Dust explosion severity characteristics of Indonesian Sebuku coal in oxy-fuel atmospheres

Frederik Norman[*,1], Sepideh Hosseinzadeh[2], Eric Van den Bulck[2], Jan Berghmans[1], Filip Verplaetsen[1]

[1]Adinex NV, Brouwerijstraat 5/3, B 2200 Noorderwijk, Belgium
[2]Katholieke Universiteit Leuven, Department of Mechanical Engineering, Celestijnenlaan 300A, 3000 Leuven, Belgium

Abstract
In oxy-fuel combustion of coal, the pulverized coal is burned with oxygen at concentrations greater than 21% which is the amount of oxygen in air. In this study the influence of enriched oxygen concentration on the explosion characteristics of Indonesian (Sebuku) high volatile bituminous coal dust is researched according to the European standard EN 14034 in a 20L sphere. The dust explosion indices (LEL, P_{max} and K_{St}-value) were first determined in air. Thereafter these indices are determined in oxy-fuel (O_2/CO_2) atmospheres (20%, 30%, 39% and 49% O_2 in CO_2).

Introduction

The ability to mix pulverized coal with oxygen at concentrations higher than the currently applied 21% in nitrogen (air applications) may well provide advantages for burner design in oxy/coal fired systems. However the risk of dust explosions increases significantly with increasing oxygen concentration and temperature. The amount of experimental data available in the literature about the effect of oxygen on the explosion characteristics on coal is very limited. An overview of these experimental results up to 2003 can be found in Eckhoff [1]. Most of the work in the past was connected to the technique of inerting as explosion prevention measure. This technique aims at making dust clouds non-ignitable by adding an inert gas to the air in order to reduce the oxygen content of the air-dust mixture. From these studies it can be concluded in general that increased oxygen content will:

- Increase the flame temperature
- Increase the speed of combustion
- Lower the lower flammability limit
- Increase the maximum rate of pressure rise

The maximum explosion pressure may experience a limited increase. In previous work, the ignition sensitivity characteristics (minimum ignition energy and minimum ignition temperatures) were researched experimentally [2, 3]. The dust explosion severity characteristics such as the maximum explosion pressure P_{max} and maximum rate of pressure rise K_{St}-value are also important parameters for the safe operation of industrial processes. For example the explosion severity data, P_{max} and K_{St}, are needed for designing constructive safety measures, such as explosion proof design, vent panels and explosion suppression systems.

Experimental Procedure

The lower explosion limit LEL, the maximum explosion pressure P_{max} , the maximum rate of pressure rise K_{St} are determined in a standard test apparatus with a volume of 20 liters, see Figure 1 (VDI 2263, Blatt 1 [4] and EN 14034 Annex C [5, 6 and 7]). This test is normally performed on the fraction of the sample with particle size less than 63 µm.

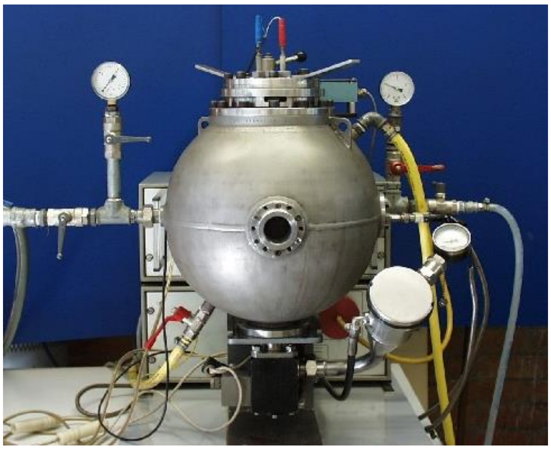

Figure 1: 20 litre sphere for the determination of the explosion indices LEL, P_{max}, K_{St}

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 maximum explosion pressure and the maximum rate of pressure rise or 1 kJ each for the lower explosion and the limiting oxygen concentration limit 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 in order to find the maximum values of explosion pressure and the rate of pressure rise. In order to determine the explosion

[*] Corresponding author: frederik.norman@adinex.be

characteristics in oxy-fuel (O_2/CO_2) atmospheres the 20 liter sphere was brought 2 times to vacuum pressure (< 0.05 bara) and flushed with the premixed O_2/CO_2 mixture. Thereafter the storage chamber (volume: 0.6 liter) was filled with a certain amount of powder (e.g. 1.0 g for a concentration of 50g/m³) and filled with the premixed O_2/CO_2 mixture until a pressure of 20 bara.

