A Model for the Minimum Ignition Energy of Dust Clouds

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Abstract:

This study refers to the minimum ignition energy (MIE) of dusts as determined by means of the Hartmann tube. To do so, six different dust with different particle size and properties are employed. A theoretical model is developed to predict the MIE based upon the physical and chemical properties of the dust. The model clearly shows the relationship between the minimum ignition energy and the minimum ignition temperature of a dust cloud. The model results in a method to calculate the MIE of dusts. Also, the time necessary for ignition can be calculated with the model. The results show that despite some limitations, the model predicts the MIE for dusts rather well. It is proposed that 40-60% energy loss would be considered when applying the model.

Keyword: Minimum Ignition Energy, Dust clouds, Minimum Ignition Temperature, Theoretical model

1. Introduction

Dust explosion constitute a major hazard in industries involving combustible dust materials. Many solids that are nearly nonflammable in bulk become explosive when dispersed in air as a fine powder and exposed to a suitable ignition source. Therefore, safety is of major importance when working with combustible dust as they can give rise to explosions. The risk for dust explosions can best be assessed by determining the explosion characteristics of dust. The minimum ignition energy (MIE) is a very important property for the assessment of the explosion risk of a combustible dust. It is standard procedure to determine the MIE experimentally by means of electrical discharges. The MIE is defined as the lowest energy of a high-voltage capacitor discharge that is capable of igniting a dust-air mixture. According to the thermal theory of electric spark ignition of Lewis and von Elbe (1961), immediately after discharge, the spark generates a small volume of hot gas. At the beginning, the temperature within the kernel increases but as soon as the ignition

volume increases, due to the flow of heat to ambient, the temperature inside of kernel decreases. In the adjacent layer of ambient gas the temperature rises and induces chemical reactions, so that a combustion wave is formed and propagates outwards. At the time that the temperature within the flame kernel has decreased to the order of normal flame temperature, the diameter of the flame kernel must have grown to a certain size for self-sustained combustion, i.e. ignition, to be established. The flame kernel has more or less a spherical shape. More detailed information on spark energy and spark generation is found in (Maly, 1984; Maly and Vogel, 1979). Several factors influence the MIE such as the discharge electric circuit inductance (Eckhoff, 2003; Eckhoff, 1975; Janes et al. 2008), turbulence (Eckhoff, 2003; Guo, 2012) dust particle size (Bartknecht, 1989), temperature (Eckhoff, 2003; Siwek and Cesana, 1995) and moisture content. These studies experimentally show the importance of the different parameters. A theoretical model is required to provide better insight and deeper understanding of the ignition phenomena. However, due to phenomena such as turbulence and heterogeneous combustion dust ignition is very complex. Also, Eckhoff reported that at the moment of ignition, sufficient particles arrive in the spark gap caused breakdown voltage. Then the dust particles in the neighbours of the spark are push away by the blast wave formed by highly pressurized spark channel. This results in the free zone be left around the spark. Thus, in contrast to gas combustion (Frederi and Sibulkin, 1991; Sibulkin and Siskind, 1987), only in a few studies researchers have tried to model the ignition process of the particles (Kalkert and Schecker, 1979).

In this study, the experimental determination of the MIE of a number of dusts is described. This is followed by a model of the ignition process based upon the temperature evolution of dust particles being submitted to the heat generated by the electric discharge.

2. Experimental work

2.1. Apparatus and test procedure

Figure 1 MIKE 3 apparatus

In principle, the MIE lies between the lowest energy value (E_2) at which ignition occurred and the energy (E_1) at which in at least 10 successive experiments no ignition was observed. This energy range is named the minimum ignition energy of a combustible dust in a mixture with air. Although the MIE is usually expressed as a range, in order to illustrate the behavior of the different combustible powders based on their MIE, only a single value shall be used instead of the energy range. This value can be estimated through the probability of ignition based upon equation (1) (CEN, 2003).

$$\log MIE = \log E_2 - I[E_2] \cdot \frac{(\log E_2 - \log E_1)}{(NI + I) \cdot [E_2] + 1} \quad (1)$$

$I[E_2]$ is the number of runs with successful ignition at E_2 and $(NI+I) [E_2]$ stands for the total number of tests at the energy level of E_2 . At least 5 concentrations need to be investigated to calculate the probability of ignition.

