Research paper

Influence of discharge circuit parameters on the measurement of the minimum ignition energy of dust–air mixtures

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Abstract

In the measurement of the minimum ignition energy (MIE) of a dust-air mixture, an ignition spark is created by discharging the electric energy stored in a capacitor between two electrodes. In many cases, an inductance of 1 mH is added in the discharge circuit to improve the incendivity of the spark. In our study, a resistance (100 kΩ), instead of an inductance, was inserted and 15 powder samples were tested to investigate the influence of the circuit conditions. In the case of sensitive powders with MIEs that are smaller than 10 mJ measured with 1 mH, the MIEs with no additional circuit element and those with inductance were almost identical ; however, the resistance increased the MIEs. In the case of insensitive powders, however, the MIEs became smaller in this order : with no additional element, with the inductance, and with the resistance. Visual observation with a high-speed video camera revealed that the blast of air caused by the spark greatly affected the ignition mechanism of a dust-air mixture.

Keywords : dust-air mixture, dust explosion, minimum ignition energy, powder

1. Introduction

The minimum ignition energy of a dust-air mixture is usually measured with an apparatus employing a Hartmann tube. According to an international standard,[1] the circuit to generate a spark to ignite a powder sample consists of a capacitor with or without an inductance of 1~2 mH. There is a consensus that the inductance may improve the incendivity of the spark by prolonging its duration and should be used for the standard test condition while the circuit without the inductance should only be used for evaluating the sensitivity to an electrostatic discharge.

On the other hand, however, some Japanese testing laboratories have long adopted an ignition circuit with a resistance instead of an inductance for their standard test method because the resistance usually facilitates ignition. Such a circuit is not only meaningful from a technical standpoint but also has a practical aspect in light of the fact that many electrostatic discharges originate from items including a high resistance, such as the human body,[2)−4)] metal powders,[5)−6)] and poorly grounded tools.[7)] With this background, a recently issued Japanese standard[8)] allows a circuit including resistance.

It is well known that the ignitability of a flammable material is greatly affected by the circuit parameter of the spark ;[9)] however, systematic studies on the influence of discharge conditions on the minimum ignition energy of dust-air mixtures are limited. In this paper, we report the result of an experiment using a modified commercial testing apparatus with different circuit parameters.

2. Experimental

2.1 The measuring apparatus

We employed a widely used commercial MIE testing apparatus (Kühner AG, MIKE-3). This apparatus produces a capacitive spark in the spark gap through a fixed small coil of 1 μH and has an optional function of adding another larger inductance of 1 mH to its discharging circuit. In this

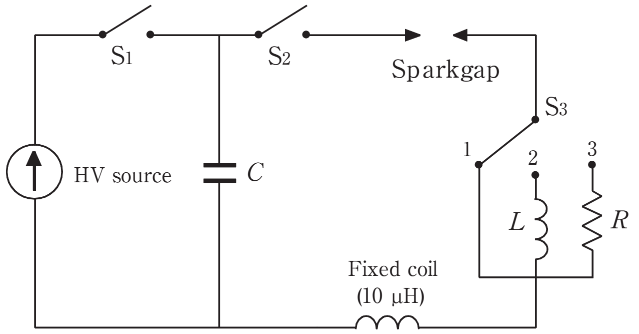


Fig. 1 Schematic circuit diagram of the MIE–measuring apparatus.
S_1 : to charge the capacitor C
S_2 : to start a spark
S_3 : to select an additional element
(1 : None, 2 : Inductance 1 mH, 3 : Resistance (10, 100 or 300 kΩ))

study, we modified the apparatus and chose to use a resistor instead of an inductance 1 mH. The schematic circuit diagram is shown in Fig. 1. A discharging current measuring system consisting of a current probe (Textronix, TCP0030) and a digital oscilloscope (Tektronix, DPO3032) was attached. A discharged charge was calculated by integrating the current with respect to time. For the visual observation of the discharge and ignition, a high-speed video camera system (Photron, FASTCAM-Ultima-RGB) was used.