K_{St} is the dust deflagration index, a volume independent characteristic which is calculated from the maximum rate of pressure rise using the cubic law equation:

$$K_{st} = V^{1/3} (\frac{dp}{dt})_{max}$$

, in which V stands for the volume of the test set-up.

Dust sample preparation

The Indonesian Sebuku coal is a low sulphur and high volatile bituminous coal. Because the explosion characteristics depend on the moisture content of the dust sample the moisture content of the tested sample was measured. A halogen moisture balance was used for this purpose. A temperature of 105°C was applied. The moisture content of the milled Sebuku Coal was equal to 9.0%. The sample was sieved < 63 µm. The particle size distribution of the sieved fraction was determined by means of a laser diffraction analysis and the median size (d_{50}) of the sieved sample was 14.9 µm.

In order to research the influence of the moisture content, the sample was also dried in a vacuum oven at 80°C and a pressure of 0.1 bara until the moisture content was between 2 and 3 %.

Experimental results in air

The following characteristics were determined for the sample “Sebuku Coal (sieved < 63 µm)” in the 20-l sphere:

lower explosion limit:	60 g/m3
max. explosion pressure:	6.6 barg
max. rate of pressure rise (20 l):	418 bar/s
K_{St}-value:	114 bar.m/s
dust explosion class:	ST 1

The following characteristics were determined for the sample “Sebuku Coal (**dried** and sieved < 63 µm)” in the 20-l sphere:

lower explosion limit:	40 g/m3
max. explosion pressure:	6.5 barg
max. rate of pressure rise (20 l):	493 bar/s
K_{St}-value:	134 bar.m/s
dust explosion class:	ST 1
limiting oxygen concentration (N_2):	12 %

It can be concluded that the dried Sebuku coal has a lower LEL of 40 g/m³ in comparison with a LEL of 60 g/m³ for the undried sample. The explosion severity characteristics are similar for the dried and undried sample. The P_{max} values are the same, while the K_{St}-value is somewhat higher for the dried sample, but the samples belong both to dust explosion class ST 1. The limiting oxygen concentration was also determined for the dried sample and was equal to 12%. This is the maximum oxygen concentration in nitrogen, in which an explosion will not occur for any dust concentration.

Since it can be concluded that the dried sample gives the worst or highest explosion characteristics, the further experiments are performed only on the dried and sieved fraction of the Sebuku coal in order to obtain conservative and safe values for the assessment of the explosion risk.

Lower explosion limits in oxy-fuel mixtures

The lower explosion limit of the Sebuku coal was determined in oxy-fuel (O_2/CO_2) atmospheres. If the measured explosion pressure (including the effect of the igniters which is about 0.2 barg) is equal to or larger than 0.5 barg, an explosion is said to have occurred. It is on the basis of this criterion that the lower explosion limit is determined, see EN 14034-3[5].

The tests were performed with the dried fractions (moisture content < 3%) of the coal samples and with 4 different oxygen/carbon dioxide mixtures. In Table 1 the lower explosion limit of the Sebuku coal is given for the different mixtures. In a 20% O_2 / 80% CO_2 no explosion occurred so no LEL value could be determined. Therefore it can be concluded that the Sebuku coal (dried and sieved < 63 µm) is not explosible in 20% O_2 / 80% CO_2 or that the limiting oxygen concentration is higher than 20% in carbon dioxide.

	LEL of Sebuku Coal					
	AIR	AIR (Dried sample)	20% O_2 / 80% CO_2	30% O_2 / 70 %CO_2	39% O_2 / 61 %CO_2	49% O_2 / 51 %CO_2
LEL [g/m³]	60	40	Not explosible (2000 J)	90	40	30

Table 1:1 The lower explosion limits

The coal is not explosible in a 20% O_2 in CO_2 mixture, while the LEL decreases from 90 g/m³ to 30 g/m³ in a 30% to 49% O2 in CO_2 mixture. It can be concluded that the LEL-values in air correspond well with the LEL values in 39% O2 / 61% CO2. There is a significant decrease of the LEL from 21% oxygen to 39% oxygen in carbon dioxide. At 49% O2 / 51% CO2 the LEL is only slightly lower to the value in 39% O2 / 61% CO2.

