Electric ignition energy evaluation and the energy distribution structure of energy released in electrostatic discharge process*

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Ignition energy is one of the important parameters of flammable materials, and evaluating ignition energy precisely is essential to the safety of process industry and combustion science and technology. By using electric spark discharge test system, a series of electric spark discharge experiments were conducted with the capacitor-stored energy in the range of 10 J, 100 J, and 1000 J, respectively. The evaluation method for energy consumed by electric spark, wire, and switch during capacitor discharge process has been studied respectively. The resistance of wire, switch, and plasma between electrodes has been evaluated by different methods and an optimized evaluation method has been obtained. The electric energy consumed by wire, electric switch, and electric spark-induced plasma between electrodes were obtained and the energy structure of capacitor-released energy was analyzed. The dynamic process and the characteristic parameters (the maximum power, duration of discharge process) of electric spark discharge process have been analyzed. Experimental results showed that, electric spark-consumed energy only accounts for 8%–14% of the capacitor-released energy. With the increase of capacitor-released energy, the duration of discharge process becomes longer, and the energy of plasma accounts for more in the capacitor-released energy. The power of electric spark varies with time as a damped sinusoids function and the period and the maximum value increase with the capacitor-released energy.

Keywords: electric spark, discharge characteristics, energy structure, ignition energy

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1. Introduction

An electric spark is an abrupt electrical discharge that occurs when a sufficiently high electric field creates an ionized, electrically conductive channel through a normally-insulating medium, often air or other gases or gas mixtures.[1] The rapid transition from a non-conducting to a conductive state produces a brief emission of light and a sharp crack or snapping sound. A spark is created when the applied electric field exceeds the dielectric breakdown strength of the intervening medium. Electric sparks are widely used in industrial and laboratory to ignite fuel/air mixtures, such as in gas or dust explosion experiments and in inter combustion engine, because the discharge process is ease to control and the electric energy is relatively concentrated.[2–5] And it also has a wide range of applications in aviation, military, metallurgy, chemical industry, and everyday life.[6,7] Electric park energy is an important parameter to evaluate the ignition properties and hazardous characteristics of electric spark.[2,3] And the electric energy of a spark is directly related to the electric resistance and the current through it. The electrical contract resistance of pulse spark plasma sintering machine had been studied by Maniere *et al.*[8,9] Precise calculation and control of the energy of an electric spark were required for the effectiveness of the ignition process and the safety of industry process. The electric spark discharge process is very complicated as it is related to electrodes spacing, capacitance, resistance, and many other factors. And the electric energy of spark is regarded as the ignition energy of flammable materials. The challenge of our present study is to evaluate the electrical resistances and the energy of an electric spark. Maly *et al.*[10–13] divided the discharge process into four stages, pre-breakdown phase, breakdown phase, arc phase, and glow phase. Usually the capacitor stored energy was taken as the electric spark energy. In practice, not all the energy stored in capacitor turns into spark energy, most of it is consumed by circuit. In order to calculate spark energy more accurately, a controllable ignition device was established. A series of experiments on electric energy release during capacitor discharge process were conducted. The dynamic characteristics and the structure of electric energy distribution have been studied.

2. Experimental device and principle

2.1. Experimental device

The experimental system includes an electric spark generation system and a measurement system. The electric spark generation system consists of a high-voltage power, an energy storage capacitor bank, an three-pole switch which is controlled by a trigger device, and a pair of tungsten elec-

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trodes, as shown in Fig. 1. The measurement system consists of a TektronixDPO7254C digital oscilloscope (2.5-GHz band width, 20-Gs/s (1 Gs = 10^{-4} T) sample rate, 8 bit), TektronixP6015A voltage probes (75-MHz band width, 20-kV maximum input voltage), and Pearson110A current monitors (10-kA maximum current, 20-MHz band width). The selection of components and technical parameters of the electric spark generation system can be found in Ref. [14]. In the present study, capacitors with capacitance of 0.4005 μF, 3.998 μF, and 31.34 μF were used and the charging voltage ranged from 7.5 kV to 14 kV. Thus the capacitor-stored energy lies in the level of 10 J, 100 J, and 1000 J respectively. First the energy storage capacitor was charged by high voltage power, and then controlled by the three-pole switch, the energy stored in the capacitor released through electric circuit and electric spark-induced plasma between the tungsten electrodes. The energy stored in capacitor can be controlled by selecting the capacitor with different capacitance in the capacitor bank and the charging voltage. Electric energy release experiments were conducted with the stored energy in the range of 10 J, 100 J, and 1000 J respectively. The dynamic current of capacitor discharging process was monitored by a current sensor. And the dynamic voltage of capacitor and spark gap during the discharge process were measured by high voltage probes. The dynamic current and voltage can be used to evaluate the structure of energy distribution and the dynamic characteristics of the capacitor discharge process.

