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Initiation of dust explosions by electric spark discharges triggered by the explosive dust cloud itself

Erlend Randeberg*, Rolf K. Eckhoff

Department of Physics and Technology, University of Bergen, Allégaten 55, N-5007 Bergen, Norway

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Abstract

An investigation of ignition of dust clouds by the use of electric spark discharges triggered by the explosive dust cloud itself has been conducted. This method of triggering capacitive sparks probably represents a realistic mechanism for initiating accidental dust explosions in industrial practice. Unlike the conventional method for determining the minimum ignition energy (MIE) in the laboratory, the delay between dust dispersion and spark discharge is not a degree of freedom. In stead, the transient dust cloud itself is used to initiate spark breakdown between electrodes set at a high voltage lower than breakdown in pure air. In the present study, different kinds of dusts were tested as 'spark triggers', and they exhibited quite different abilities to trigger breakdown. Large particles were found to initiate breakdown at lower voltages than smaller ones. In general, conductive particles were not found to initiate breakdown at lower voltages than dielectric ones when using the same dust concentration.

Minimum ignition energies (MIE) of three dusts (*Lycopodium clavatum*, sulphur and maize starch) were determined using the authors' method of study. The MIEs were somewhat higher than those obtained using conventional methods, but relatively close to the values obtained through conventional methods.

Keywords: Dust explosion; Minimum ignition energy; Spark triggering

1. Introduction

The possible occurrence of electric spark discharges is a major safety concern in industries handling combustible dusts. In a hazard evaluation, the minimum ignition energy (MIE) is a central parameter. Two separate electric discharge circuits are used in standard MIE testing (CEN, 2002; IEC, 1994), one being concerned with electrostatic discharges and the other with intrinsic safety for electrical apparatus.

The latter application was discussed by Eckhoff (2002), and it requires a more conservative experimental determination of MIE, which implies the use of electrical sparks of sufficiently long discharge times. The series impedance added for this purpose is to be removed when the purpose is to assess the sensitivity to ignition by electrostatic discharges. This is because the equivalent electric discharge circuits for accidental electrostatic spark discharges in industrial plants do not contain inductances of the order of 1 mH. The point is that the spark's incendivity is not only depending on the energy, but also on the duration of the discharge. Short sparks, especially at high energies, are found to be less capable of ignition than longer ones. This effect has been reported e.g. by Boyle and Llewellyn (1950) and Eckhoff (1975). Tests are therefore conventionally done for both short—pure capacitive—and prolonged spark. In the latter case, a series inductance or resistance is used to increase the time constant of the discharge. The inductance should, according to current standard methods, be 1–2 mH (CEN, 2002; IEC, 1994).

The spark energy is calculated based on the stored capacitor energy prior to breakdown, or by direct measurement of current and voltage as a function of time during the discharge and integration of the power versus time curve. The latter gives the 'net' spark energy, and is required especially if a series resistance is used to prolong the spark, because a substantial amount of the capacitor energy is lost in the resistor. The lowest energy that gives

* Corresponding author. Tel.: +47 55 58 94 07; fax: +47 55 58 94 40.
E-mail address: erlend.randeberg@ift.uib.no (E. Randeberg).

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ignition is normally considered the minimum ignition energy.

Tests for determining the MIE are usually done in a Hartmann tube with a transient dust cloud generated by dispersion of dust particles by an air blast. The spark is triggered between two metal electrodes some predetermined time after dispersion, using a special synchronisation system. This time delay gives an indication of the turbulence at the time of spark triggering, and it is optimised in order to give the lowest possible ignition energy. The determination of the MIE should be performed with as low turbulence as possible. However, if delay times are too long, separation of the dust inside the explosion chamber can occur and the conditions are no longer optimal for ignition.

Synchronisation of dust dispersion and spark onset represents optimal conditions for ignition that are not encountered in industrial situations. It is very unlikely that dust dispersion and an electric spark should be triggered independently of each other at optimal conditions for ignition. In reality, in industry, the dust particles themselves may actually play the main part in the triggering process. Hence, synchronised sparks as used in current laboratory tests may not resemble realistic ignition sources in industrial plants. An investigation of MIE values that can be achieved using sparks triggering by the dust cloud itself is therefore presented in this paper, and comparisons with MIEs obtained using standard tests are made.

