Influence of Discharge Conditions on the Ignitability of Lycopodium Streams Due to a Single Capacitance Discharge Spark

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Abstract - The influence of discharge conditions, including the resistance of the sparking circuit, the shape of the electrodes and the width of the falling dust on the ignitability of lycopodium streams were investigated. Discharge characteristics and the ignition phenomena were also explored. When a 100 kΩ resistor was connected in series with the sparking circuit, the lowest level of minimum ignition energy (MIE) was attained for lycopodium streams. Simultaneously, the area where flammable gas generated increased and the duration of flammable gas generation decreased. That is, the ignitability of lycopodium streams depended strongly on the discharge power and discharge duration. Electrodes with sharp tips gave smaller MIEs than those with round tips in a capacitive-inductive sparking circuit, while shape made no difference in a capacitive-resistive circuit. Streams that were too narrow required a considerable amount of energy for ignition.

Keywords: Capacitance discharge spark, Minimum ignition energy, Discharge conditions, Lycopodium.

1. Introduction

With the rapid development of powder technologies, a variety of innovative flammable powders have been produced and used in various industrial processes. Some of these powders are so sensitive that even a spark with very low energy can ignite them [1]. Accordingly, dust explosions have become a common concern in many industries that handle flammable powders. The minimum ignition energy, MIE, of dust clouds is a very important aspect of technical safety indices [2-5]. These indices are used for the assessment of the efficacy of the ignition sources expected in dust clouds [6]. In the MIE testing apparatus, the static energy stored in a capacitor is supplied to the air gap to cause an incendiary spark discharge. In accordance with the IEC standard, an inductor of 1 mH should be serially connected in the circuit to prolong the duration of a discharge in order to facilitate the ignition of dust clouds.

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In light of the actual conditions under which combustible dusts are handled, however, other passive elements, such as a resistor, should be taken into account. That is, discharge sparks have various discharge conditions, such as inductance and resistance, depending on the charged substances in various industrial processes.

The present paper deals with the influence of discharge conditions, including circuit resistance, width of the falling dust streams, and shape of electrodes, on the ignitability of lycopodium dust clouds. Discharge characteristics and ignition phenomena were also observed. The foremost endeavor of this paper is to communicate a new knowledge on the ignition behavior of ignition dust clouds to individuals working in the area of dust explosion prevention and mitigation.

2. Experimental

2.1 Minimum ignition energy testing system

Fig. 1 shows the ultrasonic vibration MIE measurement system used in this study [7]. It consists of a perspex explosion chamber, an ultrasonic power supply of 28 kHz and vibrator (Pillip: USS-2010), a vibrating horn, a V-shaped powder hopper and sieve (stainless steel), and a pair of discharging (sparking) electrodes. The discharge unit (MIES-10 type) and measuring instruments were

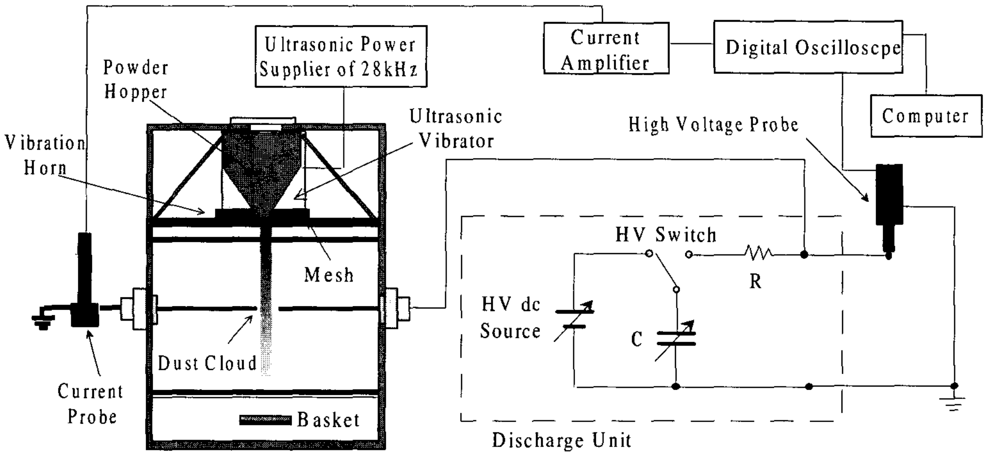


Fig. 1 Overall structure of the MIE measurement system including the *RC* circuit used to generate electrical discharges.

