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The Influence of Sieving on the Dust Explosion Characteristics of a Lignite Coal

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For the new developments in the area of coal-fired power plants, the flexibility is a major concern. The power plants must be able to operate with a high variety of coal qualities, with different particle size distribution, moisture content and ash content. In order to research the combustibility of different sieved fractions of lignite coal in solid fuel power plants, the explosion characteristics were investigated experimentally.
The aim of this study is to determine the ignition characteristics of a dried brown coal. Different sieved fractions are researched in order to investigate the influence of particle size distribution on the ignition sensitivity and explosion severity of the coal. Different explosion characteristics are determined using standardised test apparatuses, such as the MIKE-3 apparatuses and the 20-L sphere. Following characteristics are determined: minimum ignition energy (MIE), maximum explosion pressure (P_{max}), maximum rate of explosion pressure rise $(dP/dt)_{max}$ and the dust explosion constant (K_{st}). The behaviour of the explosion characteristics are related with the particle size distribution of the sieved fractions.

1. Introduction

Coal-fired power plants need to be compatible with the intermittent renewable energy sources and the fluctuating power demand. The problem with existing coal-fired power plants is that they are highly inflexible. They need a certain minimum load to operate, while decreasing the minimum load results in a larger range of generation capacity, which allows the plant to run, even when power demand is low. This avoids expensive start-up and shut-down procedures. However, reducing the minimum load is subject to certain technical limitations, such as fire stability, flame control, ignition, unburned coal and carbon monoxide (CO) emissions (Ess et al., 2017).
Fire stability might be the most important issue and occurs when there are sudden changes in firing rate or fuel quality, improper fuel-air ratios or varying flow of pulverized coal. The fire can become unstable at low loads when the incoming pulverized coal does not ignite completely. This can result in unburned pulverized coal dust clouds which can possibly be ignited at a later time, leading to an explosion inside the furnace. Several solutions exist for overcoming many of these technical limitations in case of reducing the minimal loads to increase flexibility (Ess et al., 2017).
A possible solution is the use of plasma assisted ignition burners for the start-up and as a support burner for minimum load reduction. To develop improved plasma assisted ignition systems, more knowledge is required about the boundary conditions of ignition and combustion process and about the influential parameters on the ignition and flame stabilisation. It is therefore important to determine the dust explosion characteristics of the coal samples. Similar studies for the characterisation of coal samples was performed by this group (Hosseinzadeh et al., 2015; Norman et al., 2013).
The particle size is an important characteristic when it comes to hazards related to dust, because the particle size affects the ignition sensitivity of a dust and the explosion severity of a dust explosion. A decrease in particle size will result in a decrease in minimum ignition energy (MIE), an increase in the maximum explosion

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pressure (P_{max}) and an increase in the maximum rate of explosion pressure rise $(dP/dt)_{max}$. Smaller particles have a larger specific surface area (surface area per mass) and therefore react faster. This explains why finer dust fractions contribute the most to the hazard, the finer dust particles are more easily dispersed in air and remain airborne for a longer time. The explosion hazard is mostly determined by the fine coal dust particles (Abbasi & Abbasi, 2007; Cashdollar, 2000; Eckhoff, 2003).
The first part of this paper focuses on the variation of the minimum ignition energy (MIE) with particle size distribution for three fractions of the same coal. The minimum ignition energy is the lowest electrical energy discharged by a capacitor that can ignite a combustible dust cloud. It is well known that the MIE decreases with decreasing median particle size, see Figure 1 (Eckhoff, 2003; Siwek & Cesana, 1995). For assessing the explosion sensitivity, the MIE is often determined on the sieved fraction < 63 µm. This is suggested according to the standard EN 13821 (European Commitee for Standardization, 2002) if the particle size of the sample in the plant is unknown. In some cases the MIE of the original fraction is calculated by means of an empirical correlation and the MIE-value of the fraction < 63 µm (Siwek & Cesana, 1995). The influence of the particle size on the MIE for three materials is shown in Figure 1 (Eckhoff, 2003). There is a lack of good data on the effect of narrow or broad particle size distributions on the MIE.

