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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% 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).

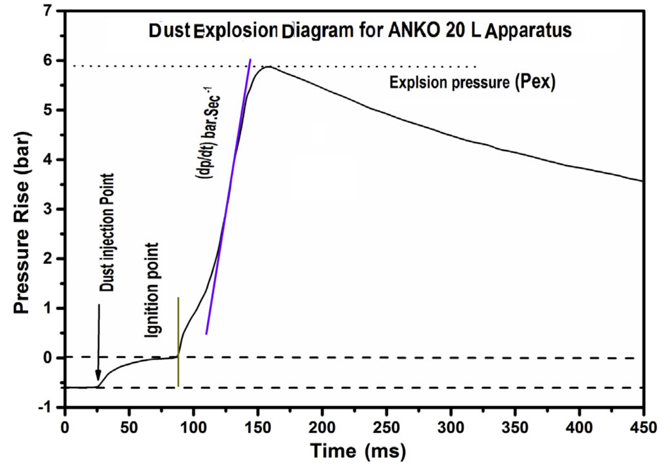

Fig. 2. Typical explosion time-pressure diagram as in ANKO program for 20 L apparatus (Yuan et al., 2014).

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

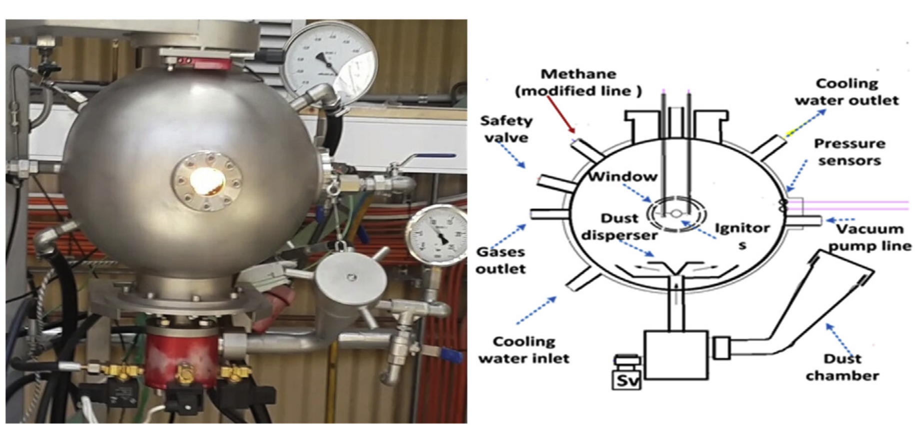

Fig. 1. Vertical cross section of 20 L dust explosion chamber.

Table 1
Proximate and particle size distrbution (PSD).

Carbon %	Moisture %	Ash %	Volatile matter %	D_{90} (μm)	D_{50} (μm)	D_{10} (μm)
56.9	1.1	10.3	31.7	111.93	29.91	4.5

pressure). Finally, for coal dust concentrations of 200, 300 and 400 g m^{-3} mixed with methane of varying concentrations, it was observed that the explosion pressure and the maximum rate of overpressure increased as the concentration of methane increased (Xu et al., 2012).

Despite the large number of studies conducted in the past in the field of coal dust cloud explosions (Bai et al., 2011; Cashdollar and Hertzberg, 1985; Cashdollar, 1996; Coward and Jones, 1952; Eggleston and Pryor, 1967; Hertzberg et al., 1988, 1981; Kuai et al. (2013); Landman, 1995; Li et al., 2012; Siwek, 1977; Torrent and Fuchs, 1989; Xu et al. (2012); Yuan et al., 2012) however, there is not much information available in open literature to address the effects of dilute methane, typically found in ventilation air methane, on coal dust cloud explosion properties. To address this short coming a comprehensive set of experiments were conducted at the University of Newcastle–Australia. This study aimed to investigate the effects of dilute methane concentrations, present in VAM, on the characteristics of coal dust cloud explosions such as (MEC), Pressure Rise (PR) and deflagration index (K_{st}).

2. Experimental setup and instrumentation

Figs. 1 and 2 show the 20 L dust explosion apparatus used in this study. The vessel includes pressure transducers, thermocouples, data acquisition, vacuum and pressurising systems, cooling system as well as remote control and operating system. The reaction and explosion occurs in the stainless steel spherical chamber, capable of handling 21 bar. A viewing port on the vessel was used to record the ignition and explosion inside the chamber with a high speed camera (Phantom 4, Black and white, 2000 fps).

