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Dust Explosion Characteristics of South African Coal in Oxy-Fuel Atmospheres

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Safety is of major importance to facilities and companies working with combustible materials like dust. To reduce the risk associated with dust, we need to assess the risk of explosion. This assessment can be based on the determination of the explosion characteristics of the dust. A fuel such as coal was allowed to combust in oxy-fuel atmospheres (mixtures of oxygen and carbon dioxide). The explosion risk was found to increase especially in oxygen enriched atmospheres with an O_2-concentration greater than 21 %. To determine the explosion characteristics of the bituminous South African coal, experiments were performed with different mixture concentrations of coal, CO_2 and O_2. Measuring the minimum ignition energy (MIE) which is an important ignition sensitivity parameter showed that the MIE decreased significantly when the oxygen concentration in the mixture was increased.
The violence of the explosion, which is a parameter for the explosion severity, is expressed by the maximum rate of pressure rise $(dP/dt)_{max}$ or K_{st}-value. This K_{st} was measured with a standard test apparatus with a content of 20 L using pyrotechnical igniters. This paper also explores the maximum burning velocity which was derived from the pressure histories. In order to achieve the burning velocities, experimental data were analyzed based upon the theoretical model of Dahoe and Van den Bulck. These models were induced by using a two-zone model for the adiabatic combustion in closed vessels. The results revealed that there is a strong relationship between the severity characteristic, the burning velocity and the oxygen concentration. However it was also observed that these coal characteristics were strongly dependent on the dust concentration. Furthermore the burning velocity reached its maximum value when the rate of pressure rise reached its maximum.

1. Introduction

The majorities of the current energy conversion systems utilize fossil fuels and discharge large quantities of carbon dioxide into the atmosphere. One of the biggest concerns in employing fossil fuel is carbon dioxide emission contributing to global warming. Oxy-fuel combustion is one of the most promising technologies for reducing extensive carbon dioxide emissions through carbon capture (Chen, 2012). Nitrogen is removed from the oxidizer in an air separation unit and the pure oxygen mixed with the recycling clean flue gas reaches the boiler (Toftegaard, 2010). Pulverized coal involves much greater reserve and lower cost. It has recently started to be used as an alternative fuel in chemical production plants. Even a fuel such as coal is able to ignite easily through the introduction of CO_2 and O_2 as an oxidizer when the concentration of O_2 is greater than 21 %. Better insights into the complex process of coal can be provided through identifying combustion characteristics in oxy-fuel atmosphere. It is acknowledged that the sensitivity of ignition is dependent on the minimum ignition energy, minimum ignition temperature and minimum explosible concentration, while the severity of explosion can be thought of in terms of maximum explosion pressure and maximum rate of pressure rise (Cashdollar, 1996). The minimum ignition energy (MIE) is the main ignition sensitivity parameter.

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The first part of this paper focuses on the MIE of South African coal in oxy-fuel atmospheres. The minimum ignition energy is the lowest energy value of the high-voltage capacitor discharge required to ignite a dust mixture. Many researchers have carried out investigations on different sorts of coal, however there are only a few studies concentrating on the bituminous South African coal. Our previous study (2014) investigated the MIE of South African coal, which determined that South African coal does not ignite with the maximum energy (1000 mJ) of the MIKE3-apparatus in air mixture. Norman (2013) examined the influence of enriched oxygen concentration on explosion characteristics of two other coals. His results indicated that the ignition sensitivity in a 30 vol% in CO_2 mixture is in good accordance with the ignition sensitivity in air. Khatami (2012) also considered the ignition characteristic and ignition delay of single coal in different fractions of O_2/N_2 and CO_2/O_2. The severity of combustion attributing to the maximum pressure and maximum rate of pressure rise was studied in the second part. These features for dusts were determined in closed standard equipment (1 m^3 vessel and 20 L vessel) over a wide concentration range. Nevertheless, because of the cooling effect of the 20 L vessel, the given explosion pressure was slightly lower than the one measured in the 1 m^3 vessel. Thus the more usual size was the 20 L vessel. Finally, the burning velocity was computed based on available methods presented by Dahoe (1996), Cashdollar (2000) and Van den Bulck (2005). In this paper, the impact of oxy-fuel atmosphere on ignition characteristics of South African coal has been explored. In addition, the maximum burning velocities were analyzed based on established theoretical methods.