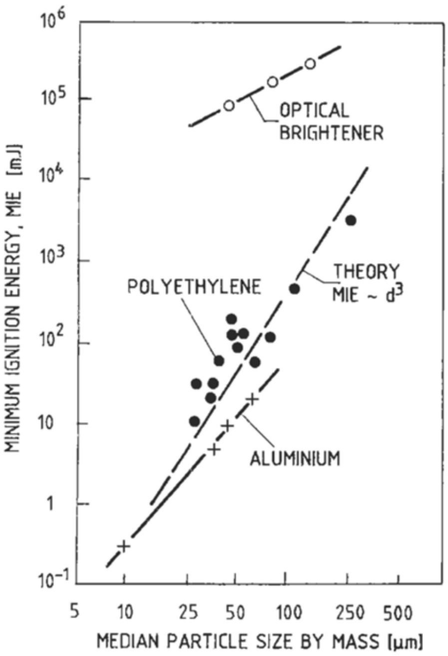

Figure 1: Minimum ignition energy of an optical brightener, polyethylene and aluminium, as function of median particle size and theoretical line for polyethylene (Eckhoff, 2003)*.*

The second part of this paper focuses on the influence of the particle size distribution on the explosion severity characteristics, such as the maximum explosion pressure (P_{max}), the maximum rate of explosion pressure rise $(dP/dt)_{max}$ and the dust explosion constant (K_{st}) for the same coal fractions. It is normally expected that both the $(dP/dt)_{max}$ and the K_{st} increase with decreasing particle size. In literature some data can be found on the influence of the median value of the particle size distribution (Cashdollar, 2000; Fumagalli et al., 2016). But there is a lack of data on the influence of sieving of a specific dust sample.

2. Experimental approaches

2.1 Dust sample preparation

The original fraction, the sieved fraction < 500 µm and the sieved fraction < 63 µm were used to investigate the influence of the particle size distribution on the MIE, the P_{max}, the $(dP/dt)_{max}$ and the K_{st}.
The particle size distribution and the median size (d_{50}) of the tested fractions was determined by means of a LA-950 V2 particle size analyser (Horiba). The particle size distributions of the different fractions are shown in Figure 2. It can be seen that only the sieved fraction < 63 µm has a narrow distribution, while the original fraction and the sieved fraction below 500 µm have a broad particle size distribution.

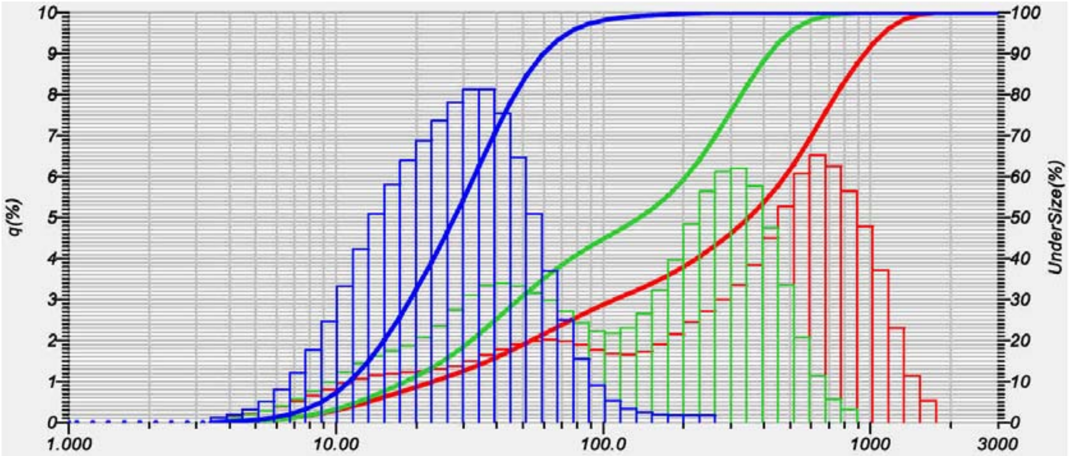

Figure 2: Particle size distribution of the different fractions of the coal sample, with the original fraction in red, the sieved fraction < 500 µm in green and the sieved fraction < 63 µm in blue, the volume% are shown as a bar graph and read out on the left side, the cumulative volume% are shown as a line graph and read out on the right side.