2.2. Dusts investigated

Six different dusts are investigated, as listed in Table 1. These dusts were chosen based on their particle size distribution, density and flammability. The Sebuku coal is from Indonesia which is a low sulphur and high volatile content bituminous coal. It was dried in a vacuum oven at 80 °C and 0.1 bar until the moisture content was less than 3%. The Niacin involves a very small amount of moisture. The other dusts were dry. Table 1 shows the properties of the dusts selected.

Table 1 List of dusts selected for the dusts tested

Dust	Particle diameter [μm]	Moisture content [%]	Bulk density [g/ml]	Particle density [kg/m³]	Heat capacity [J/kg. K]
Sebuku coal	14.9	3.00	0.520	1200	1325
Cacao	92.0	7.80	0.530	1904	1380
Niacin	17.9	0.20	0.464	1400 ("Niacin," n.d.)	1229 ("Niacin," n.d.)
Lycopodium	35.9	5.80	0.305	1096	1381
Zirconium	43.0	0.25	3.010	7000	278 ("Technical data for Zirconium," n.d.)
Oak wood	62.9	7.70	0.275	700 (Toolbox Enginner, n.d.)	2390 (Martinez, n.d.)

As indicated in literature (Bartknecht, 1989), the particle size or median value M has an influence on the minimum ignition energy. In practice, dusts normally have a broad distribution with a tail of fine particles. Such powders are more hazardous than those with the same median value but a narrow size distribution

(Cashdollar, 2000). Therefore, for safety consideration, only fine dust with $M \ll 63 \mu\text{m}$ should be tested for the determination of the minimum ignition energy (Siwek and Cesana, 1995).

All powders were milled and sieved to produce a sufficiently fine fraction for the experiments.

Figure 2 shows the particle size distribution of the dusts as a differential distribution and as a cumulative distribution. The differential distribution shows the relative percentage of each particle size measured. The cumulative distribution reports the accumulative percentage versus particle size. The median particle size on a number basis named d_{50} were determined by laser diffraction analysis according to ISO 13320. It is worth noting that the zirconium particle distribution is a bimodal distribution (two peaks). The properties of the air are listed in Table 2.

Figure 2 Particle size distribution of dust clouds, q: “diameter on cumulative %”

Table 2 Properties of air at 25 °C and 1 atm

Density [kg/m ³]	Heat capacity [J/kg. K]	Thermal conductivity [W/m. K]
1.205	1005	0.0257

3. Model for the minimum ignition energy

To model the ignition process it is assumed that the spark energy is released in a small volume between the electrodes in which dust particles are present and blast wave does not exist. The heat is released instantaneously and starts to dissipate in the air outside this volume. During the process of heat diffusion, the particles present are heated up. They reach a maximum temperature and will start cooling off when the air temperature becomes lower than the particle temperature. The larger spark energy, the higher the maximum particle temperature will be. It is assumed that when the maximum temperature is equal to the auto-ignition of the particles in a dust cloud, then the particles are ignited.

The transient temperature distribution due to conduction around a point at which an amount of energy E_0 is released instantaneously at time $t=0$ is governed by the equation (Taler and Duda, 2006):

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left(k_g r^2 \frac{\partial T_g}{\partial r} \right) + w = \rho_g C_{p_g} \frac{\partial T_g}{\partial t} \quad (2)$$

Where k_g is the thermal conductivity of gas, T_g , ρ_g , and C_{p_g} are the air temperature, the air density and the air specific heat, respectively. The term w represents the heat released. This quantity is equal to the

minimum ignition energy (E_0) at $t=0$ and is zero for positive times. The initial condition for Eq. (2) is $T_g(r,0)=T_i$, and the heat released is E_0 at $t=0$ at the origin.

The solution to Eq. (2) is given by (Mills, 1992):

$$T_g(r, t) = T_i + \frac{E_0}{(4\pi\alpha_g t)^{3/2} \rho_g C_{p-g}} \exp\left(-\frac{r^2}{4\alpha_g t}\right) \quad (3)$$

Where T_i is the initial temperature set equal to 300 K and $\alpha_g = k_g/\rho_g C_{p-g}$. At $r=0$ the air temperature is given by

$$T_g(0, t) = T_i + \frac{E_0}{(4\pi\alpha_g t)^{3/2} \rho_g C_{p-g}} \quad (4)$$

This temperature is the highest temperature in the whole temperature field at any specific time. Therefore, it is to be expected that a particle at the origin will heat up faster and to a higher temperature than any other particle. Therefore, the analysis that follows is dedicated to a particle at the origin $r=0$.