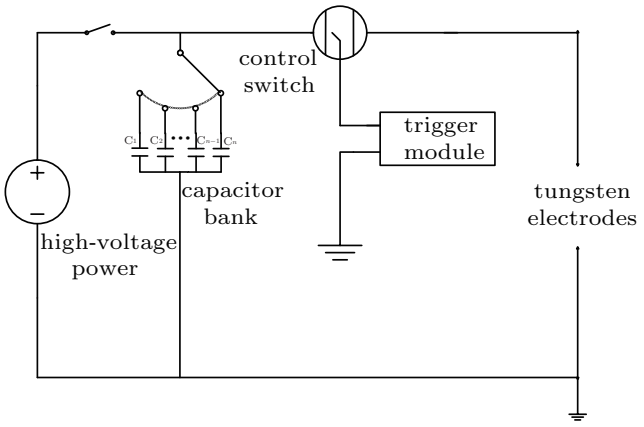


Fig. 1. Schematic graph of the spark discharge system.

2.2. Evaluation methods for electric spark energy

In the present study, the dynamic current and voltage were monitored by dynamic sensors of current and voltage respectively. And the data were recorded by a oscilloscope. A typical voltage history of capacitor and current history during the discharge process were shown in Fig. 2. It can be found that the current and voltage are all subject to periodic damping oscillation. Up to now, there is not a uniform standard for electric spark energy evaluation. In Chinese standard GB/T16428-1996,[15] International Electro Technical Commission standard IEC 61241:1994,[16] European standard EN 13821:2002,[17] and ASTM Standard E2019-03,[18] the electric spark energy is evaluated by mathematical integration of iu, that is, $E_{\text{spark}} = \int iu\,\mathrm{d}t$, where u and i are voltage and current histories respectively. The discharge processes of capacitor with capacitor stored in the range of 0.15 mJ–2025 mJ have been studied by Liu Qingming *et al.*[19] With the residual energy of capacitor discharge process considered, the capacitor released energy was calculated by using the current history of the discharge process, and the electric spark energy was evaluated by integration of iu, the rate of energy losses of capacitor and the electric circuit had been evaluated.[19] Zhang Yunming *et al.*[14] found that the phase shift between current and voltage histories of spark gap resulting from sensors cannot be neglected when the capacitor stored energy is large enough. So, the electric spark energy calculated by integration, $\int_0^t ui\,\mathrm{d}t$, could lead to a considerable error. So they raised two other methods, Joule's integration method, that is $E_{\text{spark}} = \int_0^t i^2 R_{\text{spark}}\,\mathrm{d}t$, and overall energy conservation method, that is $E_{\text{spark}} = E_{\text{released}} - \int_0^t i^2 R_{\text{circuit}}\,\mathrm{d}t$ to calculate electric spark energy. Where, E_{spark}, and E_{released} are electric spark energy and the capacitor released energy respectively. In Ref. [14] the resistance of electric-induced plasma, R_{spark}, and the resistance of circuit, R_{circuit}, were evaluated by the dynamic parameters of current oscillation and attenuation, thus may result in a considerable error. In this paper, to evaluate the energy distribution structure of capacitor-released energy, an energy conservation-based method for spark resistance evaluation is put forward.

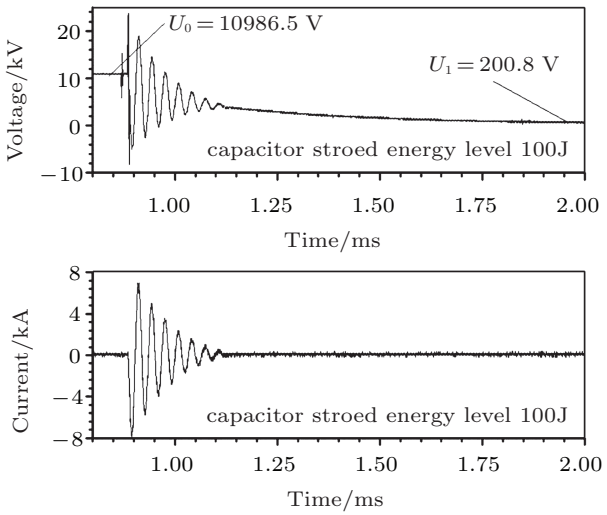


Fig. 2. Typical histories of voltage and current during capacitor discharge process (capacitor 3.998 μF, charging voltage 11 kV) obtained by the present study.