The energy of a spark W (J) was calculated by the following formulae :

(a) Circuit with no additional element or with the inductance

$$W = W_0 = \frac{1}{2}CV^2 \tag{1}$$

(b) Circuit with a resistance (effective energy)

$$\begin{aligned} W &= W_0 - W_r - W_z \\ W_r &= \int_0^T Ri^2 dt \\ W_z &= \frac{1}{2}\frac{Qz^2}{C} \\ Q_z &= CV - \int_0^T idt \end{aligned} \tag{2}$$

where C (F) is the whole capacitance of the circuit including the capacitor and stray capacitance, V (V) is the voltage of C just before discharging, i (A) is the discharging current, R (Ω) is the resistance of the additional resistor, Q_z (C) is the residual charge after discharging, and T (s) is the duration of the discharge.

Since the testing apparatus can generate seven fixed nominal discharge energies, i.e. 1, 3, 10, 30, 100, 300, and 1,000 mJ, the MIE of a sample is expressed by a range between the lowest energy that ignited the sample and the largest energy that did not. In addition, using the test data, a specific value called the statistical minimum ignition energy E_s (J) is derived by the following formula :[10]

$$E_s = 10^{\log E_2 - \frac{I[E_2](\log E_2 - \log E_1)}{(NI+I)[E_2]+1}} \tag{3}$$

where E_1 (J) is the largest energy that did not cause ignition, E_2 (J) is the lowest energy that did, I [E_2] is the number of ignitions at E_2, and $(NI+I)$ [E_2] is the total number of tests.

2.2 Powder samples

Five natural organic powders, five synthetic organic powders, one inorganic powder, and two metal powders were selected as the samples. In addition, flour with 2% of MgO as a dispersing agent[11] was also used. The powder samples and their specifications are listed in Table 1. All

Table 1 List of powder samples and their specifications.

Powder	Median diameter (μm)	Apparent density (g/cm^3)	Angle of repose (deg)	Collapse angle (deg)
Lycopodium	35.6	0.26	36.6	33.6
Anthraquinone	31.5	0.29	48.3	47.0
Sugar	43.9	0.47	52.0	47.3
Flour	64.5	0.46	55.0	47.0
Flour (+ MgO 2%)	64.5	0.53	48.0	40.0
Cornstarch	29.9	0.55	48.0	37.6
Coenzyme Q10	37.0	0.25	53.3	52.3
Polyacrylonitrile	40.2	0.45	38.6	33.0
Polypropylene	76.5	0.30	38.0	35.6
Toner	8.70	0.51	45.0	25.0
Bicyclohexanol	45.6	0.41	50.0	47.3
Sulfur	2.30	0.65	47.0	47.0
Titanium	33.2	1.46	47.3	41.6
Aluminum	23.8	0.98	51.0	44.3

the samples were dried at 50°C for 24 hours prior to the test. The temperature and humidity of the test room were 25°C and 60 % RH, respectively.

3. Results and discussion

3.1 Current wave profiles and discharge energy when a resistance is added

Typical discharge current profiles at three different circuit conditions, i.e., with no additional element, with an inductance of 1 mH, and with a resistance of 100 kΩ at the 100 mJ setting are shown in Fig. 2 (a) - (c), respectively. Although no additional element was added, a damped oscillating waveform was observed, as shown in Fig. 2 (a), due to a small built-in coil of 10 μH (therefore, the spark is not a purely capacitive one). In the case in which a resistance was added, the discharge became a simple damped form, as shown in Fig. 2 (c).