made up of a power source equipped with a high voltage dc generator and a set of capacitors ranging from 100 pF to 5000 pF, a digital storage oscilloscope (Tektronix TDS520), a current amplifier (Tektronix AM503), a high voltage probe (Tektronix P6015A), a personal computer (PC) for controlling and data processing, and other auxiliary devices. The HV switch is of high-voltage relay (Kilovac Inc.: K61C37S). It contains an inert gas, SF_6, and withstands up to 30 kV dc. It is especially used for discharging circuits because it does not generate noisy vibration known as "chattering".

To evaluate the effect of circuit electrical characteristics on measuring MIE, the discharging (sparking) electrodes had either sharp or round tips made of stainless steel rods with a diameter of 2 mm. The location of the spark gap was adjusted so that the majority of the dust stream passed within the gap.

The discharge circuit consisted of two different models to vary the duration time of the spark, namely (1) the capacitive-resistive circuit (circuit resistances of 5, 10, 100 kΩ and 1 MΩ could be connected serially to the discharge terminal), and (2) the capacitive-inductive circuit (an inductor of 0.94 mH was connected serially, in which case the inherent resistance was negligible). Dust hoppers with openings of six different sizes were specially designed so that the width of the dust streams would affect their ignitability.

The procedure for a typical routine ignition test at a certain dust concentration is as follows [7]: (1) Fill the hopper with the dust to be tested. (2) Choose the capacitor and set the spark voltage to the desired level. (3) Turn on the ultrasonic power source and adjust its current level to obtain a dust stream. (4) After confirming that the stream is constant, trigger the high-voltage circuit to cause a spark. (5) If the dust ignites within 20 sparks (at 1 s intervals), lower the energy level by decreasing either the voltage or the capacitance. If the dust does not ignite within 20 sparks, increase the energy level by adjusting either the voltage or the capacitance [2, 8]. In the case of a capacitive-inductive (*LC*) sparking circuit, since virtually all the stored energy in the capacitor appears in the spark, the net energy (in J) was given by $1/2\ CV^2$, where C is the capacitance in the circuit (in F) and V is the potential at the moment of discharge (in V). On the other hand, when a resistor instead of an inductor was connected to the sparking circuit, the net sparking energy was calculated by integrating the current multiplied by the voltage for the duration of the spark with the PC [9].

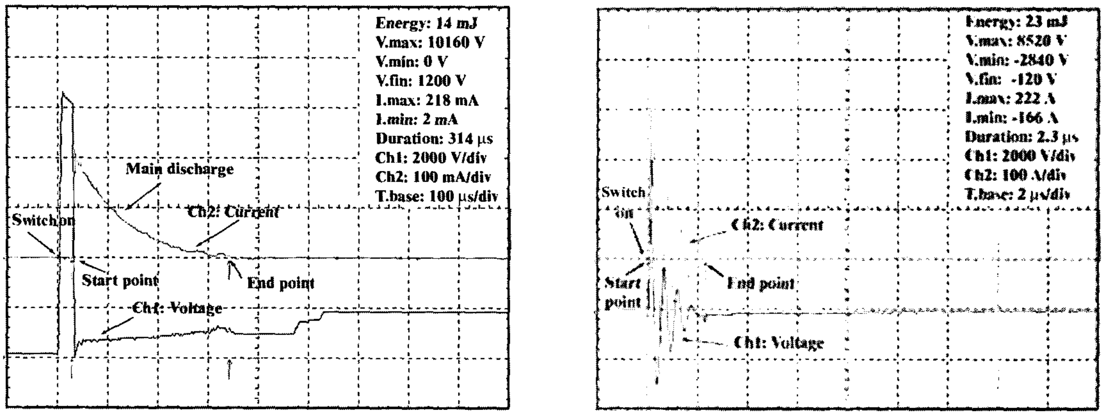
2.2 Dust sample

The dust material used in the experiment is lycopodium, which is recognized as the standard dust recommended by IEC. The particle diameter of lycopodium measured by a microscope (CS5330, NIH Image) was in the range of 28 - 33μm, and no aggregation was confirmed. The mean particle diameter, d was 31μm. The powder sample was dried up in a desiccator at 50°C for 24 hours and all the test conditions were 20 ± 3°C and 35 ± 5% RH.