2. The dust cloud acting as a spark trigger

Due to electrostatic charging, non-grounded metal objects may obtain voltages of several kilovolts in an industrial plant (Cross, 1987; Lüttgens, 1997; Lüttgens & Glor, 1989). This charging will not result in any electrical discharges as long as the field strength is within the limits of breakdown of the dielectric media—usually air—between the objects acting as electrodes. However, disturbances of the electric field can initiate breakdown and subsequently spark onset.

Particle-contamination of the electrode surface or in the space between the electrodes is an example of a source of such a disturbance, causing the electrode gap to break down at significantly lower voltages than for a non-contaminated gap. Breakdown can be initiated by microdischarges produced by the particles when they approach the electrodes, and the dielectric strength of the gas may be reduced to as low as 10% of the uncontaminated value (Laghari & Qureshi, 1981). It is shown that breakdown is initiated at a lower voltage when particles are moving freely in the space between the electrodes than when affixed to the electrode face, resulting in a sort of 'trigatron' breakdown initiation (Dakin & Hughes, 1969). Both experimental and numerical analyses have confirmed that mobile objects are able to trigger breakdown at lower voltages than fixed ones (Samuila, Dascalescu, & Tobazéon, 1995).

Large conductive particles are shown to affect the breakdown in a more pronounced way than smaller ones. Formation of particle chains is also an important factor reducing the dielectric strength of gases (Dascalescu, Samuila, & Tobazéon, 1997). Charged particles are found to decrease the dielectric strength further (Dascalescu, Samuila, & Tobazéon, 1996).

The following effects are considered relevant in the breakdown of the gap in the present context:

1. The electric field is intensified due to the presence of the particles, potentially causing the dielectric media between the electrodes to break down.
2. Charged particles—caused by e.g. triboelectric effects—contribute even more to the field intensification. They can also act as charge carriers, initiating the breakdown.
3. Conductive particles may act as protrusions at the electrodes, shortening the gap and intensifying the electric field to breakdown.

Conductive particles are reported to reduce the dielectric strength of the gas more than dielectric ones (Laghari & Qureshi, 1981).

Few reports are made on particle-initiated breakdown in the context of an electric spark acting as an ignition source. However, Eckhoff (1970) described a spark breakdown effect caused by the introduction of lycopodium particles into an electrode gap at a preset voltage somewhat lower than the breakdown voltage in air. The triggering of the spark by dust particles turned out to be more efficient than that of a UV flash.

The dust cloud itself may therefore actually be the most realistic trigger of sparks causing potential dust explosions in an industrial plant. Dispersion of dust particles into an electrode gap at a high voltage may well trigger the breakdown. The subsequent spark can then serve as an ignition source for the explosive dust cloud. This approach has been taken in the work presented here.

3. Experimental

3.1. The concept of the test apparatus used

The mechanical parts of the apparatus used in the present investigation are basically the same as those of Kühner's MIKE apparatus for determining standard MIEs. Some important modifications were made, however, mainly related to the system of dust dispersion and the spark triggering system. In a standard MIKE apparatus, the dust dispersion and spark triggering are independent of each other, whereas in the present case the dust dispersion is acting as the spark trigger.

The dust is dispersed by air with opening a valve and emptying a 50 cm^3 pressurised air reservoir, as shown in Fig. 1. The dust reservoir is placed downstream of the air

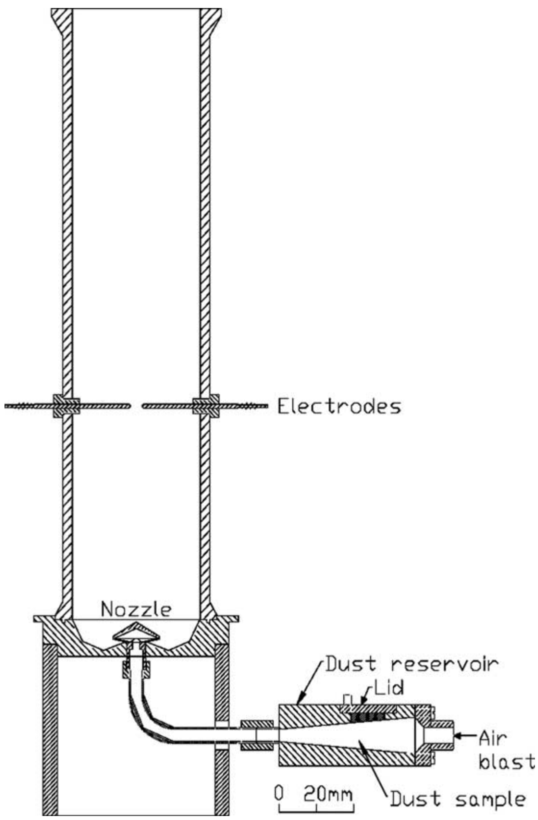

Fig. 1. Cross-section of the dust dispersion system and explosion chamber. The air blast is generated by emptying a 50 cm^3 pressurised air reservoir, fitted with a solenoid valve, upstream of the dust reservoir.

