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RESEARCH ARTICLE

Enhancement of Shock Wave From Underwater Electrical Wire-Array Explosion at a Fixed Energy by Changing Wire Connection

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ABSTRACT An energy-efficient method is developed to generate shock wave from underwater electrical wire-array explosion. By changing wire connection of cylindrical wire-array, parallel is found usually not the suitable connection of wire-array to generate shock wave at a fixed energy. The suitable connection of wire-array is determined by initial energy. At a given initial energy, resistance matching between load and external resistance is an important factor to generate shock wave, and the corresponding discharge current is critically damped discharge.

INDEX TERMS Underwater electrical wire explosion, wire-array, resistance matching.

I. INTRODUCTION

The shock wave (SW) generated by underwater electrical wire explosion (UEWE) has increasingly attracted attentions due to a growing number of applications, such as increasing the production and enhancing the recovery in oil wells [1], electrohydraulic forming [2], non-thermal food processing [3]. If the pressure of the shock wave can be greatly enhanced, some potential applications are possible. These potential applications include the inertial confinement fusion [4] and the shock wave induced phase transition [5].

Many efforts had been devoted to enhance the pressure of shock wave. The shock wave focusing is the most attractive method, many researchers replaced single wire by cylindrical liner or wire-array to generate multi shock waves focusing. Los Alamos National Laboratory used a cylindrical liner and investigated electromagnetically-driven cylindrical shock-wave implosion in water by laser shadowgraph measurements [6]. With electrical cylindrical wire-array explosion, Fedotov showed that shock wave is self-aligned into a cylindrically symmetric converging front, which significantly enhanced the pressure of shock wave due to shock focusing [7]. In order to drive a spherical wire-array consist of 40 Cu wires with 0.1mm in diameter and 31.4mm in length, Antonov used a strong power source with stored energy of 3.6 kJ [8]. Qian developed an energy-efficient method for further enhancing the shock wave generated by cylindrical wire-array [9]. The method is to replace one thick wire with N thinner wires while the total mass of these N wires is kept equal to the thick one.

However, the replacement of single wire to multi same wires usually results in decreasing of wire-array resistance. At the beginning of UEWE, little energy will deposit into wire-array due to its relatively low resistance. As a result, much energy will waste on the external resistance, and it will take much more stored energy to drive a copper atom to the same temperature compared to a single wire. This shortage will be evident when initial energy is not sufficient.

In this paper, an energy-efficient method is developed to drive electrical wire-array explosion in a fixed energy. The core of method is to change wire connection of wire-array from parallel to series. For example, the resistance of wire-array with N wires will increase N^2 times when N parallel wires are changed to N series wires. Therefore, due to its relatively high resistance compared to the paralleled one, wire-array will deposit more energy at the beginning of UEWE. Higher deposit power will lead to quicker phase change and stronger shock wave. Less energy will be waste on external resistance at the same time.

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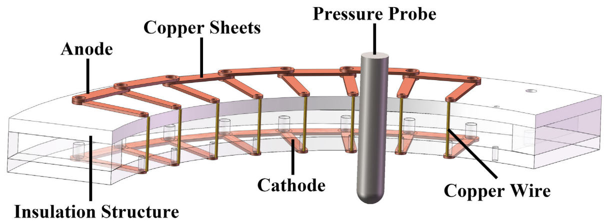
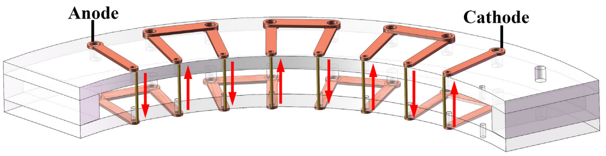


(a) A cylindrical wire-array with 8 parallel wires.



(b) A cylindrical wire-array with 8 series wires

FIGURE 1. Cylindrical wire-array in (a) parallel and (b) series.