3. Results and Discussion

3.1 Characteristics of the discharge spark

After the switch closes, the typical change of the current and voltage in the *RC* and *LC* circuits can be observed, as shown in Fig. 2. The parameters in the discharge circuit for the capacitance, charge voltage, and electrode spacing



(a) *RC* circuit (*R*: 100 kΩ) (b) *LC* circuit (*L*: 0.94 mH)

Fig. 2 Discharge current and voltage waveforms acquired by the "high-resolution mode"

Table 1 Equivalent resistance of discharge channel and discharge energy ratios to the stored energy.

Substance			10 kΩ			100 kΩ			1000 kΩ		
C [pF]	*V* [kV]	*Ec*[mJ]	E_d [mJ]	E_r [%]	*Re* [kΩ]	E_d [mJ]	E_r [%]	*Re* [kΩ]	E_d [mJ]	E_r [%]	*Re* [kΩ]
300	8	9.6	-	-	-	-	-	-	-	-	-
300	10	15	-	-	-	-	-	-	3.95	26.33	357
300	12	22	-		-	4.69	21.31	27.09	4.67	21.22	269
300	14	34	4.36	12.82	1.47	5.05	14.85	17.44	4.99	14.67	172
1000	8	32	-	-	-	7.46	23.31	30.39	-		
1000	10	50	-	-	-	8.51	17.02	20.51	10.82	21.64	276
1000	12	72	10.37	14.40	1.68	10.20	14.16	16.50	13.37	18.56	228
1000	14	113	11.37	10.06	1.11	14.72	13.02	14.97	16.95	15.00	176
2500	8	80	-	-	-	-	-	-	22.64	28.30	395
2500	10	125	13.66	10.92	1.22	25.69	20.55	25.86	28.83	23.06	299
2500	12	180	15.16	8.42	0.91	28.33	15.73	18.67	35.28	19.60	243
2500	14	281	18.00	6.40	0.68	33.79	12.02	13.66	43.75	15.56	184
5000	8	160	18.01	11.25	1.26	40.33	25.20	33.70	39.46	24.66	327
5000	10	250	21.98	8.79	0.96	53.70	21.48	27.35	56.75	22.70	293
5000	12	360	25.11	6.97	0.74	58.90	16.35	19.56	73.96	20.54	258
5000	14	563	28.98	5.14	0.54	67.63	12.01	13.65	88.30	15.68	186

C: Capacitance, *V*: Charging voltage, E_c: Stored energy, E_d: Discharge energy, R_e: Equivalent resistance

are 1000 pF, 12 kV, and 4 mm, respectively. When a charge capacitor was discharged through the spark gap, several different modes of discharge occurred depending upon the value of the series resistance. A further increase in the circuit resistance resulted in a unidirectional discharge of long duration. The time dependence of the change of currents was exponential, of the form *exp(-t/RC)*, where *RC* was the circuit's "time constant" [refer to Fig. 2 (a)]. A high initial current limited by the resistance to *V/R* flowed, gradually diminishing to zero. On the other hand, the change of voltages, except for the starting and ending of the discharge, was relatively smooth. An increase in the circuit resistor resulted in an increase in the discharge duration of the voltages, thus increasing the discharge energy.

When a series inductance was used instead of a resistance in the charge circuit [refer to Fig. 2 (b)], the current and voltage of the discharge varied in an oscillatory manner, having a relatively short discharge duration time in comparison with the *RC* circuit.