Taking the residual energy into account, the energy released during the capacitor discharge process can be obtained by

$$E_{\text{release}} = \frac{1}{2}C(U_0^2 - U_1^2), \tag{1}$$

where C is the capacitance of energy storage capacitor, U_0 and U_1 are electric voltage of capacitor before and after discharge process, as shown in Fig. 2. From Fig. 2 we can see that the voltage is gradually decreased from a certain value, U_0, and finally remains constant value U_1.

Suppose the energy released is completely transformed into heat energy, the total resistance of the spark discharge process can be obtained by

$$R_{\text{total}} = \frac{C(U^2 - U_0^2)/2}{\int i^2 \,\mathrm{d}t}. \tag{2}$$

The time interval of integration is the duration of the discharge process.

The resistance of short circuit, R_{short}, consists of wire resistance, R_{wire}, and switch resistance, R_{switch}, that is, $R_{\text{short}} = R_{\text{wire}} + R_{\text{switch}}$. R_{wire} can be obtained by four-wire electric resistance measured method, in our experiment circuit, $R_{\text{wire}} = 0.029\ \Omega$. And the short circuit resistance can be obtained by using the histories of voltage and current during the energy release process of the short circuit.

$$R_{\text{short}} = \frac{C(U_0'^2 - U_1'^2)/2}{\int i'^2 \,\mathrm{d}t}, \tag{3}$$

where, R_{short} is short-circuit resistance, U_0' and U_1' are voltage of energy storage capacitor before and after the energy release process of the short circuit, i' is the dynamic current during the energy release process of the short circuit.

The resistance of electric spark-induced plasma can be obtained by subscribing the short circuit resistance from the total resistance of the discharge circuit. By Joul's law, the electric spark energy can be expressed as

$$E_{\text{spark}} = \int i^2 \,\mathrm{d}t \cdot (R_{\text{total}} - R_{\text{short}}). \tag{4}$$

So, the energy consumed by the wire resistance is

$$E_{\text{wire}} = \int i^2 \,\mathrm{d}t \cdot R_{\text{wire}}, \tag{5}$$

and the energy consumed by switch can be expressed as

$$E_{\text{switch}} = \int i^2 \,\mathrm{d}t \cdot (R_{\text{short}} - R_{\text{wire}}). \tag{6}$$

Using Eqs. (4)–(6), the energy consumption by electric spark, wire, and switch can be calculated, so the energy distribution structure of the released energy during the capacitor discharge process can be obtained.

The capacitor-released energy consists of electric spark energy, wire-consumed energy, and switch-consumed energy. And the electric spark energy can transferred into thermal energy and blast wave (shock wave) energy. The blast wave energy can be obtained by the pressure field of shock wave.[20] The percentage of the blast wave energy to the electric spark energy is about 13% for the discharge process of capacitor with a stored energy of 100-J level. And the thermal energy can be obtained by subtract blast wave energy from the electric spark energy. For the discharge process of capacitor stored energy less than 10 J, the blast wave energy can be neglected. In the present study, only the electric spark-released energy is studied.

The dynamic temperature response of an electric spark induced by the discharge processes of capacitors with stored energy in the level of 10 J, 100 J, and 1000 J respectively had been studied.[21] And it was found that the maximum temperature of the electric spark lies between 3060 °C and 3400 °C and the duration of high temperature lies between 22 μs and 203 μs.

In the above method, the capacitor-released energy is divided into electric spark-consumed energy, wire-consumed energy, and switch-consumed energy. To electric spark generation device, the efficiency of the device, φ, is the percentage of electric spark energy to released energy, that is $\varphi = E_{\text{spark}}/E_{\text{release}}$. Besides of the electric spark energy, the power of electricity is also an important parameter to the ignition process of fuel/air mixtures. The rate of electric spark energy release can be expressed by electric spark power, that is

$$P_{\text{spark}} = i^2 R_{\text{spark}}. \tag{7}$$

3. Experimental results and analysis

3.1. Experimental results

The electric discharge experiments were conducted by using the experimental device described in Subsection 2.1. The electric spark with different energy levels can be realized by selecting energy storage capacitor with different capacitances. For 10-J, 100-J, and 1000-J capacitor storage energies, the corresponding capacitances of the energy storage capacitors are 400.5 nF, 3.998 μF, and 31.34 μF respectively.