II. EXPERIMENT SETUP

The experimental setup used here is almost the same as that detailed in our previous paper [10]. The wires are electrically exploded in the water chamber. Waveforms of discharge current i(t) and wire voltage u(t) are measured with a Rogowski coil (Pearson 101, bandwidth 4 MHz) and a voltage divider (Tektronix P6015A, bandwidth 75 MHz), respectively. All experiments are performed at different fixed energy by the charging voltage of the energy-storage capacitor of 0.5 μF in the range 15∼30 kV.

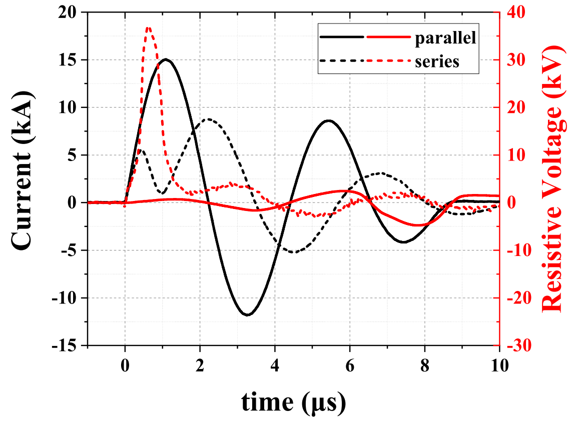
The experiments are based on the configuration of a cylindrical wire-array. The cylindrical wire-array is 200 mm in diameter and 20 mm in length. The pressure probe (PCB138A26, Piezotronics) is placed along the central axis of the wire-array. As an example, Fig.1(a) is a cylindrical wire-array with 8 parallel wires.

The wire-array setup is made of insulation structure, the current flows through wires and copper sheets. The connection of wires can be reordered by taking off some of copper sheets. As shown in Fig.1(b), the connection of wires changes from parallel to series. The red arrows in Fig.1(b) show path of current flow.

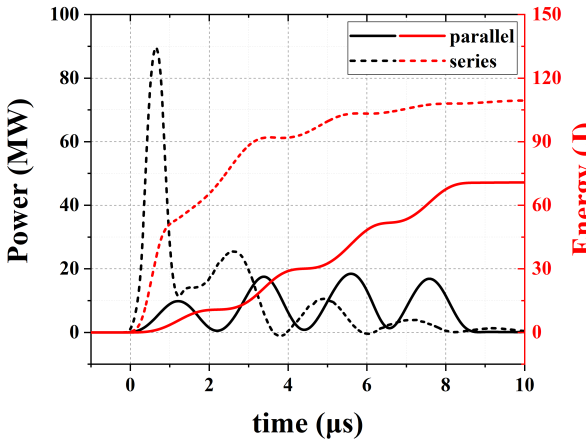
III. RESULTS AND DISCUSSIONS

The experiments were carried out by charging the capacitor voltage to 15, 20, 25 and 30 kV, at least 3 experiments are carried out in one certain connection at a certain voltage. Typical electrical waveforms of 25 kV are shown in Fig.2. The deposition power and energy is calculated by formula (1) in which u_R is the resistive voltage of the wire-array, u_W is the measured voltage of wire-array, and Lw is wire-array inductance obtained by calculation. The inductance of parallel wire-array is 130nH and series wire-array is 400nH.

$$E_d(t) = \int_0^t u_R(t) \cdot i(t) \cdot dt = \int_0^t \left[u_W(t) - L_W \frac{di(t)}{dt} \right] \cdot i(t) \cdot dt \quad (1)$$



(a)



(b)

FIGURE 2. (a) Current and resistive voltage; (b) deposition power and energy in 25 kV.

TABLE 1. Shock waves generated from different connections of wire-arrays.

Initial Voltage	Wires in Series	Wires in Parallel
15 kV	3.2 MPa	~0 MPa
20 kV	8.7 MPa	0.67 MPa
25 kV	11.8 MPa	10.9 MPa
30 kV	13.1 MPa	21.6 MPa

When the wires are connected in parallel, the resistive voltage is rather low compared to that in series. The waveform of current and voltage in parallel is like short circuit discharge. The reason for the phenomenon may be the relatively low wire-array resistance. In contrast, in the situation of series, most energy deposit in the first period, and the deposited power is much higher than that in parallel. It will lead to a stronger shock wave when the voltage is less than 25 kV. However, when the capacitor is charged to 30 kV, the wires connected in parallel generated a stronger shock wave shown in Fig.3 and Table 1 below.