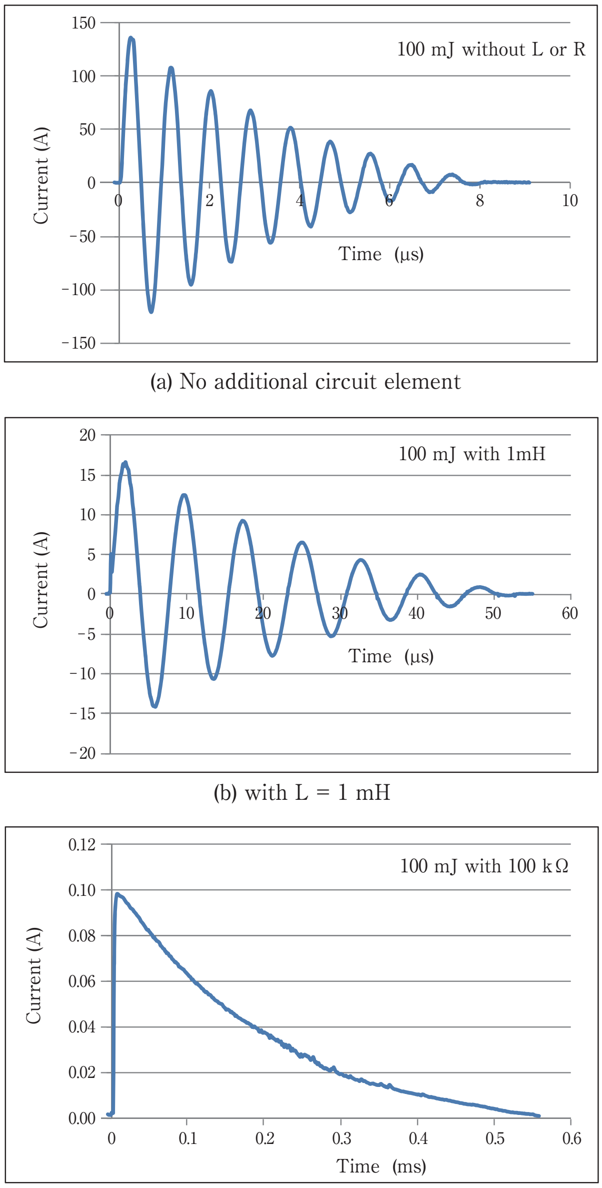
The effective energies with 10 kΩ, 100 kΩ and 300 kΩ are shown in Table 2, and the ratios to the corresponding discharge energy without an additional element or with 1 mH are shown in Table 3. As seen in Table 3, the ratio is neither constant nor linear with respect to the energy setting. However, at the same energy setting, the ratio increased as the resistance increased. This means that the equivalent resistance of the spark channel becomes progressively greater as the additional resistance increases. A resistance equal to or greater than 1 MΩ was not suitable for an ignition test because the sparks became quite unstable.

3.1 Minimum ignition energy

3.2.1 Observation of ignition and flame propagation

3.2.1.1 Lycopodium and polypropylene

The minimum ignition energies of lycopodium and polypropylene measured with no additional element or with 1 mH, 10 kΩ, 100 kΩ, or 300 kΩ are shown in Fig. 3. In the case of both samples, the MIEs with 1mH, 100 kΩ, or 300 kΩ were lower than those with no additional element



(a) No additional circuit element

(b) with L = 1 mH

(c) with R = 100 kΩ

Fig. 2 Typical current wave profiles of a spark at 100 mJ.

Table 2 Effective discharge energy of a spark under the tested circuit conditions.

	Additional element	Nominal energy (mJ) 1	3	10	30	100	300	1000
Discharge energy (mJ)	None or 1 mH	1.67	3.91	17.6	39.2	129	373	1200
	10 kΩ	–	1.07	7.06	3.54	13.8	35.3	83.5
	100 kΩ	0.86	1.86	5.94	6.62	24.4	69.6	202
	300 kΩ	–	–	8.41	10	31.9	87.6	273

Table 3 Ratio of the effective disharge energy of a circuit to the original energy

	Additional element	Nominal energy (mJ) 1	3	10	30	100	300	1000
Energy ratio (%)	None or 1 mH	100	100	100	100	100	100	100
	10 kΩ	–	27.7	40	9.03	10.7	9.45	6.96
	100 kΩ	51.7	47.6	33.6	16.9	18.9	18.6	16.8
	300 kΩ	–	–	47.7	25.6	24.9	23.5	22.8

