Experimental investigation of spark discharge energy

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Abstract. Minimum ignition energy is one of the important characteristics for electrostatic sensitivity of explosives and determination of the spark discharge energy is necessary for decision making of explosion prevention. In this paper, the real spark discharge energy was determined by the integration of the measured voltage and discharge current in a needle-to-plate configuration. The influence of the charging voltage and polarity, the charging capacitance and the electrode gap on the spark discharge energy was investigated. It is shown that the energy deposited into the discharge system is always smaller than that stored in the charging capacitor, especially at lower voltages that the discharge shows one current pulse and the energy efficiency is less than 30%. The discharge becomes complete at higher voltages when the discharge shows double pulses and the energy efficiency is close to 100%. For given charging capacitance and voltage, the real discharge energy is determined by the discharge mode rather than the electrode gap or the voltage polarity.

1. Introduction
Minimum ignition energy (MIE) is one of the important characteristics for the electrostatic sensitivity of explosives [1]. It is important for the evaluation of the sensitivity of fireworks, firecrackers, and explosive substances to the electrostatic spark, the MIE of combustible gases, flammable liquid vapours and dust/air mixtures, etc. Accurate determination of the minimum ignition energy is necessary for decision making of explosion prevention and design of intrinsically safe electrical apparatus. The determination of the MIE using a capacitive electrostatic discharge (ESD) is well established in the literatures as well as in standards [2-9]. Thereby, a capacitor with a defined capacitance is supplied by a defined voltage. Then the capacitor is discharged in a test vessel filled with a certain flammable gas/air mixture via an electrode configuration with a defined electrode diameter, electrode material and electrode gap width. The energy stored in the capacitor is calculated using the equation \( E_0 = CU_0^2/2 \), where \( E_0 \) is the energy, \( C \) is the capacitance and \( U_0 \) is the voltage supplied to the capacitance, and the transferred charge is calculated as \( Q_0 = CU_0 \). The MIE is determined by varying the capacitance, the charging voltage, the electrode diameter, the electrode gap width and the mixture composition in order to find the lowest energy necessary to ignite the given mixture. In many cases, the ESD energy is assumed to have the amount of energy or charge stored in the capacitance before the discharge.

However, the electrostatic spark discharge energy is normally not equal that stored in the capacitor (or the nominal energy). In fact the stored charge might not discharge completely after the spark, with a small amount remaining in the capacitor. Moreover, the loss of the charge stored in the capacitance

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might also be taken by some means (e.g., corona) before or after the spark discharge happening. Hence
the discharge energy is generally smaller than stored energy. For this reason, the stored charge was
sometime not used for the definition of the transferred charge thresholds or MIE (e.g., Ref. [7, 8]).
Practically, the spark discharge energy hence the ratio of the measured discharge energy to the
nominal energy depends on the used electrode radius, the gap distance between the electrodes, the
charging voltage, the charging capacitance, and usually the property of the tested explosive.

The aim of this work is to examine the correlation between the energy stored in the capacitance
before the discharge and the real spark ESD energy. The dependence of the spark energy on the
charging voltage, the capacitance, the electrode gap is studied.

2. Experimental setup
The schematic of the ESD system used in experiments is shown in figure 1.

![Figure 1. Schematic of experimental setup.](image)

The system consists of a needle-to-plate electrode, a discharge capacitor \( C \), a high voltage (HV)
power source and a HV relay switch \( K \). The needle is made of Tungsten and the radius is about 0.05
mm. The electrode gap \( d \) is from 1 to 4 mm. The capacitor \( C \) is firstly connected to the HV source
through switch \( K \), to be charged to a voltage level of \( U_0 \), then connected to the needle electrode
through an inductor \( L \) to trigger the ESD spark. The inductance \( L \) is 2.3 mH in our experiments. The
plate electrode is made of copper and grounded. Both the negative and positive high-voltage DC
power sources are tested in experiments. The voltage is measured by a digital Oscilloscope Tektronix
TDS-3054B and voltage probe, with hardware bandwidth of 500 MHz and sample rate of 5 G/s. The
voltage \( U \) on the needle is measured by a Tektronix voltage probe P6015A, while the discharge
current \( I(t) \) is sampled by the measured voltage on a non-inductance resistor \( R \), or \( I = U_R / R \) (where \( U_R \)
is measured by Tektronix voltage probe P6139A). The sampling resistance \( R \) is 1.5 \( \Omega \). The charging
 capacitance \( C \) is variable in experiments, ranging from 250 pF to 5000 pF. The real discharge energy
is determined by the integration of the voltage \( U(t) \) and current \( I(t) \) with time, or

\[
E = \int_0^T U(t)I(t)dt = \int_0^T U(t)\frac{U_R(t)}{R}dt
\]

(1)

The each discharge is repeated 5 times and the total energy is averaged. The discharge energy \( E \)
is compared with the initial stored energy in the capacitor \( E_0 = CU_0^2/2 \).

3. Results and discussion

3.1. Waveform of discharge current and voltage
We tested the ESD sparks in different conditions. The temperature and relative humidity is 25°C and 50% respectively. The spark occurs when the applied voltage is greater than a critical value. The typical waveforms of voltage and current are shown in figure 2 for gap of 1 mm and capacitance of 250 pF. The voltage is of 7 kV and the polarity is positive.