The wires in series generate comparable stronger shock waves at low initial voltage. However, series shock wave increase relatively slow compared to parallel shock wave when the initial voltage grows.

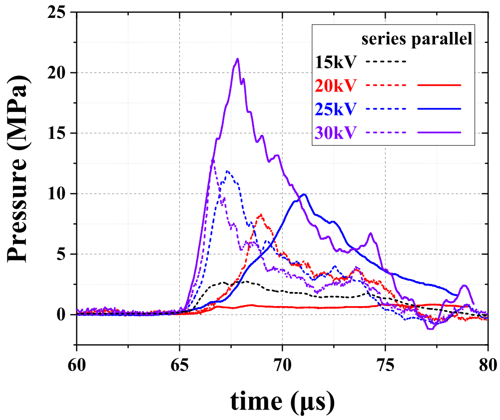
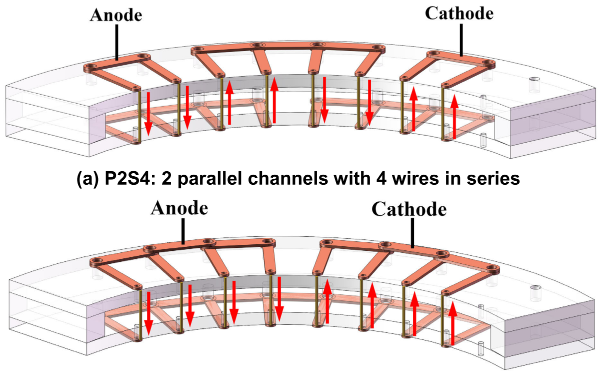


FIGURE 3. Profiles of shock wave generated by different initial voltage in series and parallel.



(a) P2S4: 2 parallel channels with 4 wires in series

(b) P4S2: 4 parallel channels with 2 wires in series

FIGURE 4. Cylindrical wire-array with (a) P2S4, (b) P4S2.

It is an interesting phenomenon reveals that improvement of wire-array resistance cannot always lead to the enhancement of convergence shock wave. To work out the reason of the phenomenon, two more groups of experiments are designed and carried out.

Fig.4 shows two new wire connections. In Fig.4(a), 8 wires are divided into 2 parallel channels, each channel has 4 wires in series, it will be named "P2S4" in this paper. In Fig.4(b), 8 wires divided into 4 parallel channels with 2 wires in series are named "P4S2". In the same way, parallel and series are renamed "P8S1" and "P1S8". The inductance of P4S2 wire-array is 210nH and P2S4 wire-array is 240nH.

We repeated the experiments in 15, 20, 25 and 30 kV on two new connections. Fig.5 shows current, resistive voltage, deposition power and energy in 25kV of two new connections. The pressure data are filled in Table 2 below, which extends Table 1. Table 2 is also transformed to Fig.6.

From Table 2 and Fig.6, we can see at the same charging voltage, the suitable connection is neither in series nor in parallel. If the initial voltage is less than 25 kV, the suitable connection is P2S4, when the initial voltage reaches 30 kV, P4S2 is better than P2S4.