The coal dust samples used in this study were obtained from a coal mine located in NSW, Australia. The samples were kept in air-sealed containers and stored in cool conditions (3 °C) to reduce any further oxidation. Representative sub-samples were despatched to external NATA accredited laboratories for proximate and PSD analyses. The results directly reported by the laboratory are shown in Table 1.

where, D_{50} is the particle size such that 50% of the distribution is less than this size. This could also be considered the median diameter. D_{90} is the particle size such that 90% of the distribution is less than this size. D_{10} is the particle size such that 10% of the distribution is less than this size.

Chemical ignitors with different energy levels of 1, 5 and 10 kJ were used to initiate the coal dust and methane. Instrument air was used to minimise the effects of moisture and any impurities associated with air on the coal dust-methane hybrid mixture explosion properties.

The coal dust was dispersed in the vessel by triggering a remote control unit. The ignitors are energized 88 ms after the dispersion process (as shown in Fig. 2). Three explosion parameters were determined, namely Minimum Explosion Concentration (MEC), Over Pressure Rise (OPR) and deflagration index (K_{st}). Fig. 2 shows a typical explosion time-pressure relationship diagram for the experimental apparatus.

The experiments were carried out and the parameters were measured and calculated according to ASTM E1226 (ASTM Standard, 2014) standard. Each experiment was repeated three times to ensure reproducibility of the obtained results.

The minimum concentration adequate for an explosion is determined by examining the pressure data from each run. A rapid increase in pressure is indicative of an explosion. The maximum rate of pressure increase from an explosion is expressed as the tangent of pressure rise as indicated in Fig. 2. Deflagration index (K_{st}), bar.m^3.s^{-1}, is the normalized pressure rise to 1 m^3, and is calculated from the following equation.

$$K_{st} = \left(\frac{dp}{dt}\right)_{\max} \cdot V^{\left(\frac{1}{3}\right)} \quad (1)$$

where $(dp/dt)_{max}$ is the maximum rate of pressure rise of a single explosion, bar.s^{-1}; and V is the volume of the explosion chamber, m^3.

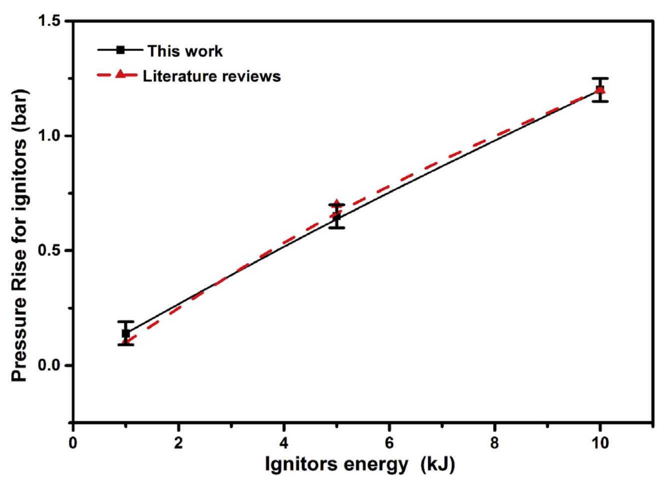

Fig. 3. Comparison of ignitors' pressure rise of this work with literature review (Cashdollar, 1996; Kuai et al., 2011).

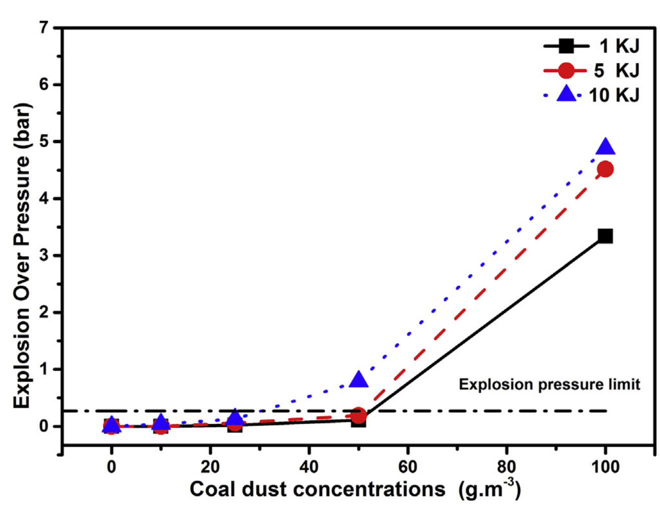

Fig. 4. MEC of coal dust (Mine B sample) with three different energy chemical ignitors.