It is seen that the discharge current shows a typical ESD current, with a stronger pulse firstly and following inversed small pulse. The rising time of the current pulse is about 10 ns and the duration is about 50 ns. The calculated discharge energy according to equation (1) is $E = 0.61$ mJ which is much lower than the nominal one in the capacitor, with a discharge efficiency of $E/E_0 = 10\%$.

When the voltage increases, the discharge current may show double peaks. Typical waveforms are shown in figure 3 for voltage of 9 kV.

Note that there is a remaining voltage about 1200 volts on the capacitor after the spark and there is a low current of 1.5 A continues through the circuit, resulting a transient power consumption of 1.7 kW in the circuit after the spark. This current lasts for several microseconds and would release the major part of the energy stored in the capacitor.

When the voltage increases, the discharge current may show double peaks. Typical waveforms are shown in figure 3 for voltage of 9 kV.

![Figure 2](image1.png)  
**Figure 2.** Waveforms of spark discharge current and voltage at $U_0 = 7$ kV, $d = 1$ mm.

![Figure 3](image2.png)  
**Figure 3.** Waveforms of spark discharge current and voltage at $U_0 = 9$ kV, $d = 1$ mm.

It is seen that the spark is firstly started by a small current, followed by a stronger second pulse. The interval between the two pulses is from several to tens of nanoseconds. The first pulse has a rising
time of about 10-20 ns and lasts for about 50-70 ns. The energy in the first pulse is small, with value of 0.9 mJ or 9% of the stored energy. The second has a rising time of 10-30 ns and lasts for as long as 200 ns. The discharge energy in the second pulse is about 8.7 mJ or 87% of the stored one. In this case, there is also a remaining voltage (about 1200 V) on the charged capacitor, but the remaining current is zero after spark. The total discharge energy is \( E = 9.6 \) mJ which is close to the nominal one in the capacitor, with a ratio of \( E/E_0 = 96\% \). This indicates that the discharge is almost complete.

3.2. Effect of polarity

For given conditions, the discharge energy is not much different for positive or negative voltage. Table 1 shows the comparison at gap spacing of 1 mm and capacitance of 250 pF. The discharge energy is averaged in several times. Generally the energy of negative voltage is slightly larger than the positive. When the discharge is complete at higher voltages, the energy is almost the same for both polarities.

| \( U_0 \) (kV) | Positive   | Negative   |
|---------------|------------|------------|
|               | \( E \) (mJ) | \( E/E_0 \) (%) | \( E \) (mJ) | \( E/E_0 \) (%) |
| 5             | 0.36       | 11.4       | 0.47       | 15.0          |
| 6             | 0.48       | 10.6       | 0.71       | 15.7          |
| 7             | 0.66       | 10.8       | 0.77       | 12.6          |
| 8             | 0.82       | 10.3       | 5.49       | 68.6          |
| 9             | 9.32       | 92.0       | 9.31       | 95            |

3.3. Effect of discharge capacitance and voltage

The discharge energy and the energy efficiency at different voltages and capacitances are shown in figure 4 and 5, respectively.

As expected, the discharge energy generally increases with the charging capacitance and the voltage. However, the discharge is not complete at lower voltages, or only a part of the charge on the capacitor is consumed. Consequently, the energy efficiency is low, typically less than 30%. In this case, the discharge energy does not depend strongly on the capacitance or the voltage (see the case of 250-1000 pF/5-7 kV in figure 4). Only when the voltage increases above a critical value so that the
discharge tends to be complete (showing a character of two discharge pulse), the discharge energy will be close to the stored energy in the capacitor and the efficiency becomes nearly 100%.

3.4. Effect of discharge gap
The spark discharge energy at different gap is nearly the same if the charging capacitance and the voltage is the same. Table 2 shows the examples of discharge energy at capacitance of 250 pF and two voltages of 7 kV and 10 kV. It is seen that the discharge energy at 7 kV is smaller compared with the energy in the capacitor and the energy efficiency is small with value around 11%. At 10 kV, the discharge energy is close to the stored energy in capacitor and the efficiency is nearly 100%. This result indicates that the discharge energy relates to the discharge mode rather than the electrode gap. For this reason, the measurement of the ESD energy might be taken under different configurations.

Table 2. Discharge energy at various gap.

| d (mm) | 7 kV  | 10 kV  |
|-------|-------|--------|
|       | E (mJ) | E/E₀ (%) | E (mJ) | E/E₀ (%) |
| 1     | 0.66   | 10.8    | 12.0   | 96.0     |
| 2     | 0.75   | 12.2    | 11.7   | 93.6     |
| 3     | -      | -       | 11.8   | 94.4     |

4. Conclusion
We have investigated the ESD spark discharge in air with a needle-to-plane configuration. It is shown that there are two discharge modes at low or high voltages, characterized by single or double current pulses respectively. The discharge energy at lower voltages is generally small and the efficiency is less than 30%. The discharge at higher voltages is complete and the efficiency is nearly 100%. The spark discharge energy increases with the changing capacitance as well as the voltage, but it does not depend on the voltage polarity or the electrode gap.

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