2. Experimental Approaches

2.1 Material tested

As far as the particle size has a significant role in explosion characteristics, the South African coal was milled and sieved. The median value of the particle size distribution that was measured by the laser diffraction analysis was 15 µm. The proximate and ultimate analysis determined is given in Table 1.

Table 1: Properties of the South African Coal

Proximate analysis (wt. %)	South African
Fixed carbon	56.6
Volatile material	27.1
Moisture content	2.1
Ash	14.2
Ultimate analysis (%)	
Carbon	67.5
Hydrogen	4.26
Nitrogen	1.76
Oxygen (by difference)	26.48
Gross calorific value (MJ/kg)	27.37

2.2 Ignition sensitivity

One of the most important parameters to determine the ignition sensitivity is the minimum ignition energy which is influenced by several factors such as moisture, ignition delay time and dust concentration. Dust concentration and ignition delay time had to be systematically varied until a minimum value for the ignition energy was detected. The minimum ignition energy was measured by using an electrical spark igniter (MIKE 3 apparatus from KUNHER) and a modified Hartmann tube, following the method defined in the standard EN 13821 (Cesana & Siwek, 2001).

2.3 Ignition severity

The severity of explosion is defined by the maximum explosion pressure (P_{max}) and maximum rate of pressure rise $(dP/dt)_{max}$. These parameters were measured by means of a standardized test sphere with a volume of 20 L in accordance with the EN 14034-1and 2 (EN 14034-2, 2011). The ignition delay was at set 60 ms which is standard for the 20L-sphere test. The ignition source located in the center of the explosion vessel consisted of two chemical igniters each having energy of 5 kJ. K_{st}, the dust deflagration index, measures the relative explosion severity compared to other dusts. The K_{st} value shown in Eq(1), can be used to calculate the maximum rate of pressure rise $(dP/dt)_{max}$ for different volumes through the cubic law:

$$K_{St} = V^{1/3}(\frac{dP}{dt})_{max} \quad (1)$$

In order to achieve the burning velocity, experimental data were analyzed by established theoretical methods. Theoretical methods relying on maximum pressure and K_{st} were based on the adiabatic combustion such as the two zone model presented by Lewis (1951). Dahoe (1996) proposed a theoretical expression for the time derivate of the vessel pressure for central ignition in a spherical vessel:

$$\frac{dP}{dt} = \frac{3(P_{max}-P_0)}{R}[1-(\frac{P_0}{P})^{1/\gamma}\frac{P_{max}-P}{P_{max}-P_0}]^{2/3}(\frac{P}{P_0})^{1/\gamma}S_u \quad (2)$$

Theoretically, the highest rate of pressure rise, $(dP/dt)_{max}$, should occur when the pressure attained its maximum value, P_{max}; however, pressure-time curve for the dust explosion vessel exhibited an inflection point. The most accepted explanation for this phenomenon is that after ignition the spherical flame will propagate till flame reaches the vessel wall. The following expression was found for the K_{st}:

$$K_{st} = (36\pi)^{1/3}(P_{max}-P_0)(\frac{P_{max}}{P_0})^{1/\gamma}S_u \quad (3)$$

where P_{max} and P_0, respectively, are the maximum and the initial pressure inside the combustion vessel, γ is the specific heat ratio of unburned reactants and S_u is the burning velocity at maximum pressure. The model of Dahoe is based on the assumption that specific heat of both unburnt and burnt mixture remains constant. Furthermore, Cashdollar (2000) provided a simpler expression which does not take into account γ .