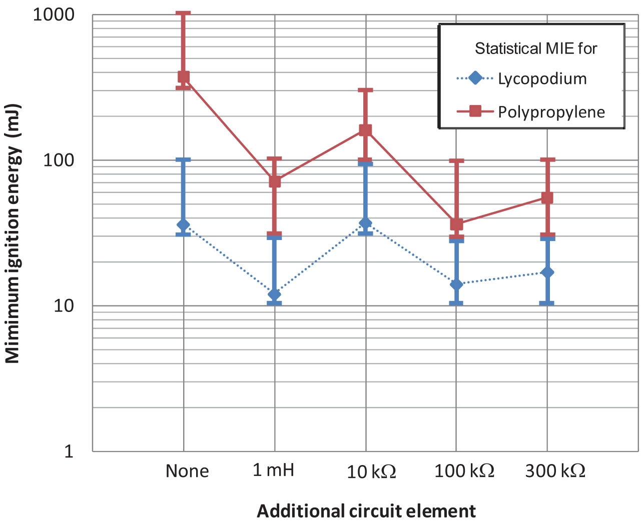


Fig. 3 MIE for lycopodium and polypropylene under various circuit conditions.

or 10 kΩ.

Sequential photographs of lycopodium just after ignition, extracted from high-speed video pictures (4500 FPS), are shown in Fig. 4. The concentration of the dust-air mixture was 250 g/m^3. From the figure, the following characteristics are recognized :

(a) When no additional element was added, the flame kernel created just after the spark was immediately blown away from the vicinity of the spark gap, and the flame began to propagate 1.3 ms later at a point far from the spark gap. When 10 kΩ was used, the kernel also moved away from the gap, and it took 0.9 ms for the flame to initiate propagation. It is considered that a spark with a relatively short duration of discharge (32 μs for "no additional element" and 620 μs for "with 10 kΩ") and higher average power (37.5 kW and 135 W, respectively) caused a blast of air that was strong enough to blow off the kernels to a zone not heated up by the spark.

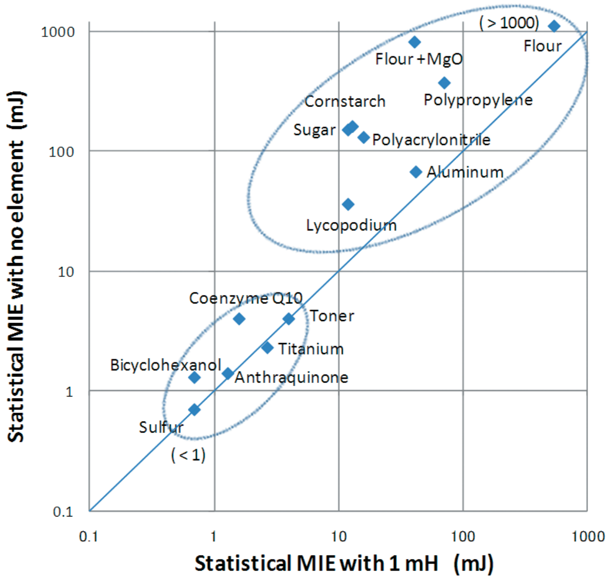
(b) When 1 mH, 100 kΩ, or 300 kΩ was used, the kernel stayed in the vicinity of the spark gap and developed rapidly into flames. In this case, it is considered that the air blast was much milder than that with no additional element or 10 kΩ and the powder particles were effectively heated because of the longer duration (176 μs, 4.3 ms, and 12.5 ms, respectively) and lower average power (6.8 kW, 47 W, and 22 W, respectively)

3.2.1.2 Bicyclohexanol

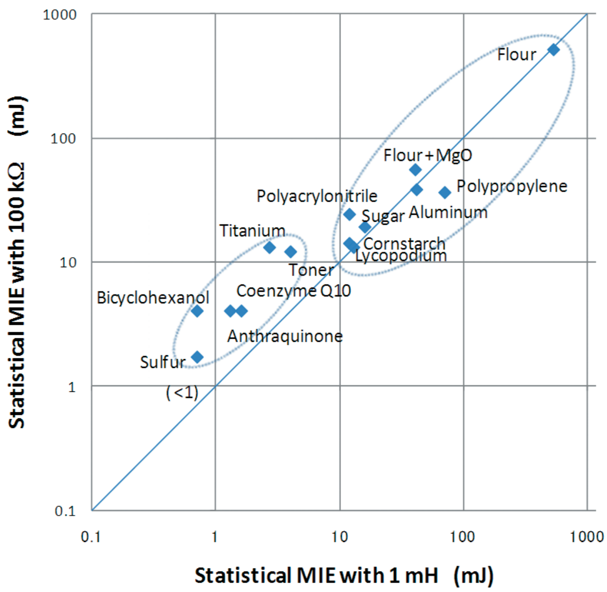
Sequential photographs of bicyclohexanol just after ignition are shown in Fig. 5. The concentration of the dust-air mixture was 333 g/m^3. The energy settings were 3 mJ for the circuit with no additional element and with 1 mH and 10 mJ for that with 100 kΩ. The ignition and flame propagation patterns were quite similar to each other and almost no influence of a blast of air was observed.