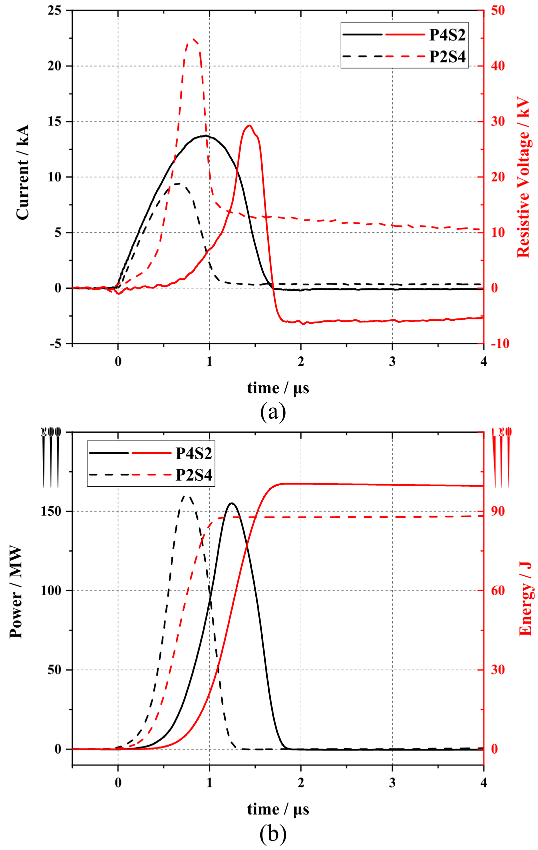


FIGURE 5. (a) Current and resistive voltage; (b) deposition power and energy in 25kV.

TABLE 2. Shock waves generated from different connections of wire-arrays.

Initial Voltage	P1S8	P2S4	P4S2	P8S1
15 kV	3.2 MPa	8.1 MPa	1.9 MPa	~0 MPa
20 kV	8.7 MPa	16 MPa	11 MPa	0.67 MPa
25 kV	12 MPa	20 MPa	17 MPa	11 MPa
30 kV	13 MPa	23 MPa	30 MPa	22 MPa

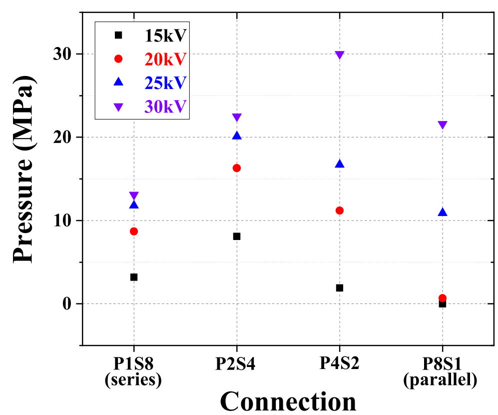


FIGURE 6. Shock waves from different connections in different initial voltage.

Taking 25 kV as an example, wire-array with P2S4 connection generate the highest shock wave of 20 MPa. Current

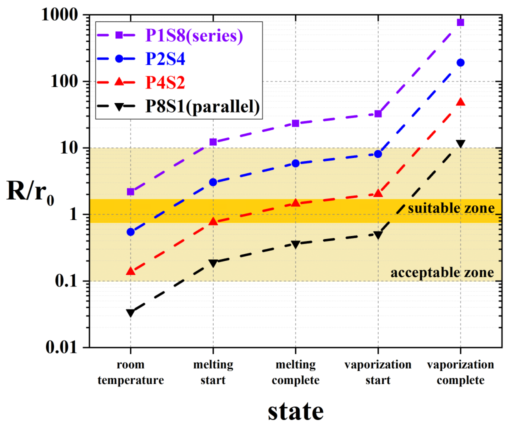


FIGURE 7. Ratio of wire-array and external resistance in different connections and different states.

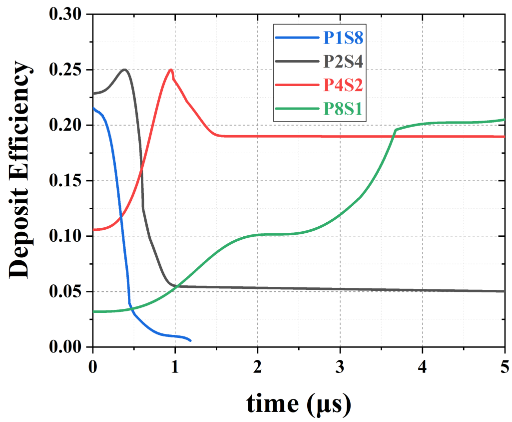


FIGURE 8. Deposit efficiency of 25kV.