$$K_{max} = 4.84(P_{max}-P_0)\frac{P_{max}}{P_0}S_u \quad (4)$$

In addition, Van den Bulck (2005) introduced an algebraic expression formulated in terms of mean specific heat ratio of the unburnt reactant (γ) and burnt product (g_b)

$$K_{max} = 4.836g_b[(\frac{P_{max}}{P_0})^{1/\gamma}-1]P_{max}S_u \quad (5)$$

To simplify the formula, the mean value for specific heat ratio of burnt product (g_b) and unburnt product (γ) come across computing different type of gas fuel, assumed being equal to 1.09 and 1.33 respectively.

$$K_{max} = \frac{4.836}{0.9}[(\frac{P_{max}}{P_0})^{1/1.33}-1]P_{max}S_u \quad (6)$$

3. Results and discussion

3.1 The effect of oxy-fuel atmosphere on minimum ignition energy

The experiments were carried out to determine the minimum ignition energy (MIE) of South African in oxy-fuel atmosphere, with the oxygen mole fraction in the range of (20-50 %). As the minimum ignition energy with inductance in the discharge circuit was more conservative than the minimum lowest ignition energy determined without inductance, all tests were performed with an inductance of 1 mH. The results are depicted in Figure 1. The MIE could not be determined with Mike 3 in a 20 vol% O_2 in CO_2, because the coal mixture cannot be ignited with the highest energy of 1000 mJ. It can be seen that the MIE is strongly affected by the oxygen concentration. Furthermore, it can be clearly realized that MIE decreased significantly with increasing oxygen concentration. Indeed it was observed that the MIE decreased from 840 mJ in a 30 vol% to 14 mJ and 2.5 mJ in 40 vol% and 50 vol% O_2 respectively. In conclusion, South African coal know to be non-sensitive in air for electrostatic ignition, becomes extremely sensitive through the introduction of enriched O_2 - CO_2 atmospheres with more than 30 % oxygen.

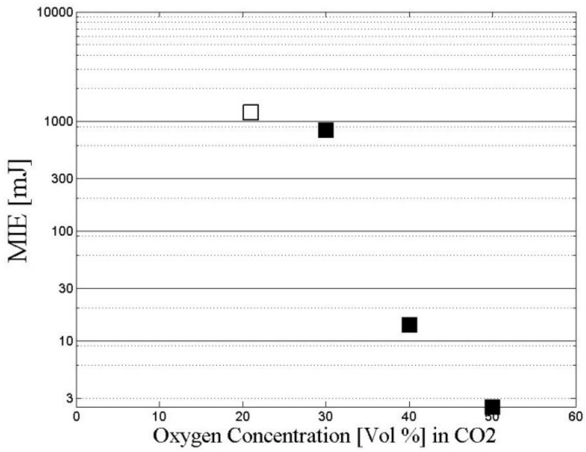

Figure 1: Influence of oxygen concentration on minimum ignition energy of South African coal

3.2 The explosion severity characteristics in oxy-fuel atmospheres

Figures 2 and 3 represent and compare the influence of enriched oxygen on the maximum pressure and maximum rate of pressure rise in 20 L vessel. According to the standard procedure, three test series were carried out. It was found that both P_{max} and $(dP/dt)_{max}$ were strongly dependent on the powder concentration. The optimal concentration or the concentration with the highest P_{max} and $(dP/dt)_{max}$ was also dependent on the oxygen concentration. It was observed that for the 39 vol% O_2 in CO_2 mixture the maximum pressure and maximum rate of pressure rise, 9.9 bar and 905 bar/s were obtained at a concentration of 1000 g/m³. For the 51 vol% O_2 in CO_2 mixture, these values increased to 12.3 bar and 1984 bar /s. This corresponds with a K_{st}-value of 246 bar m/s and 538 bar m/s at 39 vol% O_2 and 51 vol% O_2 respectively. The maximum pressure was obtained at a concentration of 1250 g/m³, while the maximum rate of pressure rise was obtained at a much higher concentration of 2500 g/m³.