3.2.2 Minimum ignition energies for all samples

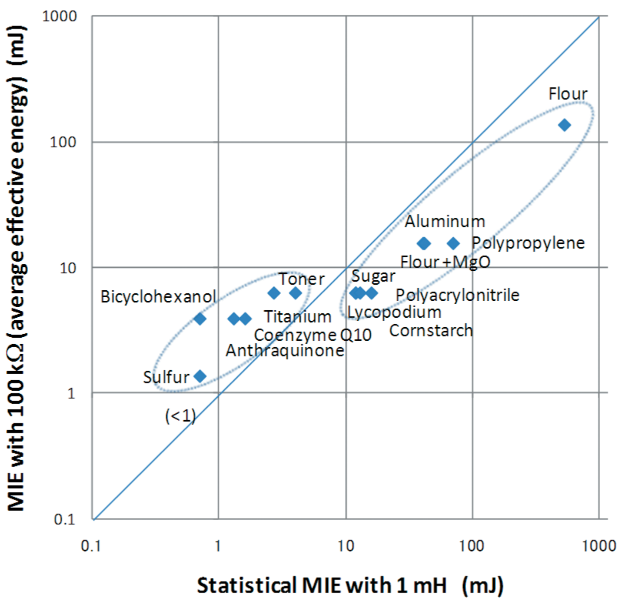
For all the samples, the MIEs taken from three different



(a) with 1 mH vs. with no additional element



(b) with 1 mH vs. with 100 kΩ



(c) with 1 mH vs. with 100 kΩ (effective energy)

Fig. 6 Comparison of statistial MIEs taken with different circuit conditions.