outlet valve, and the dusts are forced further downstream by the air blast through a pipe and into a mushroom shaped nozzle at the bottom of the explosion chamber, from which a transient explosive dust cloud is generated in the main chamber. The explosion chamber is a 1.2 l glass tube, identical to the one used in the MIKE apparatus. The same applies to the steel bottom of the explosion chamber.

By forcing the dust particles through a nozzle, particle agglomerates are torn apart and the effective particle size is reduced, described by e.g. Yamamoto and Suganuma (1984). This method is different from the conventional dispersion method of placing the dust in the bottom of the explosion chamber and dispersing the dust cloud by exposing the particles to an air blast. Shear forces between the particles and downstream tube, in addition to collisions with the nozzle wall contribute to reduced agglomeration in the explosive dust cloud.

The electrodes are 2 mm diameter tungsten rods. The tips are sharpened, but in order to reduce the generation of corona, they are slightly rounded off. The electrode gap distance was set at 8 mm throughout the tests presented here.

3.2. Spark triggering tests

Preliminary triggering tests showed that different dusts were able to trigger the spark breakdown at significantly different preset gap voltages. Comprehensive tests were therefore done to investigate the lowest voltage at which various dusts initiated breakdown. The weight of dust dispersed, and hence the nominal concentration, and the dispersion pressure of the 50 cm^3 reservoir were held constant for the different dusts. For all the triggering tests, a discharge capacitance of 3 nF was used, and there was no added series inductance in the discharge circuit.

Sparking was detected on a digital oscilloscope (*Tektronix TDS360*), using a simple capacitive coupling between the wire leading to the high voltage electrode and a wire acting as a probe. The coupling consisted of some windings of the detection probe wire around the high voltage wire, thus forming a small capacitance between the oscilloscope and the discharge circuit. However, small capacitance, the sudden change in current at the time of discharge gave rise to an easily detectable voltage proportional to the rate of change of current. This signal was filtered through an *RC* low pass filter to avoid high frequency noise and made it possible to identify the true discharge signal as a well-defined pulse. The oscilloscope was triggered by the signal sent to the solenoid valve at the time of opening, and the time between this signal and the spark detection signal was equal to the delay between dispersion onset and spark discharge.

Tests were done by setting the voltage significantly below the level leading to breakdown in pure air. With the electrodes and the distance between them as described earlier, the breakdown value in air was about 13 kV. At this voltage sparks occurred without the presence of any dust particles in the gap. The voltage was then set at a relatively low value, e.g. 6 kV, and the dust sample was dispersed into the explosion chamber. If no spark was detected, the voltage was increased in steps of 0.5 kV and the test repeated until the spark was triggered in three successive trials. This voltage was considered the lowest 'stable triggering voltage' of the configuration.

3.3. Experimental procedure used in the ignition tests

In the apparatus presented here, one or several capacitors in parallel were first charged through a charging resistor to the selected static DC high voltage. The value of the charging resistor R was chosen so that only single sparks could occur during the duration of the transient explosive dust cloud, due to a sufficiently large time constant RC, depending on the discharge capacitor C.

The voltage between the electrodes was set at the selected value U prior to the dispersion, and the dust particles triggered the electrical breakdown. A schematic outline of the electric circuit is given in Fig. 2.

The energy generated in the spark was assumed equal to the stored capacitor energy prior to breakdown, $\frac{1}{2}CU^2$, where C is the capacitance of one or several capacitors in parallel and U is the potential difference over the capacitors. The value of U was measured with the high

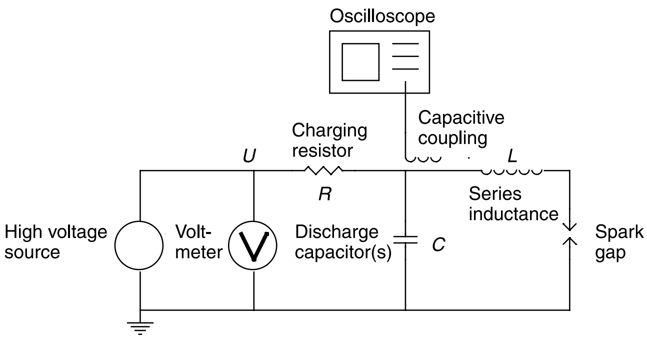

Fig. 2. Schematic layout of the electric discharge circuit. The voltmeter is integrated in the high voltage source, measuring the output voltage *U*. The series inductance *L* was not included in tests with pure capacitive sparks.

voltage source's voltmeter, because the charging resistor is transporting virtually no current when the capacitor is fully charged.