The equivalent resistances of the discharge channel and discharge energy ratios to the stored energy are summarized in Table 1. The equivalent resistance, *Re*, was calculated using formula (1) [10]:

$$Re = R\,Ed/(Ec - Ed), \qquad (1)$$

where *R* [Ω] is the resistance, *Ed* [mJ], the discharge energy, and *Ec* [mJ], the stored energy.

The discharge energy ratio to the stored energy, *Er*, was calculated using formula (2):

$$Er = Ed/Ec, \quad (2)$$

where Ed [mJ] and Ec [mJ] are the discharge and the stored energy, respectively.

The experiment results of Table 1 confirm the following points:

(1) Re and Er increase with an increase in the resistance of the discharge circuit under constant capacitance and charging voltage.

(2) Re and Er decrease with an increase in the charging voltage under constant capacitance and resistance of the discharge circuit.

(3) Re and Er increase with an increase in the capacitance of the discharge circuit under constant resistance of the discharge circuit and charging voltage.

It follows from what is described above that Re and/or Er are correlated with the magnitude of the discharge current; the lower the discharge current, the more energy that is required to maintain the discharge.

3.2 Influence of resistance in the circuit on dust ignitability

Fig. 3 shows the influence of circuit resistance on the MIE for lycopodium. The dotted line in the Fig. indicates

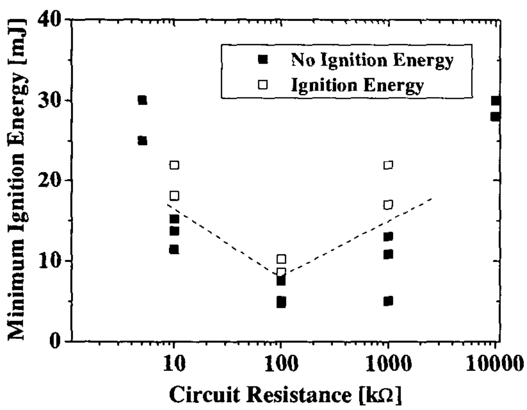


Fig. 3 Influence of resistance on the MIE of lycopodium.

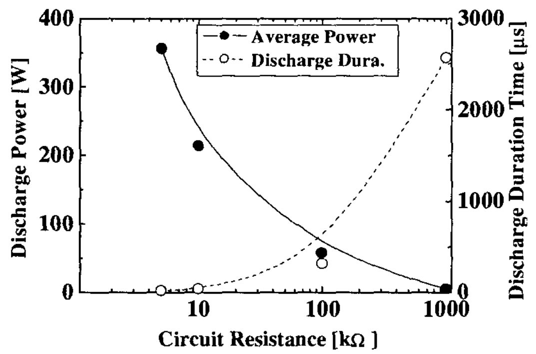


Fig. 4 Discharge power and discharge duration time as a function of the resistance of the circuit.

the MIE that lies between the no-ignition and ignition energies [1]. A circuit resistance of 100 kΩ provided the lowest MIE for ignition, about 7.5 mJ, where the electrode spacing was 4 mm and both the electrodes were round.

This result suggests that the ignition of dust depends on the discharge power along the gap and the discharge duration. The discharge power and discharge duration times were measured as a function of the circuit resistance under constant conditions of the discharge circuit except for resistance, as presented in Fig. 4. With increasing circuit resistance, the discharge duration time increased, and the discharge power decreased. Both conditions, three hundred microseconds (or over) and fifty watts (or over), are necessary for efficient ignition of lycopodium dust streams.

3.3 Observation of the ignition phenomena

An ignition phenomenon was observed as a function of the inductance and resistance under constant conditions of discharge (capacitance, 1000 pF; charging voltage, 12 kV; electrode spacing, 4 mm). The flame propagation by the discharge spark was monitored every millisecond by a high-speed camera, as shown in Fig. 5. As a result, the ignition delay, defined as the time elapsed to the initiation of flame propagation from the kernel, was 10 to 20 milliseconds for lycopodium dust streams; a rise in the temperature of particles was initiated by the discharge spark, and, subsequently, a self-heating reaction of particles started and formed a kernel for flame propagation leading to ignition [11]. When an inductor of 0.94 mH was connected serially, it was confirmed that the dust particles stopped transiently in the heating area between electrodes because of the discharge power, which had high density, 1x104 W, and short discharge duration time, 2.3µs. The flame propagated symmetrically up and down, as shown in Fig. 5 (a).