Table 2
The OPR in open literature review for 100 g.m^{-3}coal dust.

Authors	Ignitor energy (kJ)	OPR (bar)
(Amyotte et al., 1991; Cashdollar, 1996; Mittal, 2013)	1	3.3, 3.5, 3.9 respectively
(Amyotte et al., 1991; Hertzberg et al., 1988)	5	4.5, 4.1 respectively
(Going et al., 2000)	10	5.7

3. Results and discussion

3.1. Ignitors' energy

The ignition source is a crucial factor in fires and explosions. The hot surface, single particles ignition, flame, shock wave, electrostatic energy and electrical current are all potential ignition sources (Landman, 1995; Parnell et al., 2013; Thomas et al., 2013; Xie et al., 2012). In a VAM capture duct the methane gas and coal dust particles are the hazardous fuel. Explosions are limited to the rate of energy or heat transferred to the hybrid mixture. In addition, it has been proven that the minimum explosion limit for gases and dust reduces with increasing energy of ignition sources (Landman, 1995; Parnell et al., 2013; Thomas et al., 2013; Xie et al., 2012). Therefore, understanding the effect on ignition energy on dilute methane–coal dust hybrid mixtures is essential to address and eliminate the explosion hazards in VAM capture ducts. To consider and evaluate the potential hazard of ignition energy, three ignition energies (1, 5 and 10 kJ) were used.

These ignitors had been detonated in the system without fuel for two goals. The first goal is identifying the pressure rise caused by ignitors and the maximum pressure rise to determine the Over Pressure Rise (OPR), from the following equation.

$$OPR = P_{ex} - P_{ignitors} \tag{2}$$

where $P_{ignitors}$ represent the pressure rise of ignitors, bar; and P_{ex} represent the pressure rise of the single test, bar. The second goal is checking the validity of the system by comparing experimental data with literature sources (see Fig. 3).

It was found that there is a good agreement with work that had been done by Cashdollar, 1996; Kuai et al., 2011. The small deviation between this work and the literature value for pressure rise at 5 kJ is likely due to the position or direction of ignitors toward the

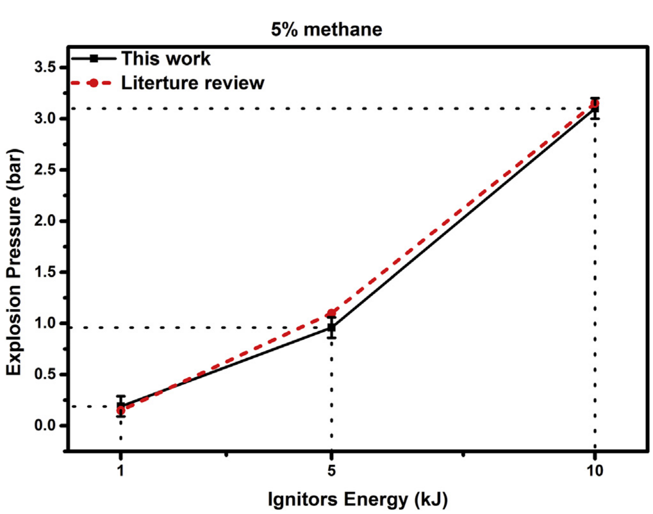

Fig. 5. Comparison of a 5% methane explosion pressure with literature review (Cashdollar and Hertzberg, 1985).