The capacitors used had a capacitance between a few pF and 10 nF. Capacitance values above 100 pF were prepared by using one or more commercially available high voltage capacitors in parallel. For lower capacitance value a parallel plate capacitor with plastic plates of different thickness as the dielectric medium was used. In addition, the stray capacitance of the discharge circuit was included when calculating the total capacitance involved in a spark discharge. This value was about 14 pF, a result of capacitive coupling between wires and circuit elements, and the capacitance between the electrodes. The capacitance of the parallel plate capacitors and the stray capacitance were measured using an *RCL* meter (*Escort ELC-131D*).

Ignition tests were carried out both with and without series inductance in the discharge circuit, i.e. with both pure capacitive and prolonged sparks. The series inductance used was a simple wire-wound coil with plastic core with an inductance of $L = 0.7$ mH, which is of the same order as the standard value of 1–2 mH (IEC, 1994).

Using the dust cloud itself as a spark trigger, offered a somewhat unstable ignition source. This was especially true when the voltage was set quite low compared with the breakdown voltage in pure air. A general trend was that the delay between dust dispersion and spark breakdown increased when lowering the voltage. Therefore, if the voltage was set as low as possible, the turbulence at the time of spark triggering was reduced, thus improving the conditions for ignition. However, at nominally identical conditions, the delay between dispersion and spark triggering varied substantially between tests.

Ignition tests were performed in series of ten successive trials at each energy level. The mass of dust dispersed and the dispersion pressure were held constant throughout the ten trials. If sparkover did not occur, the trial was discarded and a new one was carried out until the spark was triggered ten times at the specific energy level. The frequency of ignition was recorded at each energy level, both for pure capacitive and prolonged sparks.

When the capacitor energy was lowered to the region of low ignition probabilities, some of the experimental parameters were varied and new tests were done to see if higher ignition probabilities could be obtained. The parameters adjusted were nominal dust concentration and dispersion pressure. The pressure could, however, not be set any lower than about 5 bar(g) because of poor dispersion at lower pressures.

4. Results and discussion

4.1. Various dust clouds acting as spark triggers

The results of the spark triggering tests are presented in Table 1, giving the lowest voltages at which the spark was triggered 3 times successively for various dusts. The nominal concentration used was 750 g/m^3.

One trend seems relatively clear: coarse particles trigger the dust at somewhat lower voltages than finer ones of the same material. This behaviour is in agreement with what is reported by Dascalescu et al. (1997). However, the effect may be also be related to the dispersion of the particles.

The data shows no pronounced difference between conductive and dielectric particles in the ability to initiate breakdown, as would be expected from the literature. In fact, it is not possible to distinguish between the particles based on this property.

In general, it is difficult to identify the properties that can account for the different behaviour of the particles. Investigations of the permittivity of the dielectric particles

Table 1
Spark triggering voltages. Summary of the voltages (in steps of 0.5 kV) at which the same nominal concentration of different dusts gives three consecutive triggerings of the spark. The electrode configuration and discharge circuit are described in the text

Dust type	Stable triggering voltage (kV)
Pure air (no dust)[a]	13.0
Lycopodium clavatum	7.5
Magnesium, very coarse	7.5
PMMA[b], coarse fraction	8.0
Maize starch	8.5
PMMA, fine fraction	8.5
Niacinamide	8.5
Aluminium	9.0
Bronze	9.0
Niacin	9.5
Coal (Indonesian)	10.0
Rice flour	10.0
Rape flour	10.0
Silicon, coarse fraction	10.0
Sulphur	10.0
Silicon, fine fraction	11.0

[a] Somewhat difficult to determine the breakdown voltage accurately due to electrode imperfections and occurrence of corona discharge.
[b] PMMA, poly methyl methacrylate.

could potentially give useful information. The same applies to the particles' shape.