To illustrate the details of energy calculation, a typical energy release process of a capacitor of 3.998-μF was taken as an example. The charging voltage of the capacitor was about 11 kV. And the voltage history of the energy storage capacitor and the typical current history during the capacitor discharge process are shown in Fig. 2.

By using the above-mentioned method, the electric spark-, wire-, and switch-consumed energies can be calculated as follows:

$$E_{\text{spark}} = 28.29\ \text{J},\ \ E_{\text{wire}} = 50.64\ \text{J},\ \ E_{\text{switch}} = 162.48\ \text{J}.$$

And the rate of energy conversion of the electric generation device is $\varphi = 11.7\%$. A series of discharge experiments with different capacitors and different charging voltages are conducted and the energy consumed by electric spark, wire, and

switch have all been calculated. Thus the energy structure can be obtained.

3.2. Results analysis

3.2.1. The structure of energy distribution

The energy and the rate of energy release are the main parameters related to electric spark application in industry and scientific research. For an electric spark generated by capacitor discharge device, the characteristic parameters of electric spark are closely related to the circuit of device. During the energy release process of the spark generation device, only a part of the capacitor-released energy is transformed into the electric spark energy, and the others is consumed by wire and switch. In this section, the energy structure of the capacitor-released energy during the capacitor discharge process is studied.

For the calculation of the electric spark energy, three methods, that is *ui* integration method, Joule's law method with spark resistance calculated by the parameters of current oscillation, and over all energy conservation method, were compared by Zhang Yunming *et al.*[14] In their opinion, the Joule's law method with electric spark resistance calculated by the parameters of current oscillation has more advantages than the other two methods in calculating the electric spark energy. In this paper, Joule's law has been used to evaluate electric spark energy, wire-consumed energy, and switch-consumed energy with the resistance evaluated by energy conservation law and parameters of current oscillation respectively. The spark energy evaluated by Joule's law with resistance calculated by energy conservation law and parameters of current oscillation were denoted by E_{spark1} and E_{spark2} respectively. The capacitor-released energy and the electric energy evaluated by two different methods described above with the capacitor-stored energy level of 10 J, 100 J, and 1000 J are shown in Fig. 3. Figure 3 shows that both of the released energy and the electric spark energy are increased with the increase of initial charging voltage under different energy levels. The increasing rate of released energy with initial charging voltage is much greater than that of the electric spark energy. The electric spark energy evaluated by Joul's law with resistance evaluated by energy conservation laws follow energy conservation law strictly, that is, $E_{\text{release}} = E_{\text{spark1}} + E_{\text{wire}} + E_{\text{switch}}$. So, E_{spark1} is used to analyze the energy structure of the released energy. And the higher the energy level is, the greater the proportion of the spark energy to release energy is, as shown in Fig. 3 and Table 1.

The variations of electric resistance with charging voltage with different energy levels are shown in Fig. 4. From Fig. 4 we can see that with the increase of energy level, both R_{total} and R_{spark} decrease. The upper curve represents the total resistance, while the lower curve represents the spark resistance. Figure 4 shows that the decreasing rate of R_{total} is greater than that of R_{spark}. So, with the increasing of charging voltage at the same energy level and with the increasing of energy level, the ratio of the spark resistance to the total resistance increases, and the rate of the energy conversion of the electric generation device increases. In addition, with the increasing of the energy level, the capacitor-released energy increases, the circuit is more prone to produce spark and the reliability of spark discharge has also been enhanced.