When resistor (100 kΩ) was connected, the kernel formed in the heating area moved downward. The area in which flammable gas was generated was larger, and the time of flammable gas generation was shorter than those of the others because the discharge spark was adequate for igniting lycopodium dust streams in consideration of the discharge power, 58W, and the discharge duration time, 314µs. The upward flame propagation started below about 4 mm of the spark point [see Fig. 5 (b)], which agrees with data obtained by the following formula (3):

$$D = v \cdot T, \quad (3)$$

where D [m] is the moving distance of the kernel formed by the discharge spark, v [m/s], the average velocity of the

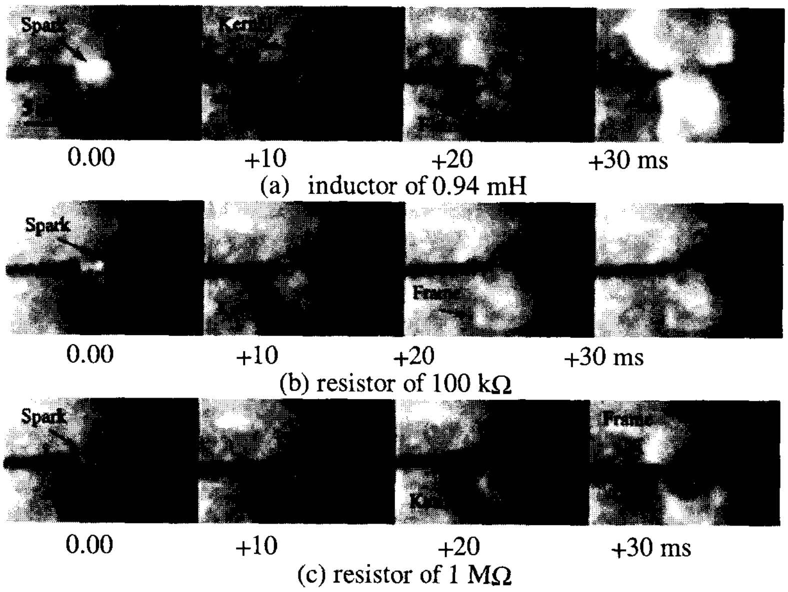


Fig. 5 High-speed video recordings of the ignition of lycopodium dust streams.

particles, and T [s], the ignition delay time elapsed to the initiation of flame propagation from the kernel.

As a result, observed by the high-speed video camera described earlier, the velocity of particles and the ignition delay were about 0.40 m/s and 0.01 ms, respectively.

When resistor (1 MΩ) was connected, the discharge power, 5W, was insufficient for ignition, while the heating area became larger owing to the relatively long discharge duration of 2.5ms. The ignition delay was the longest, and the upward flame propagation started at below about 8mm of the spark point [see Fig. 5(c)].

3.4 Influence of discharge electrode shape on dust ignitability

Table 2 shows the influence of the shape of a discharge electrode (sharp or round tips) on the ignitability of lycopodium with a constant concentration of dust and under a constant condition of discharge circuit (electrode spacing, 4mm). The electrodes with sharp tips gave smaller MIE values than those with round tips in an *LC* circuit. This could be attributable to the shorter discharge duration for sharper tips because a larger radius of curvature promotes heat dissipation. In an RC circuit, however, the sharp and round tips gave similar MIE values. This could be attributable to the relatively long discharge duration and the impartial dissipation of discharge powder during that time. A similar result was also obtained in the case of the 6mm of electrode spacing.

Consequently, the shape of the electrode influences the MIE of lycopodium streams in an LC circuit but has little influence on the RC circuit.