Further investigations should therefore be done to examine which particle properties that are influencing the mechanisms of breakdown.

4.2. Evaluation of the minimum ignition energies obtained

The different dusts' ability to trigger the spark discharge was employed in ignition experiments. However, significant scattering of the delay times between dispersion and spark triggering was recorded.

The ignition frequencies of three dusts were investigated for a range of energy levels. The dusts were *L. clavatum*, sulphur and maize starch. The maize starch was dried prior to testing, whereas the *L. clavatum* powder had its natural moisture content of about 3%. The sulphur powder contained no moisture. The ignition frequency was plotted both for pure capacitive and prolonged sparks. However, the maize starch could not be ignited with pure capacitive sparks, using even the highest capacitor value available. The ignition frequencies for maize starch therefore only contain data for prolonged sparks.

The lowest energy level giving ignition of *L. clavatum* dust was 14 mJ using prolonged sparks, and 30 mJ using pure capacitive sparks. The ignition frequency curve is shown in Fig. 3. Logarithmic trend lines have been added to the curves, crossing the abscissa at 9.5 and 26 mJ, respectively, thus giving an indication of the ignition energy when the ignition frequency approaches zero. A dotted line is also added, showing the typical frequency of ignition in a conventional MIE test (Eckhoff, 1975).

The lowest energy level at which the sulphur dust was ignited was 1.8 and 2.3 mJ for prolonged and pure capacitive sparks, respectively. The ignition frequency is shown in Fig. 4. No trend lines have been added due to the significant scattering of the points obtained.

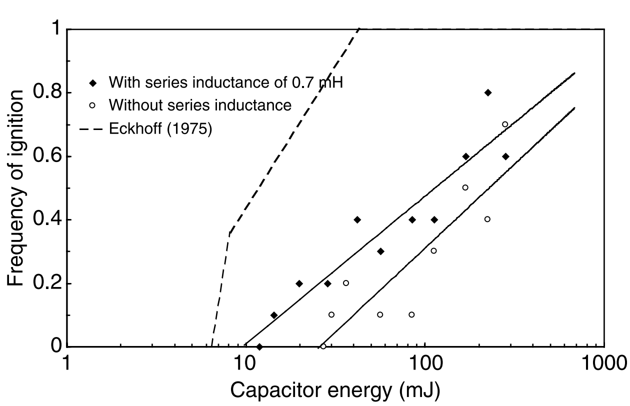

Fig. 3. Frequency of ignition for transient clouds of *Lycopodium clavatum* in air as a function of stored capacitor energy for pure capacitive and prolonged. Each point represents 10 ignition trials. Logarithmic trend lines are added. The dotted curve is from a conventional MIE test with synchronised sparks.

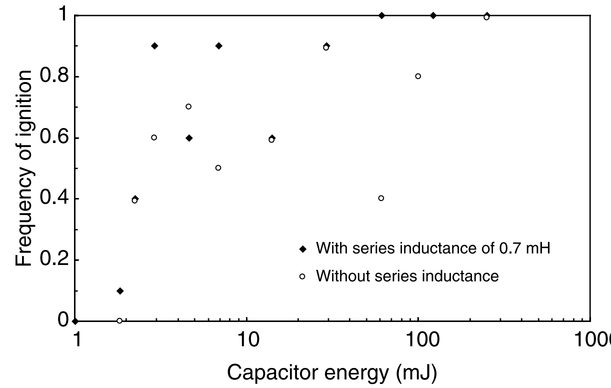

Fig. 4. Frequency of ignition for transient clouds of sulphur in air as a function of stored capacitor energy for pure capacitive and prolonged sparks. Each point represents 10 ignition trials.

Maize starch was ignited at an energy level of 45 mJ at the lowest. The ignition frequency as a function of capacitor energy is presented in Fig. 5. A logarithmic trend line is included in the curve, crossing the abscissa at 28 mJ.

The MIE obtained for *L. clavatum* is somewhat higher than the conventional value of about 6 mJ obtained e.g. by Eckhoff (1975). The same worker estimated the MIE for sulphur dust to be less than 0.3 mJ, but the assessment of the spark energies used in this experiment might be too low. The lowest value achieved in this work is an order of magnitude higher, but is worth noticing the abrupt reduction in ignition frequency at low energies in Fig. 4. The non-optimised conditions at the time of triggering may play an increasingly important role when reducing the energy to this level.