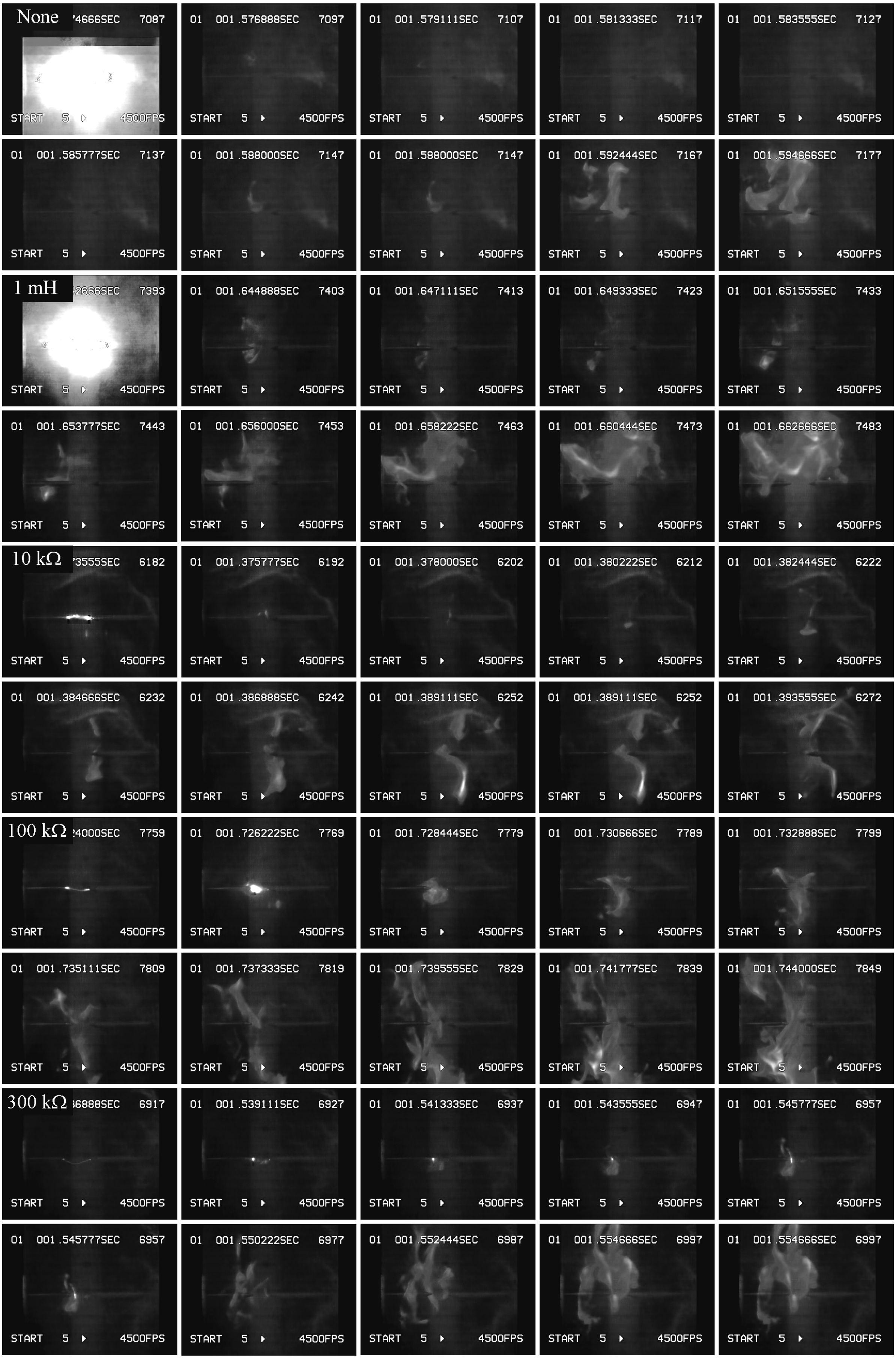


Fig. 4 Ignition and flame propagation of lycopodium under different circuit conditions.