In order to find the temperature of a single particle with volume V and surface area A present at $r=0$, the following assumptions are made (Kalkert and Schecker, 1979):

- The temperature around the particle is spatially uniform and equal to $T_g(0, t) = T_g$.
- The mass of the particle does not change.
- The Biot number is less than 0.2. Therefore, the temperature inside the dust particle is uniform.

A lumped-capacitance thermal balance gives (Yarin & Hetsroni, 2004):

$$m_p C_{p-s} \frac{dT_s}{dt} = hA(T_g - T_s) \quad (5)$$

Where T_s is the dust particle temperature, m_p is the particle mass, C_{p-s} is the heat capacity of the dust, h is the convective heat transfer coefficient and A is the particle surface area. The gas temperature from Eq. (4) is substituted into Eq. (5) giving:

$$m_p C_{p-s} \frac{dT_s}{dt} = hA\left(T_i + \frac{E_0}{(4\pi\alpha_g t)^{3/2} \rho_g C_{p-g}} - T_s\right) \quad (6)$$

The convective heat transfer coefficient, h is given as

$$h = \frac{Nu k_g}{d_p} \quad (7)$$

where d_p and Nu are the particle diameter and the Nusselt number respectively. Due to the use of small particles, the Nusselt number is assumed constant ($Nu=2$) (Yarin and Hetsroni, 2004).

At $t=0$, the gas temperature (T_g) at $r=0$ becomes infinite, which is unrealistic. Therefore, it is assumed here that the gas temperature at the initial point of particle heating is equal to the spark temperature, which is assumed to be 2000 K. The time to reach this value, according to equation (4) is called t_g . This value is only dependent on E_0 and its dependence is shown in Figure 3 over a wide range of energy values.

Figure 3 Time t_g as a function of different ignition energy values; t_g is the time required for gas to reach a temperature of 2000 K after sparking

The solution to the diffusion equation (3) is applied to the lumped capacity equation only for times larger than t_g . Redefining the time t equation (6) becomes:

$$m_p C_{p_s} \frac{dT_s}{dt} = hA(T_i + \frac{E_0}{(4\pi\alpha_g(t+t_g))^{3/2}\rho_g C_{p_g}} - T_s) \quad (8)$$

The solution to Eq. (8) is given by:

$$T_s(t) = \left(300e^{b(t+t_g)} + 2D \left(-\frac{e^{b(tg+t)}}{\sqrt{t_g+t}} + \frac{b\sqrt{\pi}\text{erf}(\sqrt{-b(t_g+t)})}{\sqrt{-b}} \right) - 2D \left(-\frac{e^{bt_g}}{\sqrt{t_g}} + \frac{b\sqrt{\pi}\text{erf}(\sqrt{-bt_g})}{\sqrt{-b}} \right) \right) \frac{e^{-bt}}{e^{bt_g}}$$

Where (9)

$$D = \frac{6*2*E_0*\alpha_g}{\rho_s C_{p_s} (4\pi\alpha_g)^{\frac{3}{2}} d_p^2}$$

$$b = \frac{6 * 2 * k_g}{\rho_s C_{p_s} d_p^2}$$

The heat necessary to ignite a particle is proportional to the third power of the diameter but the speed to heat up a particle is inversely proportional to the first power of the diameter. Lower heat up speed means higher MIE. So the MIE according to the model should be proportional to the diameter to a power somewhat less than 3.

It is assumed here that the MIE is the smallest value of E_0 at which the maximum temperature of the particle is equal to the ignition temperature of the particle in a dust cloud (such as determined in a BAM oven).

The algorithm to calculate the MIE through Eq. (9) can be summarized as follows.

1. Assume a value for E_0
2. Find t_g from Eq. (4) or Figure (3), where it was assumed that $T_g(t_g)=2000$ K
3. Insert t_g and the powder properties into Eq. (9)
4. Calculate the maximum temperature $T_{s, \max}$
5. Compare the $T_{s, \max}$ with the minimum ignition temperature (MIT) experimentally determined
6. (a) If $T_{s, \max}$ is higher than the MIT, choose a lower value for E_0 , steps 2-5 are repeated until the maximum temperature of a particle becomes equal to MIT.