The relative moisture content of the tested fractions was determined with a XM 60 halogen moisture balance (Precisa). A temperature of 105 °C and a stop criterion of 2 digits per minute were applied. Volatile components which are liberated at or below the set temperature of the moisture balance (105 °C) are included in the moisture content. The properties of the different fractions are presented in Table 1.

Table 1: Properties of the coal samples

	Sieved < 63 µm	Sieved < 500 µm	Original fraction
Moisture content [$\%_{wt}$]	9.1	9.1	9.1
Median particle size (d_{50}) [µm]	28	137	351
Mean particle size [µm]	33	184	422
< 63 µm [%]	91	36	22
< 200 µm [%]	100	59	38
< 500 µm [%]	100	95	62

2.2 Ignition sensitivity

The minimum ignition energy (MIE) is one of the most important parameters for the ignition sensitivity of a dust. This parameter depends on multiple variables like moisture content, ignition delay time and dust concentration. The MIE was measured by using the standardized MIKE-3 apparatus (Kuhner), according to the EN 13821 standard (European Commitee for Standardization, 2002; Siwek & Cesana, 1995). The test is normally performed on the fraction of the powder with a particle size < 63 µm, but for this purpose the tests were performed on the original fraction and the sieved fractions < 500 µm and < 63 µm of the coal sample.

By definition, MIE data refer to protracted capacitor discharges. These are generally more incendive than purely capacitive discharges. The results obtained under such conditions (with inductance) can be applied to operational conditions only if the capacitors occurring in plant installations are also discharged via an inductance. Models to assess the risk of mechanical sparks are based on MIE values measured with inductance. Only when the incendivity of electrical discharges - especially of electrostatic discharges - with regard to dust/air mixtures is to be assessed, the minimum ignition energy must be determined without an inductance in the discharge circuit. In this case the tests were performed with an inductance of 1 mH in the discharge circuit (Siwek & Cesana, 1995).

Model calculations show that the MIE increases to third power of the median particle size (M) for dusts with a spherical shape and a uniform particle diameter as described in Equation 1 (Siwek & Cesana, 1995).

$$MIE_2 = MIE_1 \cdot \left(\frac{M_2}{M_1}\right)^3 \quad (1)$$

But dust particles are almost never spherical and the size of dust particles in a mixture is generally very different. Considering this, an estimation of the MIE based on a proportionality to the second and a half power of the median particle size seems to be more conservative and is in better agreement with the experimental results. The dependence of the MIE on the median particle size M can be described by the empirical correlation in Equation 2 (Siwek & Cesana, 1995).

$$MIE_2 = MIE_1 \cdot \left(\frac{M_2}{M_1}\right)^{2.5} \tag{2}$$

The dependence of the MIE on the median particle size is only valid when $M_1 < M_2$. Equation 2 can be used to estimate MIE_2 in a range from 1 to 500 µm when MIE_1 for a dust with a known particle size distribution M_1 is known at room temperature. This makes experiments with coarser dusts unnecessary. The validity of this equation for this coal sample will be investigated in the results.