TABLE 3. Resistance of four wire-arrays at different states.

State	P1S8	P2S4	P4S2	P8S1
room temperature	0.36 Ω	90 mΩ	23 mΩ	5.6 mΩ
melting start	2.0 Ω	0.5 Ω	0.13 Ω	0.032 Ω
melting complete	3.9 Ω	1.0 Ω	0.24 Ω	0.060 Ω
vaporization start	5.4 Ω	1.3 Ω	0.33 Ω	0.084 Ω
vaporization complete	126 Ω	32 Ω	7.9 Ω	2.0 Ω

waveforms from Fig.2(a) and Fig.5(a) indicate that wire-array of P2S4 connection undergoes a critically damped discharge. We consider the reason for the phenomenon is resistance matching. By careful calculation [11], the resistance of four wire connections at different states are calculated and listed in Table 3 and Fig.7 below. The external resistance (r_0) is measured to be about 165 mΩ.

$$R_{PmSn} = R_{single} * \frac{n}{m} \tag{2}$$

Taking consideration of the simplest circuit with external resistance (r_0) and growing load resistance R. The deposition power into the load resistance is

$$P = I^2R = \left(\frac{U}{r_0 + R}\right)^2 \cdot R = \frac{U^2}{r_0} \cdot \frac{1}{2 + \frac{R}{r_0} + \frac{r_0}{R}} \tag{3}$$

The deposition power maximizes when $R = r_0$. Fig.6 shows the ratio of wire-array resistance and external resistance at different states. "Suitable zone" and "acceptable zone" in Fig.6 means very high and relatively high energy deposition efficiency. In each UEWE experiment, the ratio R/r_0 rises along the corresponding dotted line with variable speed.

In the condition of low initial voltage, the ratio rises with low speed, and the location of early state on Fig.6 is important to generated shock wave. That is the reason why P2S4 (blue line) generates stronger shock wave. Although P1S8 (series) has similar initial position in room temperature, however, in the experiments P1S8 goes out acceptable zone straightly. By contrast, P2S4 goes in and out suitable zone, and then goes out acceptable zone. It reveals that in this case, P1S8 will have no chance to generate stronger shock wave at any voltage compared to P2S4.

When the energy is sufficient, the ratio rises fast at the beginning, P4S2 will advantage over P2S4 gradually. That is why P4S2 generated stronger shock wave in 30 kV. Furthermore, we can indicate P8S1 (parallel) will advantage over others when increasing to ultra-high initial voltage.

Furthermore, we define deposit efficiency as formula (4) below, and feed the profiles of load resistance obtained from Fig.2(a) and Fig.5(a) into formula (4), the profiles of deposit efficiency are list in Fig.7.

$$E = \frac{1}{2 + \frac{R}{r_0} + \frac{r_0}{R}} \tag{4}$$

From Fig.8, we can see only P2S4 and P4S2 reach the maximum of deposit efficiency quickly, which is consistent with the theory of resistance matching, generating stronger shock wave. The increase of initial voltage always speeds up the arrival of maximum point, it is no doubt P8S1 will reach the maximum point quicker when the voltage increase to 40 kV or higher. It is worth noting that this is a qualitative analysis, not a quantitative analysis.

IV. CONCLUSION

To summarize, we develop an energy-efficient method to generate shock wave from underwater electrical wire-array explosion. By changing wire connection of cylindrical wire-array, parallel is found usually not the suitable connection of wire-array to generate shock wave at a fixed energy. The suitable connection of wire-array is determined by initial energy of wire-array. At a given initial energy, resistance matching is an important factor to generate shock wave. By observing ratio of wire-array and external resistance at different states of wire-array, the suitable connection ratio curve should locate both side of suitable zone.

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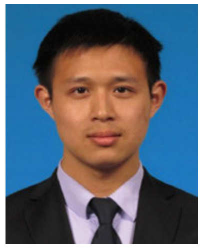

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