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Effects of ignition energy on fire and explosion characteristics of dilute hybrid fuel in ventilation air methane

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ABSTRACT

Deflagration explosions of coal dust clouds and flammable gases are a major safety concern in coal mining industry. Accidental fire and explosion caused by coal dust cloud can impose substantial losses and damages to people and properties in underground coal mines. Hybrid mixtures of methane and coal dust have the potential to reduce the minimum activation energy of a combustion reaction. In this study the Minimum Explosion Concentration (MEC), Over Pressure Rise (OPR), deflagration index for gas and dust hybrid mixtures (K_{st}) and explosive region of hybrid fuel mixtures present in Ventilation Air Methane (VAM) were investigated. Experiments were carried out according to the ASTM E1226-12 guideline utilising a 20 L spherical shape apparatus specifically designed for this purpose.

Results: obtained from this study have shown that the presence of methane significantly affects explosion characteristics of coal dust clouds. Dilute concentrations of methane, 0.75–1.25%, resulted in coal dust clouds OPR increasing from 0.3 bar to 2.2 bar and boosting the K_{st} value from 10 bar m s^{-1} to 25 bar m s^{-1}. The explosion characteristics were also affected by the ignitors' energy; for instance, for a coal dust cloud concentration of 50 g m^{-3} the OPR recorded was 0.09 bar when a 1 kJ chemical ignitor was used, while, 0.75 bar (OPR) was recorded when a 10 kJ chemical ignitor was used.

For the first time, new explosion regions were identified for diluted methane-coal dust cloud mixtures when using 1, 5 and 10 kJ ignitors. Finally, the Le-Chatelier mixing rule was modified to predict the lower explosion limit of methane-coal dust cloud hybrid mixtures considering the energy of the ignitors.

1. Introduction

The most common dust explosion occurs in underground coal mines. In coal mine tunnel, coal dust explosion is usually caused by gas explosion. Moving at the speed of sound, the pressure wave resulting from the gas explosion lifts the deposited coal dust in the air. Then the gas flame reaches the coal dust causing a dust explosion which is more severe than the first one (Beidaghy Dizaji et al., 2014; Bidabadi et al., 2015, 2014, 2013; Soltaninejad et al., 2015). Between the years 1780 and 2012, over 2000 reported accidents were caused by dust explosions worldwide. These caused significant loss of life, property and environments impacts (Yuan et al., 2015).

Addressing the hazards of coal dust and methane are important factors for identifying the limits and severity of explosions (Coward and Jones, 1952). According to Eckhoff, 2003, the dust explosion elevation depends on essential factors such as: dust composition, the percentage and type of oxidizer, ignition source, dust concentrations and dispersing velocity.

In the 1930s, the first standard for dust explosibility tests, the Hartman apparatus, was developed at the US Bureau Institute of Mines. It was observed that flammable gases mixing with clouds of ignitable dusts, even at concentrations below the Lower Flammable Limit (LFL) of gases, could enhance the explosion of dust clouds (Amyotte et al., 1991). Indeed, the type and property of the dust is limiting the influence of dust in hybrid mixture explosion. On one hand, for a dust like cork, It has proven the cork dust works as an inert and cause increase the Lower Flammable Limit (LFL) of flammable gases (Pilão et al., 2006). Jiang et al. (2014), also shows that the niacin and cornstarch increase the LFL of methane and/or ethane. On the other hand, it had been experimentally proven that the coal dust reducing the LFL of flammable gas (i.e. methane) (Bartknecht, 1981; Benedetto et al., 2012; Dufaud et al., 2008; Garcia-Agreda et al., 2011; Landman, 1995).

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Many researchers have investigated the effects of the presence of methane on coal dust cloud explosions to understand the ignition and explosion properties of such hybrid mixtures.

The effect of ignition energy on the explosion characteristics of coal dust has been studied by a number of people. Hertzberg et al., 1988 studied the characteristics of Pittsburgh seam coal dust (particle size minus 74 μm) using a 20 L apparatus; specifically, P_{max} (Maximum Pressure Rise) and K_{st} of the coal dust. Coal dust concentrations ranging from 50 to 1000 g m^{-3} were ignited at four ignition energies (0.5, 1, 2, 2.5 and 5 kJ). The results revealed that the Minimum Explosion Concentration (MEC) values measured were below 200 g m^{-3}. Also, MEC values changed with the strength of the ignitor; the Lower Explosive Limit (LEL) for the dust cloud decreased as the strength of the ignitors increased. The K_{st} values ranged between 20 m/s to 40 m/s depending on the strength of the ignitors for concentrations below 500 g m^{-3}. K_{st} values were unaffected for concentrations higher than 500 g m^{-3} (Hertzberg et al., 1988).

Yuan et al., 2012 used a 20 L apparatus to determine the MEC for a given ignition energy. They observed that the volatile matter content has a significant impact on the MEC of coal dust. The MEC noticeably reduces for coal dust with higher volatile matter. In another study Cashdollar, 2000 determined that the effect of particle size is at least as important as that of volatile compounds. In this study he used Pittsburgh and Pocahontas coals of particle size below 74 μm. It was revealed that the MEC was within the range of 75–200 g m^{-3}. Moreover, it was observed that the pressure rise and the deflagration index reduced sharply for concentrations below 200 g m^{-3}.