2.3 Explosion severity

The explosion severity is defined by the maximum explosion pressure (P_{max}), maximum rate of explosion pressure rise $(dP/dt)_{max}$ and the dust explosion constant (K_{st}). These parameters depend on multiple variables like moisture, ash, particle size and dust concentration. These parameters were measured by using the standardized 20-L sphere apparatus (Kuhner), following the method defined in the standard EN 14034-1 and EN 14034. The dust sample is dispersed into the explosion chamber with compressed air from a storage container via a special distribution system. The tests are performed with two pyrotechnic igniters of 5 kJ each for the P_{max} and $(dP/dt)_{max}$ as ignition source. The course of the explosion is recorded as a function of time (with two quartz pressure sensors), and from the pressure- time curve the explosion pressure and the rate of pressure rise are recorded. The dust concentration is varied over a wide range until there is no further increase in either the P_{max} or $(dP/dt)_{max}$ (European Commitee for Standardization, 2006; Siwek & Cesana, 1995). The $(dP/dt)_{max}$ [bar/s] is volume dependent. By applying the "cubic law" it can be converted to the dust explosion constant (K_{st}-value, [bar·m/s]), which is independent of the volume V [m^3] (Equation 3).

$$(dP/dt)_{max} \cdot V^{1/3} = K_{st} \tag{3}$$

The test is normally performed on the fraction of the powder with a particle size < 63 µm, but for this purpose the tests were performed on the original fraction and the sieved fractions < 500 µm and < 63 µm.

3. Results and discussion

3.1 The influence of the particle size distribution on the MIE

The particle size dependence of the MIE is researched experimentally with different fractions of the coal, namely the sieved fraction < 63 µm (d_{50} = 28 µm), the sieved fraction < 500 µm (d_{50} = 137 µm) and the original fraction (d_{50} = 351 µm). The MIE of these three fractions was determined experimentally. The MIE of the sieved fraction < 63 µm lies between 30 mJ and 100 mJ, the MIE of the sieved fraction < 500 µm lies between 100 mJ and 300 mJ and the MIE of the original fraction lies between 100 mJ and 300 mJ. The experimental statistical MIE for the different fractions is equal to 50 mJ, 240 mJ and 240 mJ respectively (Table 2).
The calculated MIE of the sieved fraction < 500 µm is obtained by filling in the experimental statistical MIE of the sieved fraction < 63 µm and the median particle size of both fractions in Equation 2. This gives a calculated MIE of 2696 mJ for the sieved fraction < 500 µm. The calculated MIE of the original fraction can be determined in a similar way that gives a calculated MIE value of 28322 mJ (see Table 2 and Figure 3). The calculated MIE-values are significantly higher than the experimental values, because the model does not take into account the broad particle size distribution of the coal samples. It can be seen that the empirical correlation of Equation 2 even leads to a non-conservative estimation of the MIE because the experimental MIE is much lower than the calculated value for the original fractions. It is important that the MIE value of powders with a coarse particle size distribution is determined experimentally and not calculated by means of an empirical correlation.

Table 2: Experimental statistical MIE and calculated MIE for the different fractions of the coal sample

	Sieved <63 µm	Sieved <500 µm	Original fraction
Median particle size (d_{50}) [µm]	28	137	351
Experimental statistical MIE [mJ]	50	240	240
Calculated MIE (Eq. 2) [mJ]	50	2696	28322

The correlation between the experimental statistical MIE-values is clearly different from the empirical correlation suggested in Equation 3. A power is calculated using the experimental statistical MIE from the sieved fractions of 63 µm and 500 µm. The experimental MIE correlation follows a power of 0.983 instead of 2.5, which results in Equation 4.

$$MIE_2 = MIE_1 \cdot \left(\frac{M_2}{M_1}\right)^{0.983} \quad (4)$$

This indicates that the experimental MIE correlation predicts that the MIE-value will increase slower than the increase in median particle size. The experimental MIE correlation predicts a MIE-value of 600 mJ for the original fraction, while the experimental value remains constant between the original fraction and the sieved fraction < 500 µm. This can be explained by the fact that the influence of median particle size on the MIE-value decreases with increasing median particle size or that the influence of median particle size is less important for broad particle size distributions. The particles larger than 500 µm seem to have no influence on the MIE-value. Although the median value increases, the fine fraction is still present in the broad distribution and will lead to lower than expected MIE values. This highlights that the empirical correlation for the MIE is not accurate for broad particle size distributions.

