is excellent compared to figure 3.
3.3. Analysis of Experimental Results

When electrical breakdown occurred between the main discharges electrodes, strong pulsed current reached 4100 A and pulsed voltage reached 750 kV cm\(^{-1}\). A shunting plasma channel with high temperature and high pressure developed on a nanosecond timescale. Therefore, the applied voltage and consequently high energy (several tens of kilojoules) were used to induce the electrical breakdown of water. In the first phase, the application of this long-duration high-voltage pulse between a pair of electrodes leads to the development of bubbles where gas discharge takes place. Moreover, the UEDT is associated with the emission of a powerful shock wave propagating radially into the water. The pressure waves generated have peak values in the range of 10\(^2\)–10\(^3\) MPa [7].

The single-discharge energy \(W\) of the main electrodes is described by

\[
W = C U^2 \cdot 2^{-1}
\]  

where \(C\) is the value of the tank capacitor and \(U\) is the charging voltage. The shock wave propagated along the radius of the spread. The peak pressure \(P(r, t_r)\) can be approximated by [8]

\[
P(r,t_r) = 4 \left[ \frac{n+1}{n+1-n} \left( 1 + \frac{n+1}{rC_0^2} \right)^{1/2} \right] \left( \frac{2n}{(n-1)} \right) - B
\]  

According to equation 2, \(r\) is 48 mm, and the metal susceptible pressure strength is calculated as about 69.42 MPa.

Scale attached to the walls of the tube is mainly composed of inorganic salt deposits such as sour barium, magnesium silicate and calcium carbonate. These deposits attach to the tube inner wall through a strong adhesion force. Because of the elastic modulus, the vibration frequency and especially the acoustic impedance of the metal are different from those of scale, and the shock-wave propagation therefore produces different mechanical effects. Usually, owing to the small pipe diameter, the spherical surface pressure released from the channel of the discharge can be approximately considered as a planar pressure wave in the case of a long discharge channel distance. Theoretical analysis of a shock wave propagating in different media reveals that the acoustic impedance of scale is less than that of metal. Under the action of the shock wave, scale and the metal wall will be compressed, but when the wave reflected from the metal wall reaches the boundary between the scale and water surface, there is a new reflection wave. This reflected wave can be transformed to a stretching wave. Influenced by the stretching wave, descaling will occur along the direction from the...
metal wall to the scale. The tensile stress is synthesized by a wave front (reflection wave of scale and water) and wave tail (reflection wave of the metal wall). With the generation of spalled scale and a new boundary surface appearing repeatedly, scale constantly undergoes spalling and breaks down, until the majority of scaling is divorced from the inner tube wall.

4. Conclusion
Scaling is removed by UEDT through the effect of the stress wave function in different solid media stuck to a pipeline. The strong tensile stresses separate the scale layer from the conduit wall, and thus have an excellent cleaning effect. By increasing the discharge voltage or the number of discharges, the cleaning effect can be improved. Compared with other removal methods, UEDT is not affected by the structure and the forms of a metal tube, and the technology does not negatively affect the mechanical properties of the tube. Meanwhile, this method has characteristics of high efficiency, strong shock pressure and low energy cost, and is thus very effective in removing scale from pipe fittings such as "U-shape" and spiral pipes. Therefore, UEDT has large-scale application prospects in industrial pipeline cleaning.

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