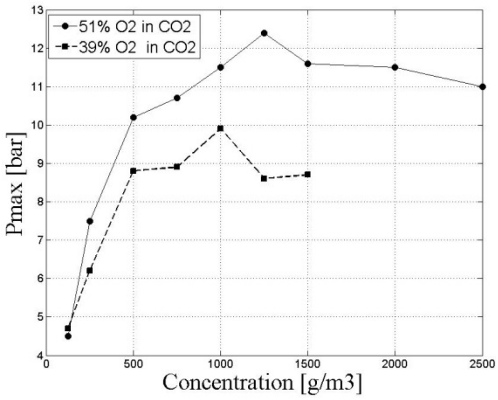

Figure 2: The maximum pressure P_{max} as a function of the South African coal concentration

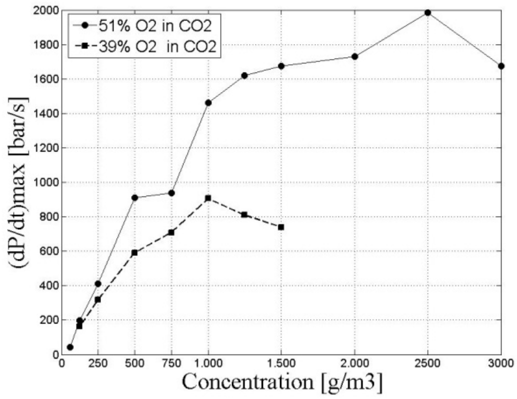

Figure 3: The maximum rate of pressure rise $(dP/dt)_{max}$ as a function of the South African coal concentration

As mentioned before, the burning velocity depends strongly on the shape of the vessel the effect of which is defined by K_{st} value. Figure 4 shows the effect of oxygen level on burning velocity based upon the established methods. It is clear that the burning velocity follows the same trend as the maximum rate of pressure rise. In addition, the burning velocity is also significantly dependent on the O_2-concentration, such as the previous parameters. The maximum burning velocity was 1.75 m/s in 50 % O_2 in CO_2 at a dust concentration of 2000 g/m³, whereas for mixtures of 39 % O_2 the maximum value was 0.95 m/s at a dust concentration of 1000 g/m³.

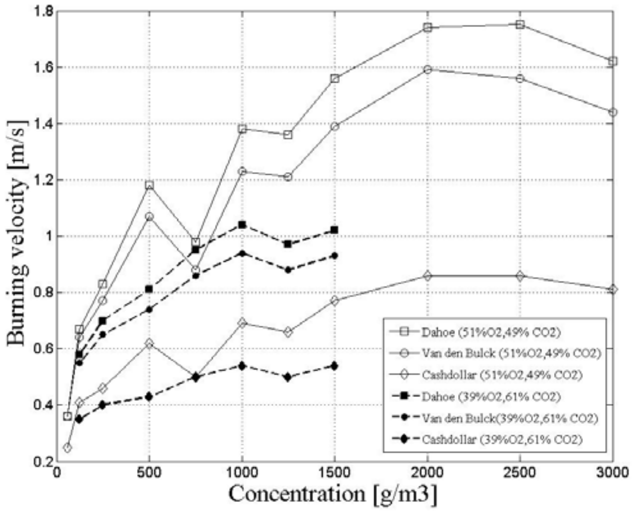

Figure 4: Comparison of the burning velocities of South African coal in Oxy-fuel atmospheres

It can be seen that the Dahoe method produced higher values for average burning velocities in comparison with the methods of Van den Bulck and Cashdollar. The difference observed between the data of Dahoe and Van den Bulck arises from the inequality of the specific heat ratio of the unburnt reactants and the burnt products. Meanwhile in the Dahoe method this value for reactant and product was considered 1.4. Also this discrepancy increases markedly when the burning velocity is calculated using the Cashdollar expressions. The reason for this underestimation is due to the omission of γ .

4. Conclusions

A series of experiments were carried out to study the impact of oxygen enriched atmosphere on explosion characteristics of South African coal. The burning velocity for different oxy-fuel conditions was derived from different methods. It was observed that the characteristics of coal are to a large extent dependent on the fraction of oxygen concentration. It has been shown that the burning velocity depends significantly on the concentration of the dust and also on the fraction of oxygen in the mixture. As well it can be derived that the Cashdollar expression provides less reliable burning velocities in comparison with the Van den Bulck and Dahoe theoretical methods.

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