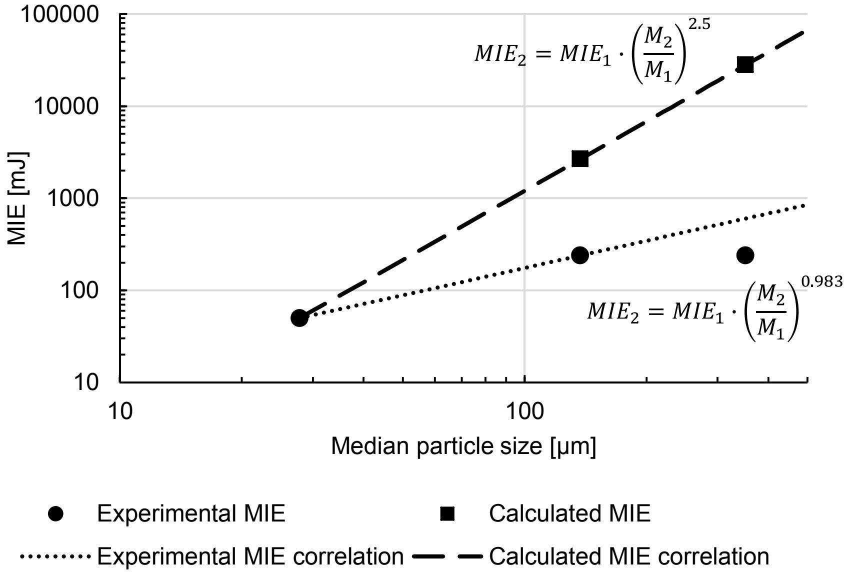

Figure 3: Experimental and calculated MIE for the different fractions.

3.2 The influence of the particle size distribution on the P_{max} and K_{st}

The second part of the paper concerns the test results of the explosion severity characteristics, the P_{max}, $(dP/dt)_{max}$ and the $K_{st.}$ These characteristics were determined on the different fractions of the coal sample, namely the original fraction, the sieved fraction < 500 µm and < 63 µm in order to investigate the influence of the particle size distribution on the P_{max}, $(dP/dt)_{max}$ and the K_{st}. The test results in Table 3 show that there is only a slight increase of P_{max} with decreasing particle size and no significant differences for the K_{st}-values of the different fractions. The measured values fall between the measuring error (P_{max} ± 10 % and K_{st} ± 12 %). This means that the influence of median particle size on the P_{max}, $(dP/dt)_{max}$ and the K_{st} is not significant for sieved fractions of the same coal sample as long as the fractions have a broad particle size distribution (see Figure 2). More narrow particle size distributions of milled fractions of the same coal should be investigated to research the influence of particle size more thoroughly.

Table 3: P_{max} and K_{st} of the different fractions of the coal sample

	Sieved < 63 µm	Sieved< 500 µm	Original fraction
Median particle size (d_{50}) [µm]	28	137	351
P_{max} [barg]	7.4	7.1	6.9
$(dP/dt)_{max}$ [bar/s]	510	492	522
K_{st} [bar·m/s]	138	134	142

4. Conclusions

Several experiments were carried out to study the impact of sieving on the MIE, P_{max} and K_{st} of a lignite coal sample. It was observed that a smaller median particle size results in a lower MIE, but it must be noted that the influence of the median particle size becomes less important for high median particle sizes or broad particle size distributions. The empirical correlation for the MIE cannot be applied on the different sieved fractions of the coal with a broad particle size distribution and therefore more experiments are needed in order to obtain reliable values for assessing the explosion risk. It was shown that the median particle size has no significant influence on the P_{max} and K_{st} for different sieved fractions of the same coal.

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