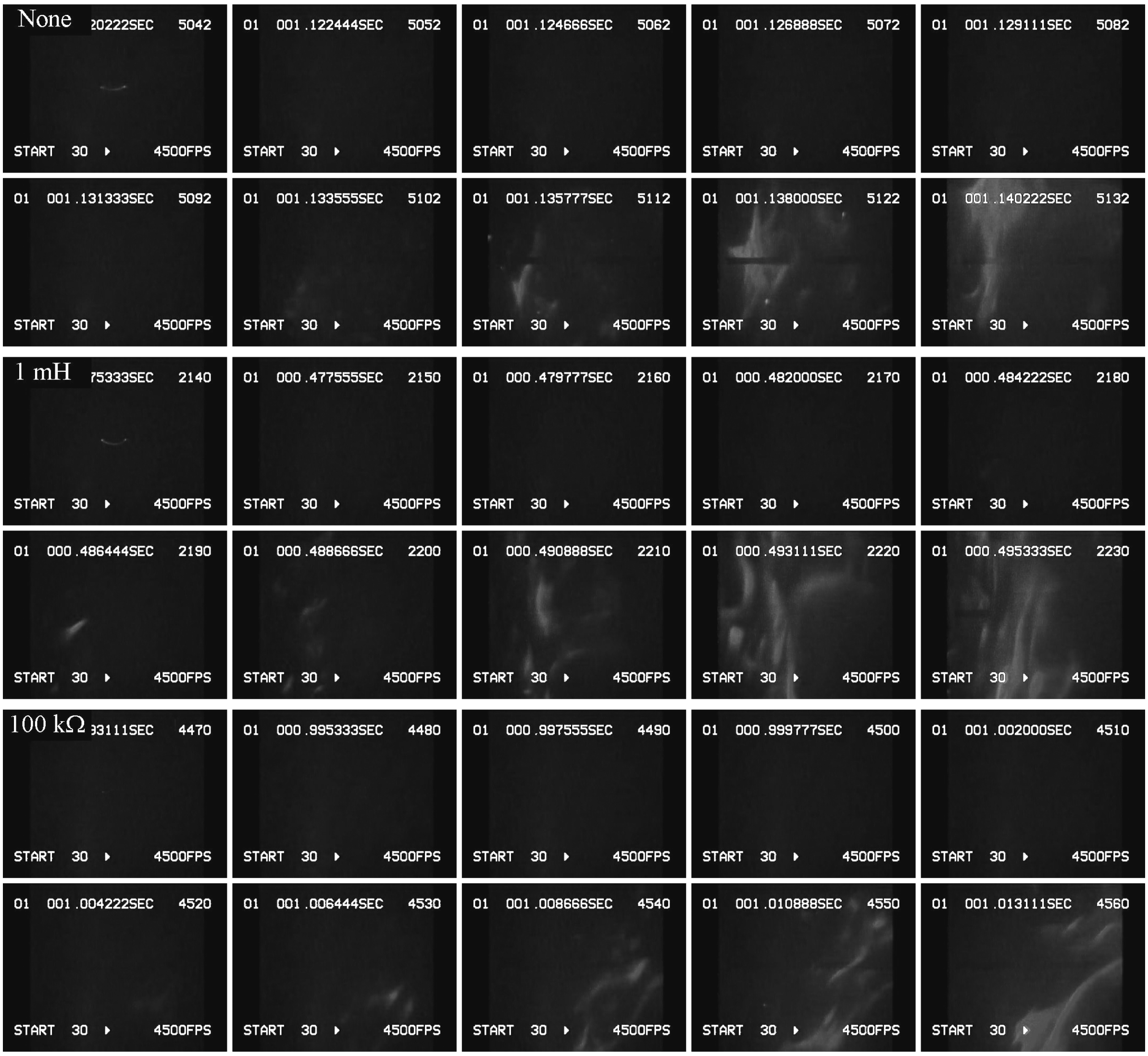


Fig. 5 Ignition and flame propagation of bicyclohexanol under different circuit conditions.

circuit conditions (no additional element, 1 mH and 100 kΩ) are listed in Table 4. A comparison of the statistical MIEs (1mH) with the others is shown in Fig. 6 (a) - (c). In the case of 100 kΩ (effective energy) (Fig. 6 (c)), the average value between the upper and lower limits was adopted.

From the figure, the following characteristics are recognized :

(a) In a comparison of "1 mH" and "no additional element," as shown in Fig. 6 (a), the powders in the small-MIE group (anthraquinone, coenzyme Q10, bicyclohexanol, titanium, sulfur, and toner in the lower circle) do not show much difference in the MIE ; however, in the large-MIE group (lycopodium, cornstarch, polyacrylonitrile, sugar, aluminum, flour, flour+MgO, and polypropylene in the upper circle), the MIEs taken with no additional element, except those for aluminum, are much larger than those with 1 mH. Generally, it is considered that, when testing with a spark of low energy, the blast of air lacks the strength to deflect a flame kernel. In the case of aluminum, it has a large specific gravity, as in Table 1, and is less affected by the blast.

(b) In the comparison of "1 mH" and "100 kΩ," as shown in Fig. 6 (b), on the contrary, powders belonging to the small-MIE group required much more ignition energy with 100 kΩ than with 1 mH, while powders belonging to the large-MIE group were ignited by almost the same energy, and if compared by the effective energy, as shown in Fig. 6 (c), their MIEs were much lower than those with 1 mH. This suggests that powders in the small-MIE group are sensitive to the power rather than the duration of a spark. As shown in Fig. 5, the blast of air caused by a spark seems to be too small to affect the ignition of the small-MIE group.