Explosion severity characteristics in oxy-fuel atmospheres

The tests are performed with the dried and sieved < 63 µm fraction of the Sebuku coal in different mixtures of oxygen and carbon dioxide from 20% up to 49% oxygen. The different explosion indices are presented in Table 2. Although Sebuku coal is not explosible in 20% O_2 / 80% CO_2 , see previous section the maximum explosion pressure, 5.3 barg, and maximum rate of pressure rise, 24 bar m/s, can be determined in a mixture of 20% O_2 / 80% CO_2, see Figure 2. This may seem to be a contradiction but it can be explained by the fact that the ignition energy that is used for the determination of the explosibility (2000 J) is lower than the ignition energy (10000 J) that is used for the determination of the explosion severity characteristics.

It can be seen from Table 2 that for increasing oxygen concentration the maximum explosion pressure also increases. The maximum explosion pressure in air, 6.5 barg, corresponds to a value between 20% and 30% oxygen in carbon dioxide, for which the P_{max} is equal to 5.3 barg and 8.0 barg respectively. The K_{St}-value also increases with increasing oxygen concentration. The K_{St}-value obtained in air corresponds well with the value in 30% O_2 / 70% CO_2. At 39% O_2/ 61% CO_2 a maximum explosion pressure of 10.7 barg and a maximum rate of pressure rise K_{St} of 342 bar m/s (St 3) are obtained, see Figure 3 and Figure 4.

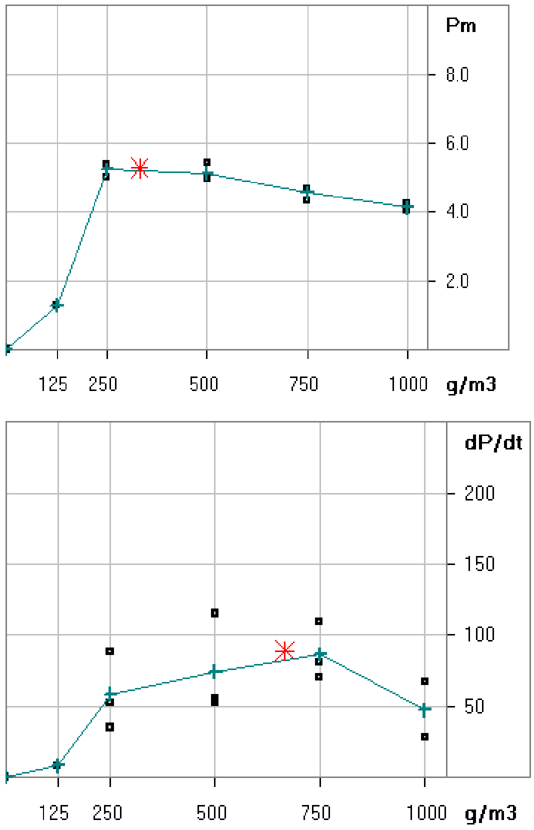

Figure 2: The explosion pressure and the maximum rate of pressure rise in 20% O_2/ 80% CO_2

	Sebuku coal					
	AIR	AIR (Dried)	20% O_2 / 80 % CO_2	30% O_2 / 70 % CO_2	39% O_2 / 61 % CO_2	49% O_2 / 51 % CO_2
LEL [g/m³]	60	40	Not explosible (2000 J)	90	40	30
P_{max} [barg]	6.6	6.5	5.3	8.0	10.7	12.2
$(dP/dt)_{max}$ [bar/s]	418	493	89	479	1259	1868
K_{St} [bar.m/s]	114 (St 1)	134 (St 1)	24 (St 1)	130 (St 1)	342 (St 3)	507 (St 3)