Table 2 Comparison of MIE in an electrode with sharp or round tips

Division	Minimum Ignition Energy [mJ]	
	0.94 mH	100 kΩ
Sharp	32 (32)	7.4 (8.5)
Round	50 (50)	7.2 (8.3)

( ): 6mm of electrode spacing.

3.5 Influence of the width of dust streams on dust ignitability

The influence of the width of the falling lycopodium dust streams on its ignitability was investigated experimentally. The dust hoppers had openings of six different sizes, about 3, 6, 12, 20, 30, and 40mm, so that the width of the dust streams could be changed. The ignition energy was measured as a function of the width of the falling dust streams with a constant concentration of dust (electrode spacing, 4mm), as given in Fig. 6. The

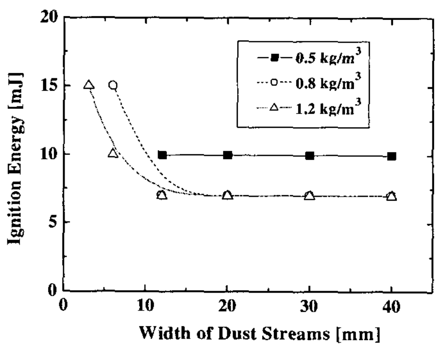


Fig. 6 Ignition energy measured as a function of the width of the falling dust streams with a constant dust concentration.

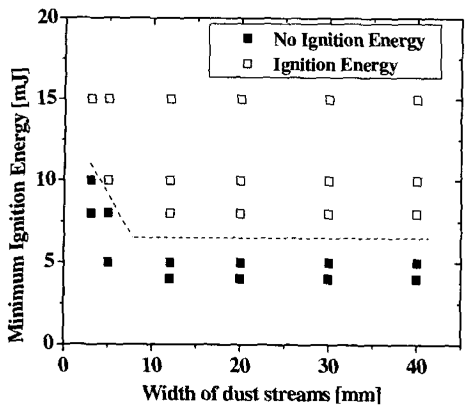


Fig. 7 Relationship between MIE and the width of falling lycopodium streams.

relationship between the MIE and the width of falling dust streams is shown in Fig. 7. As a result, the dust streams that was 12mm and wider ignited the lycopodium using the lowest energy, about 7.5mJ. This may be attributable to the fact that some of the spark energy was lost in space without heating the dust and/or the propagation of the flame was restricted when the stream was too narrow. Therefore, dust streams with an extremely narrow width require a considerable amount of energy for ignition.

4. Conclusions

The influence of circuit resistance, electrode shape, and width of dust streams on the ignitability of lycopodium dust streams was examined experimentally. Discharge characteristics in circuit resistance and the ignition phenomena were also observed. The results are summarized as follows:

(1) The equivalent resistance and the discharge energy ratio to the stored energy increased with an increase in the circuit resistance and the capacitance of the discharge circuit, while it decreased with an increase in the charging voltage.

(2) The circuit resistor of 100 kΩ ignited the lycopodium dust clouds with the lowest energy; the electrode spacing was 4mm, and both electrodes were round.

(3) When a resistor of 100 kΩ was serially connected to the discharge circuit, the area in which flammable gas was generated was larger, and the duration of flammable gas generation was shorter. That is, the ignitability of lycopodium streams depended strongly on the discharge power and discharge duration.

(4) Electrodes with sharp tips gave smaller MIEs than those with round tips in a capacitive-inductive (*LC*) sparking circuit, while shape made no difference in a capacitive-resistive (*RC*) circuit.

(5) Streams that were too narrow required a considerable amount of energy for ignition. Streams that were 12mm or wider gave the lowest MIE for ignition in this study.

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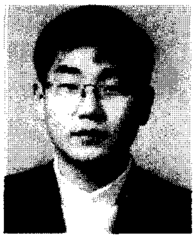

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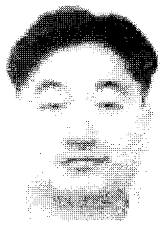

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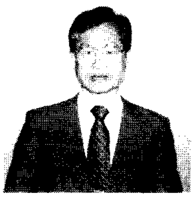

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