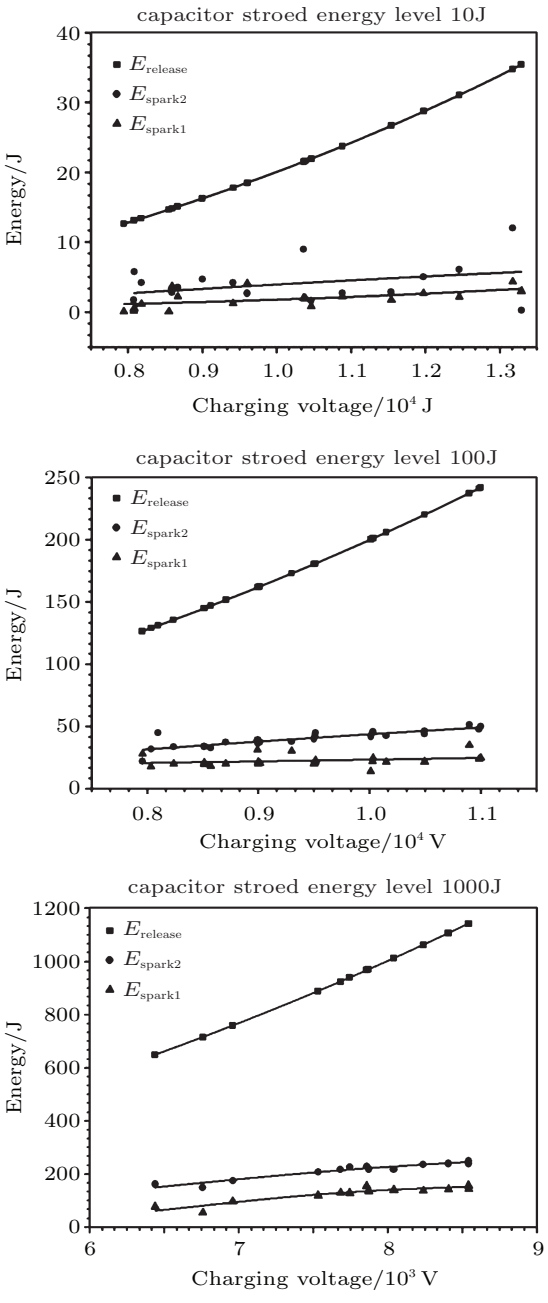


Fig. 3. Variations of energy with initial charging voltage.

Table 1. Energy distribution structure during capacitor discharge process.

Energy level	E_{release}	E_{spark}	E_{wire}	E_{switch}
10 J	1	0.084	0.048	0.868
100 J	1	0.127	0.204	0.669
1000 J	1	0.133	0.322	0.545

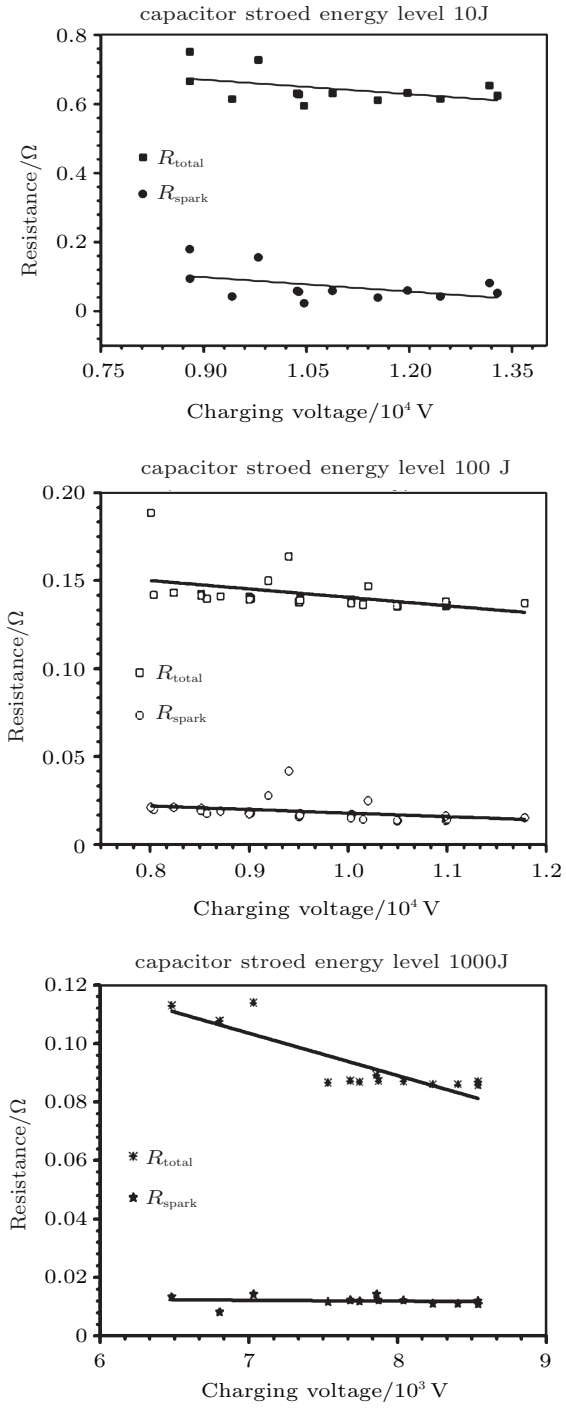


Fig. 4. Variations of discharging resistance with initial charging voltage.