Table 2: The explosion indices in oxy-fuel atmospheres

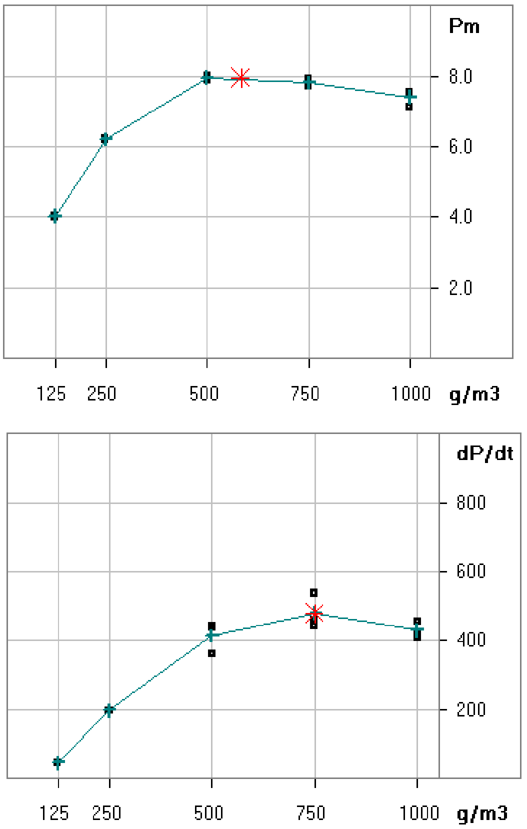

Figure 3: The explosion pressure and the maximum rate of pressure rise in 30% O_2/ 70% CO_2

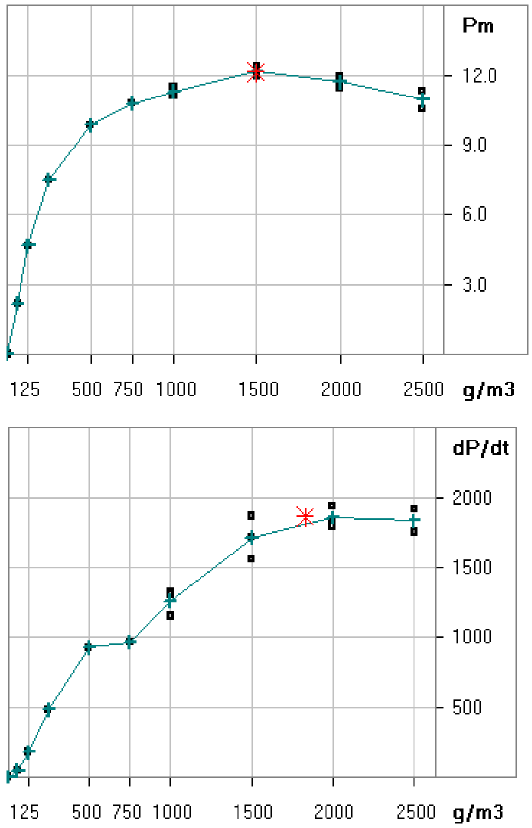

Figure 5: The explosion pressure and the maximum rate of pressure rise in 49% O_2/ 51% CO_2

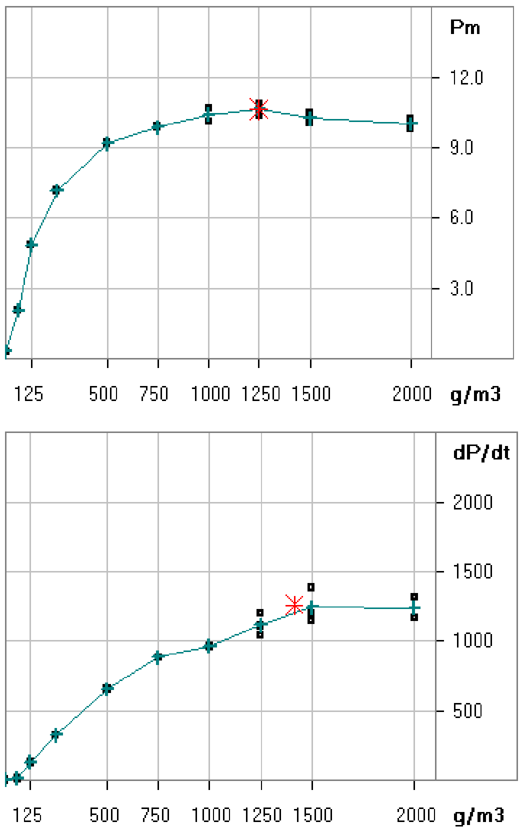

Figure 4: The explosion pressure and the maximum rate of pressure rise in 39% O_2/ 61% CO_2

At 49% O_2 / 51% CO_2 a maximum explosion pressure of 12.2 barg and a maximum rate of pressure rise K_{St} of 1868 bar/s or 507 bar m/s are obtained, see Figure 5. It can also be seen that the maximum pressure is obtained at a concentration of 1500 g/m³ and the maximum rate of pressure rise is obtained at 2000 g/m³, while in air the optimal concentrations for P_{max} and K_{St} are 500 g/m³. This can be explained by the fact that for higher oxygen concentrations the “stoichiometric” dust concentration increases.