(b) If $T_{s, \max}$ is lower than the MIT, choose a higher value for E_0 , steps 2-5 are repeated until the maximum temperature of particle becomes equal to MIT.

The time at which the minimum ignition energy is obtained, is called t_s , the time necessary for ignition. Similar to the MIE, this value is dependent on the powder properties.

Table 3 shows the minimum ignition temperatures of the powders used in this study.

Table 3 Minimum ignition temperature of powders

Dust	MIT [K]	Source
Sebuku coal	790	(Wu et al., 2013)
Cacao	760-840	(Material safety data sheet :Cacao powder, 2010)
Niacin	850	(<i>Safety Data Sheet</i> , 2013)
Lycopodium	680	(Addai et al., 2016)
Zirconium	670	Experiment
Oak wood	755	(“The Engineering toolBox,” n.d.)

4. Results and Discussion

4.1. Experimental Results

Since turbulence has a significant influence on the MIE, tests should be carried out at different turbulence levels. To this purpose, tests are performed at three different delay times. In this work, three ignition delay series were applied; i.e. 90 ms, 120 ms and 150 ms; or 120 ms, 150 ms and 180 ms. The lowest ignition energy among these three tests series is considered to be the MIE. All tests were performed with an inductance of 1 mH. Figure 4 shows the experimental results for various dusts as a function of the dust concentration. The x -axis is the concentration of dust dispersed in the 1.2 L explosion vessel (mass/1.2 L). The y -axis shows the ignition energy. A solid dot indicates ignition and a hollow square shows that there was no ignition at that specific concentration and energy value. Figure 4 (a) illustrates that Sebuku coal is ignitable at 100 mJ at 5 different concentrations, whereas at 30 mJ, it is not able to ignite. Applying Eq. (1), the MIE of Sebuku coal is equal to 55 mJ. Similarly, Cacao is able to ignite at 1000 mJ within the whole range of concentrations, whereas at 300 mJ it is not capable of ignition at any concentration (see Figure 4b). The MIE of Cacao is, therefore, equal to 350 mJ. The minimum ignition energy of Oak wood is equal to 42 mJ (Figure 4c). In addition, it is seen in Figure 4d that Zirconium is able to ignite at 1 mJ at one concentration. Consequently, its MIE is outside the range of the MIKE 3-apparatus. Table 4 gives a summary of the results.

Figure 4 Ignition energy as a function of dust concentration loaded in the MIKE3 apparatus (a) Sebuk coal (b) Cacao (c) Oak wood (d) Zirconium. A solid dot indicates ignition and a hollow square shows that there was no ignition at that specific concentration and energy value

Table 4 Minimum ignition energy of powders

Dust	MIE (mJ)
Sebuk	55
Niacin	1.6
Cacao	350
Lycopodium	4
Oak wood	42
Zirconium	<1

The difference in MIE of the substances (Table 4) can be attributed to several properties. First, an increase in the dust particle size decreases the surface area exposed to ignition and consequently the MIE increases (Cesana and Siwek, 2001). Secondly, dusts with higher volatility are more prone to ignition. In fact, a dust with more volatile content tends to produce more combustible gas which leads to easier combustion. In addition, the moisture content of powder plays an important role.

4.2 Model evaluation

Table 5 compares the minimum ignition energies obtained from the model with those determined experimentally. It was pointed out above that the particle size distribution for zirconium has two-peaks. It is expected that finer particles are prone to ignition easier than heavier ones. Therefore, the first peak, 13 μm , is the diameter responsible for ignition initiation leading to minimum ignition energy of 0.33 mJ.

Table 5 Comparison of MIE obtained experimentally and Eq. (10)

Substance	MIE (mJ) experimental	MIE (mJ) Eq. (9)	Time required to ignite, t_s (ms)
Zirconium	<1	0.33	2
Niacin	1.6	1	4
Lycopodium	4	1.6	7
Oak wood	42	15	21
Cacao	350	140	73
Sebuku coal	55	0.4	3

Figure 5 compares the experimental MIE versus the calculated ones. Since several parameters influence the minimum ignition temperature, inaccuracies will exist in the values of Table 5. Therefore, the error bars present the effect of ± 50 K minimum ignition temperature variation on the MIE that was calculated and the results are indicated as error bars in Figure 5. The red line stands for conditions where experimental and model data are equal.