On the other hand, it can be found that $E_{spark2} > E_{spark1}$, and that can be explained by the different methods of spark resistance calculation. In calculation of resistance with parameters of discharge current oscillation, the oscillation and attenuation of current are expressed approximately by exponentially damped sine function, and thus may result in some errors. While in calculation of resistance with energy conservation law, current oscillation from experiment is used, instead of the approximation function. So the resistance calculated by the energy conservation law is more accurate than that calculated by oscillation parameters of discharge current.

To study the structure of the released energy, we calculate the ratios of spark energy, wire-consumed energy, and switch-consumed energy to total release energy respectively. The results are listed in Table 1, where the errors of E_{spark}, E_{wire}, E_{switch} are accurate to 1‰, 0.12%, and 2.1%. It can be seen from Table 1 that with the increasing of energy level, the percentage of spark energy to released energy and that of wire-consumed energy to released energy is increased while the percentage of switch-consumed energy to released energy is decreased gradually. With the increasing of energy level, the capacitor stored energy increases, the whole circuit is prone to discharge, the discharge current increases and the duration of discharge process becomes longer. However, the wire resistance can be seen as a constant in a short time, so the wire-consumed energy becomes larger gradually. As shown in Table 1, switch resistance consumes most of the release energy.

3.2.2. Dynamics of electric discharge process

The power of electric spark ($P_{spark} = i^2 R_{spark}$) is also an important parameter of electric spark discharge process. Figure 5 shows a typical power history of electric spark discharge process under three different energy levels. It can be seen that the power of electric spark oscillated with amplitude exponentially damps. With the increase of energy level from 10 J to 1000 J, the period of power oscillation increases from 0.01 ms to 0.05 ms, and the maximum power value is relatively increases from 700 kW to 1700 kW. At lower energy level, the capacitor stored energy is small, and the duration of the discharge process is short. While in the high energy level, the capacitor stored energy is large, the duration of the discharge process is long. This phenomenon can be found in histories of power, voltage, and current.

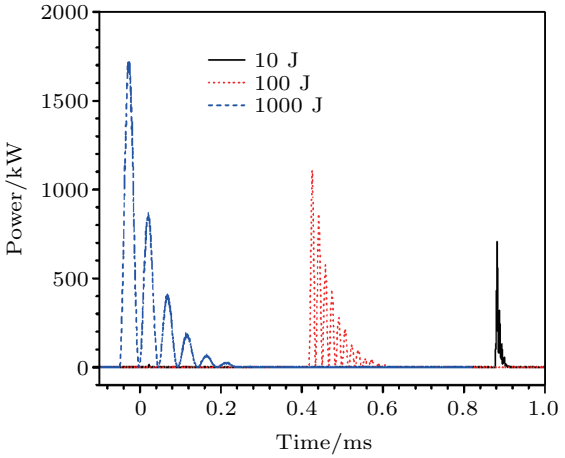


Fig. 5. (color online) Power history of the electric spark.

4. Conclusions

In conclusions, we investigated the evaluations electric resistance during capacitor discharge process based on energy conservation law. With the increases of the capacitor stored

energy from 10 J to 1000 J, the total resistance of the discharge circuit decreased from 0.7 Ω to 0.08 Ω while the resistance of the spark-induced plasma decreased from 0.1 Ω to 0.01 Ω. We also calculated the energy consumed by electric spark-induced plasma, wire, and switch and analyzed the energy distribution structure of the capacitor-released energy. Both of the capacitor-released energy and the spark energy increase with the increase of the stored energy. In general, most of the capacitor released energy are consumed by circuit, including wire and switch. Just a little part of it (8.4%–13.3%) is transformed into electric spark energy. With the increasing of capacitor stored energy, the proportions of spark energy and wire-consumed energy to capacitor release energy increase gradually. While the proportion of switch-consumed energy to capacitor-released energy decreases gradually.

The variation of power of electric spark induced plasma with time follows exponentially damped sinusoids function. With the capacitor stored energy increase from 10 J to 1000 J, the maximum power of electric spark-induced plasma increased from 700 kW to 1700 kW and the duration of the discharge process increased from 0.01 ms to 0.05 ms.

We measured the histories of current and voltage of electric spark during the electric energy release process of capacitors. It is found that both voltage and current can be expressed as an exponentially damped sinusoids function

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