In order to research the influence of the ignition source, the two chemical ignitors were replaced by a spark ignition from a high voltage ignition source (15 kV). This spark ignition has an equivalent ignition energy of about 10 J according VDI 2263, Blatt 1 [4], which is much lower than the 10000 J of the two pyrotechnic igniters. The following characteristics were determined for the “Sebuku Coal (dried and sieved < 63 µm)” in the 20-l sphere with the spark ignition in a mixture of 50% O_2 / 50% CO_2, see Figure 6:

max. explosion pressure:	11.9 barg
max. rate of pressure rise (20 l):	1356 bar/s
KSt-value:	368 bar.m/s
dust explosion class:	ST 3

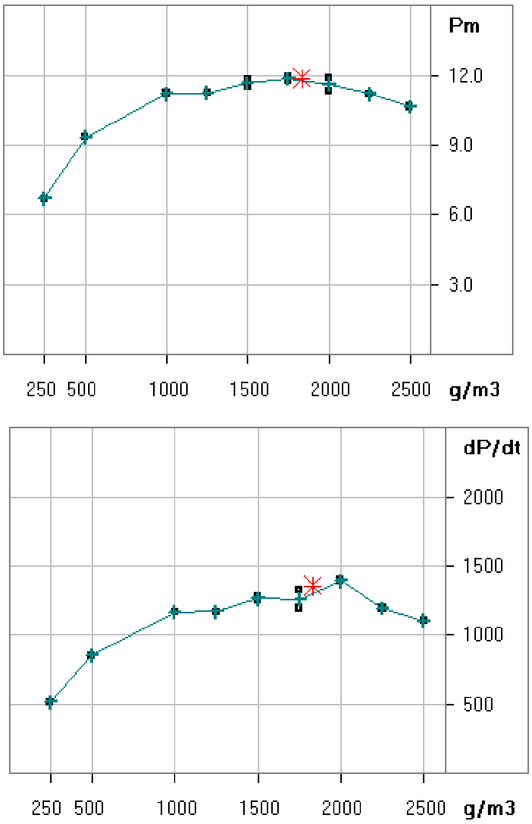

Figure 6: The explosion pressure and the maximum rate of pressure rise in 50% O_2/ 50% CO_2 with spark ignition

It can be concluded that the maximum explosion pressure is not influenced by the used ignition source, while the obtained K_{St}-value is significantly lower when a spark ignition is applied, 368 bar m/s instead of 507 bar m/s. This can be explained by the higher ignition energy and the higher initial turbulence caused by the pyrotechnic igniters, which increase the flame speed and consequently the K_{St}-value.

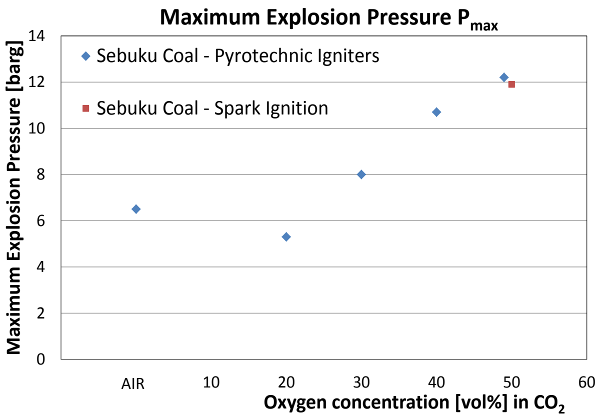

Figure 6: The maximum explosion pressures in function of the gas mixture concentration

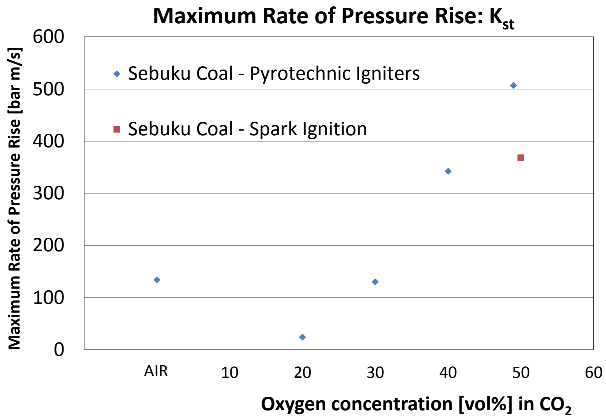

Figure 7: The maximum rate of pressure rise K_{St} in function of the gas mixture concentration