4. Conclusion

The influence of a discharge circuit parameter on the ignitability of a dust-air mixture differs from powder to powder. One phenomenon that greatly affects the ignitability is the strength of the blast of air caused by the spark that moves the flame kernel away and blocks the flame propagation. The blast of air becomes stronger as the duration of a spark becomes shorter and the discharging energy grows larger ; therefore, powders with a large MIE (ca. larger than 10 mJ measured with an inductance of 1 mH) are generally influenced more than those with a small MIE (ca. less than 10 mJ). On the other

Table 4 MIE for all powder samples.

Powder	MIE (statistical MIE) (mJ) and dust concentration (g/m^3)			
	None	1 mH	100 kΩ	100 kΩ (effective energy)
Lycopodium	30<MIE<100 (36), 1250	10<MIE<30 (12), 750	10<MIE<30 (14), 750	5.9<MIE<6.6
Anthraquinone	1<MIE<3 (1.4), 1250	1<MIE<3 (1.3), 1250	3<MIE<10 (4.0), 1250	1.9<MIE<5.9
Sugar	100<MIE<300 (150), 2000	10<MIE<30 (12), 1250	10<MIE<30 (24) 1250	5.9<MIE<6.6
Flour	MIE>1000	300<MIE<1000 (540), 3000	300<MIE<1000 (510), 1500	70<MIE<202
Flour (+ MgO 2%)	300<MIE<1000 (810), 750	30<MIE<100 (41), 1250	30<MIE<100 (55), 2000	6.6<MIE<24.4
Cornstarch	100<MIE<300 (160), 1250	10<MIE<30 (13), 1250	10<MIE<30 (13), 1000	5.9<MIE<6.6
Coenzyme Q10	3<MIE<10 (4.0), 1250	1<MIE<3 (1.6), 1000	3<MIE<10 (4.0), 1250	1.9<MIE<5.9
Polyacrylonitrile	100<MIE<300 (130), 1500	10<MIE<30 (16), 1500	10<MIE<30 (19), 1250	5.9<MIE<6.6
Polypropylene	300<MIE<1000 (370), 1250	30<MIE<100 (71), 1000	30<MIE<100 (36), 750	6.6<MIE<24.4
Toner	3<MIE<10 (4.0), 360	3<MIE<10 (4.0), 360	10<MIE<30 (12), 360	5.9<MIE<6.6
Bicyclohexanol	1<MIE<3 (1.3), 1250	MIE<1 1250	3<MIE<10 (4.0), 1250	1.9<MIE<5.9
Sulfur	MIE<1 2500	MIE<1 2500	1<MIE<3 (1.7), 2500	0.9<MIE<1.9
Titanium	1<MIE<3 (2.3), 3000	1<MIE<3 (2.7), 2500	10<MIE<30 (13), 3000	5.9<MIE<6.6
Aluminum	30<MIE<100 (67), 1250	30<MIE<100 (42), 750	30<MIE<100 (38), 1250	6.6<MIE<24.4

hand, in the case of powders with a small MIE, the power of a spark affects their ignition more than the blast of air.

With these experimental facts in mind, we suggest that, when carrying out a test on the minimum ignition energy of a powder, the user of the test powder should select the discharge circuit parameter considering the possible ignition sources in the environment in which the powder is handled.

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可燃性粉じん・空気混合気の最小着火エネルギー測定における放電回路条件の影響

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可燃性粉じん・空気混合気の最小着火エネルギー（MIE）の測定において，着火用のスパークはコンデンサに蓄えた静電エネルギーを電極対で放電させることによって生成する。通常，スパークの着火性を向上させるために１mHのインダクタンスを付加することが多い。一方，日本では従来からインダクタンスの代わりに抵抗（100kΩ）を挿入することも行われている．本研究では，放電回路の着火性への影響を調べるため，付加回路なし，インダクタンス付加および抵抗付加の三つの回路条件で，15種類の試験粉体の最小着火エネルギーを測定した。その結果，１mH付加回路での測定値約10mJを閾値として，これよりも小さいMIEの粉体では，付加回路なしとインダクタンス付加でのMIEはほぼ等しく，抵抗付加ではいくぶん大きくなった。また，10mJを超える粉体では，付加回路なし，インダクタンス付加，抵抗付加の順に小さい値となった。高速度カメラによる観測では，スパークによって発生する気流が着火機構に大きな影響を与えていることが確認された。

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