The MIE data for maize starch reported show significant scattering, with values ranging between about 10 and 300 mJ (HVBG, 1997). This is probably due to variation in the level of agglomeration—and thus effective particle size—and moisture content in different samples. Bartknecht (1993) indicated a MIE of 10 mJ. This is somewhat lower,

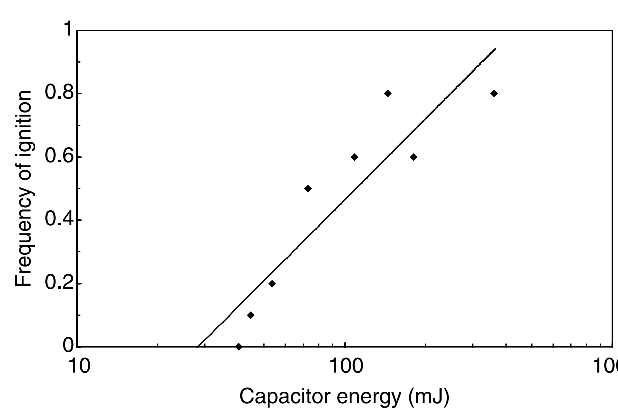

Fig. 5. Frequency of ignition for transient clouds of maize starch in air as a function of stored capacitor energy for prolonged sparks with a series inductance of 0.7 mH. Each point represents 10 ignition trials. A logarithmic trend line is added.

but of the same order as the values found with the present method.

Ignition experiments were also conducted using the Calibration-Round-Robin dusts CaRo00/01 (Cesana, 2001) and CaRo 03 (Cesana, 2004), niacinamide and niacin, respectively. These dusts offer good reference values for MIE determined by conventional methods. However, both dusts turned out to be difficult to ignite, even at quite high energies. The reason of this is believed to be the tendency of the dusts to trigger the spark at short delay times, and thus high turbulence at time of spark onset. Conclusive investigations could therefore not be conducted with these dusts.

The experiences of the niacinamide and niacin dusts illustrate an important difference between the conventional methods for determining MIE and the one presented in this paper. In order to achieve ignition at low energies, it is important that both the dust concentration is optimal and the turbulence as low as possible. When the dust cloud is used as a spark trigger, it is quite unlikely that both these parameters are optimal at the time of spark discharge.

This most probably accounts for the fact that the minimum ignition energies obtained in the present studies are somewhat higher than those found for the same dusts with conventional tests methods.

It is also worth comparing the dotted curve in Fig. 3, which is obtained using a conventional MIE test, and the trend lines obtained with the present method of spark triggering. The most striking difference is the steepness of the curves, which illustrates that the conditions for ignition, even at relatively high energies, are far from optimal when the sparks are not synchronised. However, the curves seem to cross the abscissa at points which are relatively close to each other, illustrating that the conventional MIE values are quite close to the lowest ignition energies obtained using a somewhat more industrially relevant spark triggering method.

5. Conclusions

1. An investigation of the minimum ignition spark energy of dust clouds has been conducted. Unlike the standard MIE test methods, the spark was triggered by the explosive dust cloud. Before dust dispersion, the voltage across the spark gap was preset to a high voltage somewhat lower than the breakdown voltage in air only. The dust particles present disturbed and intensified the static electric field between the electrodes, causing electrical breakdown and spark discharge.
2. The dust cloud's ability to trigger the spark, in this way, measured as the lowest voltage at which breakdown occurred, is strongly depending on the material involved. The present studies indicate that coarse particles cause greater disturbance of the field, thus producing breakdown at lower voltages, than fine particles. In general, conductive particles are not found to initiate breakdown at lower voltages than dielectric ones, when using the same dust concentration. Further investigations on which particle properties are important for breakdown should be undertaken.
3. Ignition frequencies as a function of spark energy are found for three different dusts: *L. clavatum*, sulphur and maize starch. The minimum ignition energies are somewhat higher than those found using conventional methods. In addition, the ignition frequencies are relatively low even at high energies. This is probably because dust concentration and turbulence are not optimal at the time of spark onset.
4. It is believed that spark triggering by the explosive dust cloud itself utilizes a relevant mechanism of spark ignition in an industrial context, where optimal independent dispersion and spark triggering is highly unlikely, and that the ignition energies obtained using this method are industrially relevant. However, the ignition energies obtained in conventional MIE tests are of the same order, illustrating that conventional tests probably give somewhat conservative, but still industrially relevant results.

Acknowledgements

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