In similar study by Kuai et al., 2013, it was concluded that ignition of carbonaceous dust (including coal dust cloud) significantly depends on ignition energy. In addition, he determined that low energy ignition sources could cause under-driving phenomena which may not give accurate results on MEC.

In VAM systems, the presence of methane gas and coal dust mixtures may enhance the explosivity of coal dust. Torrent and Fuchs, 1989 was the first to test a hybrid (coal dust-methane) mixture in a 20 L vessel. He found that 3% of methane could increase the maximum explosion pressure about 33%. Landman, 1995 used a 40 L explosion vessel to examine the effect of methane on coal dust explosions. A 4% methane-air mixture was mixed with 500 g/m^3 coal dust. They concluded that the presence of methane increases the risk of explosion of the mixture.

A modified 20 L apparatus with 2.5 kJ chemical ignitors was used by Cashdollar, 1996. The purpose of this study was to identify the explosive regions for coal dust-methane hybrid mixtures (1.5%

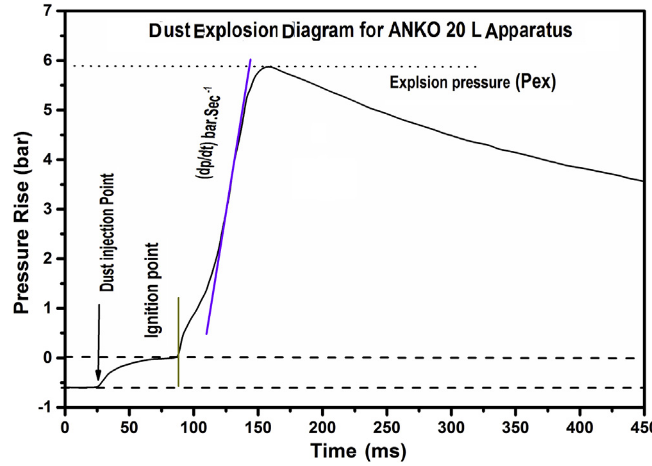

Fig. 2. Typical explosion time-pressure diagram as in ANKO program for 20 L apparatus (Yuan et al., 2014).

and 2.5% of methane). Cashdollar showed how these methane concentrations could reduce the MEC of a coal dust cloud. On the other hand, Bai et al., 2011 studied the over pressure and flame propagation of methane-coal dust/air mixtures using a 20 L apparatus with methane concentrations ranging from 4.5% to 8% and coal dust concentrations ranging from 25 to 70 g m^{-3} Li et al., 2012, also investigated the effects of methane concentration on coal dust cloud explosions. A 20 L apparatus with 10 kJ chemical ignitors was used. Three coal dust samples of different rank were used (anthracite, bituminous and lignite) with coal dust concentrations ranging from 50 to 500 g m^{-3} and for methane gas concentrations ranging from 5% to 12.5%. When 5% methane was added to 125 g m^{-3} of coal dust, the pressure increased from 6.75 bar to 8.4 bar, and the deflagration index increased from 22 bar m s^{-1} to 62 bar m s^{-1}. Adding 12.5% methane to the same coal dust concentration (125 g m^{-3}), the pressure rose from 6.75 to 8.4 bar, and the deflagration index rose from 22 bar m s^{-1} to 85 bar m s^{-1} (Li et al., 2012).

In a similar study by Xu et al., 2012 he used a lower methane concentration (3%) mixture with coal dust (100–700 g m^{-3}) to investigate the maximum explosion pressure. He concluded that the pressure rise (PR) of explosion decreased as the diameter of the coal dust particles increased. Moreover, with agreement from previous studies, there was an optimum concentration at which the peak of explosion pressure was obtained (maximum explosion

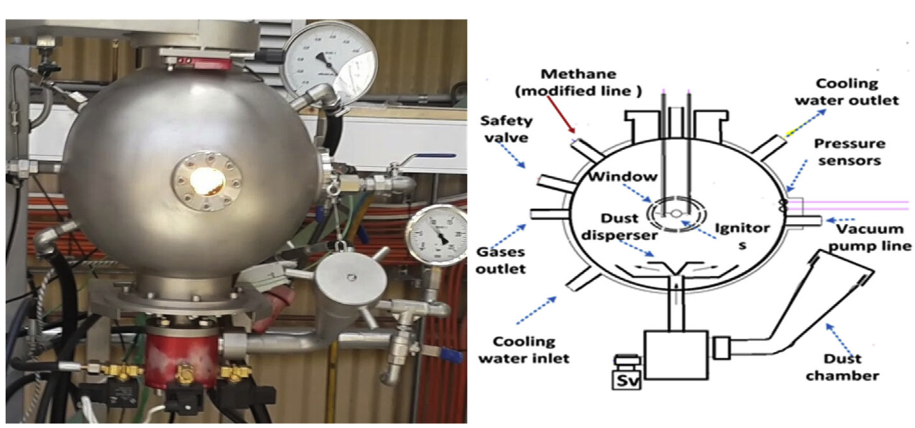

Fig. 1. Vertical cross section of 20 L dust explosion chamber.