Table 5 indicates that for Sebuku coal, the minimum ignition energy obtained through the model proposed is much lower than the one obtained experimentally. This is also clearly seen in Figure 5. This can be attributed to the complicated combustion process of the coal. Coal contains a volatile material that is released at a low temperature. It is this gas that is ignited and the combustion in the beginning is in the gas phase while gas is generated from inside a particle. Afterwards, the combustion proceeds inside the particle itself. The model proposed assumes that the combustion occurs spontaneously in the particle.

Figure 5 Comparison of the experimental MIE values versus the ones obtained through our model for various powders

The data of cacao, wood and lycopodium express that the experimental values are around 2.5 times bigger than those obtained through Eq. (9). For niacin, the experimental value is 1.6 times bigger than what the model proposed. This difference can be attributed to several parameters which are not taken into account in the model. These include: the electrical energy dissipation into the electrodes, energy loss due to radiation from the spark to the surroundings and conduction losses to the electrodes. In addition, there are the assumptions made in the model about particle shape, cloud ignition temperature etc. The contribution of these uncertainties cannot be separately distinguished. However Eisazadeh-far (Eisazadeh-Far et al., 2010) reported that radiation can dissipate 20 % -60 % of discharge energy depending on spark duration and spark temperature. Also in their work, 25-30 % of discharge energy was dissipated by the cathode conduction and the thermal boundary layer. Finally, they concluded that only 10-25 % of discharge energy is converted to thermal energy. Teets and Sell (Teets and Sell, 1988) indicated that the largest fraction of energy dissipation is due to conduction losses to the electrodes. Belinger et al. (Belinger et al., 2011) focused on one value of ignition energy (55 mJ) and they found that half of the total energy is lost during ignition. Beloni (Beloni, 2011) reported that the minimum ignition energy of Mg is 25 mJ and the predicted spark energy to this powder is 11 mJ which indicates that 56% of spark energy is lost. He also compared the predicted energy delivered to the particle with the total spark energy for several dusts and he concluded that the measured heat energy varies from 50 to 90 % of the total spark energy. Hertzberg et al. (Hertzberg et al. 1985) introduced an effective spark energy based on the pressure rise ΔP generated by the spark discharge in a chamber of constant volume (V):

$$E_{effective} = 2.5\Delta PV \quad (10)$$

They applied their model to several dusts in the Hartmann tube. Their results showed that the effective energy for lycopodium and polyethylene is 40% and for Pittsburgh coal 75% less than the capacitance energies.

The black line in Figure 5 shows that there is 60% discrepancy between the experimental results and the model ones. For Niacin, the discrepancy is 40%. This can be attributed to its short ignition time which allows less time for energy losses during ignition (Hosseinzadeh, 2018). Table 5 also shows the time required for ignition for different powders. Except for Sebuk coal, this table suggests that as the MIE of a dust decreases, the time taken for the combustion to start ignition also decreases.

Kalkert et al. (Kalkert and Schecker, 1979) proposed a model based on the physical properties of one single particle. They proposed the following expression to calculate the MIE of dusts in air:

$$E_0 = (4\pi k_g)^{\frac{3}{2}} \rho_g C_{p-g} \left[\frac{\ln 2 \rho_s C_{p-s}}{12 k_g} \right]^{3/2} T_{max} d_p^3 \quad (11)$$

T_{max} is defined as the gas temperature around a particle at ignition time assumed to be 1000 °C (Kalkert and Schecker, 1979).

Figure 6 compares the experimental results obtained with the semi-quantitative model developed by Kalkert (Kalkert & Schecker, 1979) and our present model. To use the model proposed, the value resulting from Eq. (9) should be multiplied by 2.5. It is clearly seen that the experimental data are very close to data provided by Eq. (9). Although there is no experimental value for MIE of zirconium, Eq. (9) predicts a value of 1mJ while the experimental value is less than 1mJ. Figure 6 shows that the Kalkert model predicts values that are far from the experimental ones.

Figure 6 Comparison of experimental minimum ignition energy (MIE) of dust with corrected theoretical models where a 50% loss of spark energy is incorporated

5. Conclusions

In the present study, the minimum ignition energy of several dusts is determined in the Hartmann tube. It is observed that the minimum ignition energy of dusts varies over a wide range of values. A model of the ignition process is developed, based upon the thermal behavior of particles submitted to the heat of the discharge. It results in MIE values that are close to the observed ones when heat losses from the discharge are accounted for. It is proposed to incorporate a 40-60% energy loss when applying the model.

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