Discussion and conclusions

As can be seen from Figure 6 and Figure 7, the maximum explosion pressure and the maximum rate of pressure rise are strongly dependent on the oxygen concentration. The maximum explosion pressure obtained in air corresponds with a value between 20 and 30 % oxygen in carbon dioxide. The maximum explosion pressure increases almost linearly with increasing oxygen concentration. The maximum rate of pressure rise in air corresponds with the value obtained in about 30% O_2 in CO_2. This can be explained by the higher heat capacity of CO_2 than that of N_2. Man and Gibbens [8] studied the ignitability in a 20l explosion bomb under oxy-fuel conditions and concluded that the concentration of O_2 in CO_2 that gave a similar ignition comparable to that in air lies between 30 and 35%, which corresponds well with the observations in this study. The maximum rate of pressure rise increases almost more than linearly with increasing oxygen concentration.

For the primary prevention or the elimination of flammable dust mixtures in oxy-fuel atmospheres the O_2-concentration must be kept lower than 20%, which is the LOC of the Sebuku coal in CO_2-mixtures. As long as the O_2-concentration is lower than 25-30% in CO_2, the constructive measures calculated for coal dust in air are still valid. Only the maximum explosion pressure is 23% higher for the 30% O_2/ 70 CO_2 mixture than in air. For the application of explosion venting as a protective system according to EN 14491:2012 [9], this will lead to the same increase of the surface of the vent area.

In air these coal dusts lead to moderate explosions with K_{St} values below 200 bar m/s, while in 50% O_2 in CO_2 very strong explosions with K_{St}–values of more than 500 bar m/s are obtained. In industry these high K_{St} values are only obtained in air for some metal powders, such as fine Aluminum powder, Magnesium or Phosphorus.

It has also been observed that the applied ignition source has a significant influence on the obtained maximum rate of pressure rise, while the influence on the maximum explosion pressure is minimal.

Acknowledgements

The work reported here is part of the European FP7 project RELCOM (Reliable and Efficient Combustion of Oxygen/Coal/Recycled Flue Gas Mixtures). In this project the full scale deployment of oxy-coal firing is researched both by experimental studies and by combustion modelling.

References

[1] R.K. Eckhoff, Dust Explosions in the Process Industries, 3rded. Gulf Professional Publishing/Elsevier, Boston, MA, 2003

[2] F. Norman; J. Berghmans; F. Verplaetsen, Procedia Engineering 45 (2013) 399-402.

[3] D. Wu, F. Norman, F. Verplaetsen, J. Berghmans E. Van den Bulck, Experimental analysis of minimum ignition temperature of coal dust clouds in oxy-fuel atmospheres. The 6th Clean Coal Technologies Conference, 12-16 May, Thessaloniki, Greece (2013).

[4] VDI 2263 Blatt 1: Staubbrände und Staubexplosionen; Gefahren, Beurteilung, Schutzmaßnahmen; Untersuchungsmethoden zur Ermittlung von sicherheitstechnischen Kenngrößen von Stäuben. Berlin: Beuth Verlag, 1990.

[5] EN 14034-1/2 (2004) European Standard: Determination of the explosion hazards of dust clouds, Determination of the Maximum Explosion Pressure p_{max} of Dust Clouds, European Committee for Standardization, Brussels, Belgium.

[6] EN 14034-2 (2006) European Standard: Determination of the explosion hazards of dust clouds, Determination of the Maximum Rate of Explosion Pressure Rise $(dp/dt)_{max}$ of Dust Clouds, European Committee for Standardization, Brussels, Belgium.

[7] EN 14034-3 (2006) European Standard: Determination of the explosion hazards of dust clouds, Determination of the Lower Explosion Limit of Dust Clouds, European Committee for Standardization, Brussels, Belgium.

[8] C.K. Man and J.R. Gibbins, Factors affecting coal particle ignition under oxyfuel combustion atmospheres. Fuel. 90 (2011) 294-304.

[9] EN 14491 (2012) European Standard: Dust explosion venting protective systems, European Committee for Standardization, Brussels, Belgium.