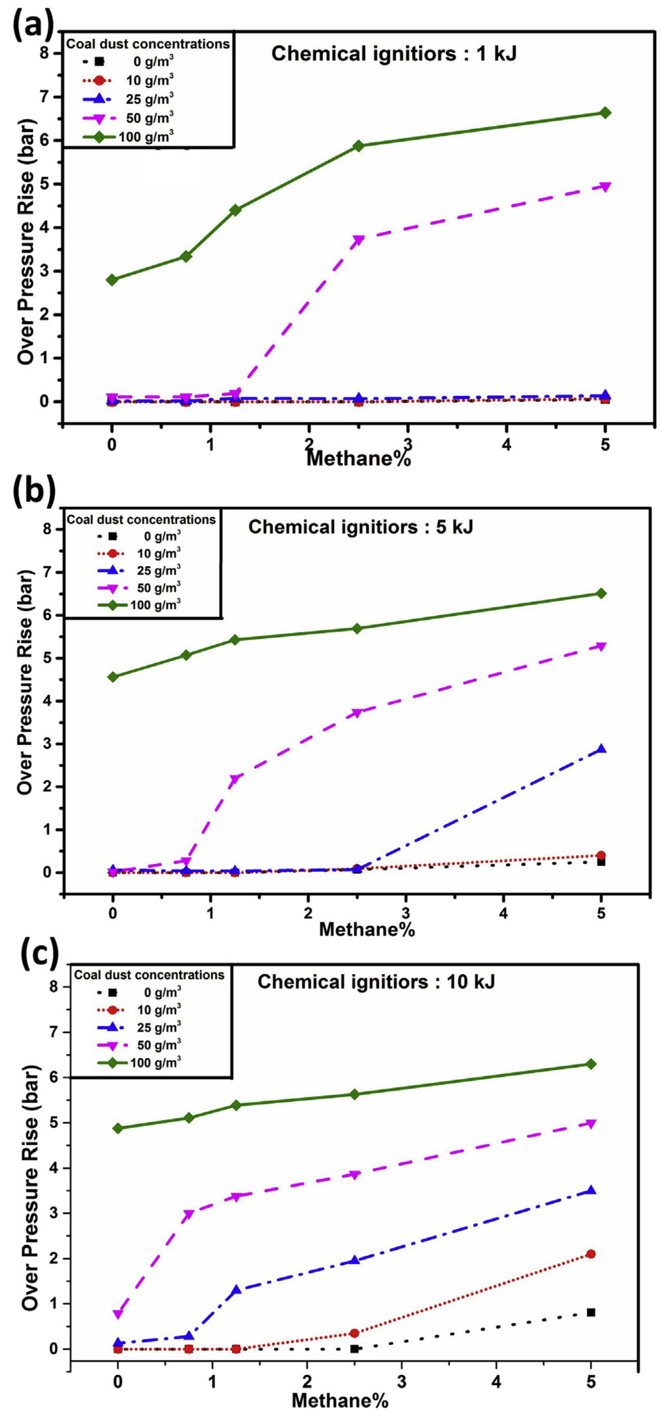

Fig. 6. OPR for hybrid coal dust methane mixture using (a) 1 kJ ignitors, (b) 5 kJ ignitors, (c) 10 kJ ignitors.

pressure transducer. For the 10 kJ ignitor, exactly the same value was obtained as in literature (Cashdollar, 1996; Kuai et al., 2011).

3.2. Coal dust over pressure explosions

As mentioned previously, the concentration of coal dust in a VAM capture duct is typically in the range below 50 g m^{-3} low. Thus dilute concentrations of coal dust cloud were used for this study (10, 25, 50 and 100 g m^{-3}). A plot of explosion OPR vs coal dust concentration at each of the three ignitor energies (1, 5 and 10 kJ) are shown in Fig. 4.

As expected, there was no change in pressure at a coal dust concentration of 10 g m^{-3}, implying that no explosion occurred inside the vessel. At a coal dust concentration of 25 g m^{-3}, the over pressure rise was slightly higher for the 10 kJ ignitors as compared to the 1 kJ and 5 kJ ignitors at the same concentration. This may be due to transport of the flame inside the vessel; however the concentration was not high enough to reach the LEL. At a coal dust concentration of 50 g m^{-3}, an OPR of 0.79 bar was recorded for the 10 kJ ignitor and a 0.21 bar OPR was recorded for the 5 kJ ignitor, while only 0.11 bar OPR was recorded for the 1 kJ ignitor. Over 100 Explosions were observed through the sight glass of the 20 L apparatus.

At 100 g m^{-3} a significant change in pressure was recorded at each of the three ignitor energies. These results were in good agreement with studies done by other researchers investigating the MEC of coal dust (see Table 2).

3.3. Methane explosions

Variable dilute methane-air mixtures were injected into the 20 L apparatus via the modified methane line. Methane concentration of 5% was used. The results are shown in Fig. 5 below:

As expected, there was no explosion or pressure rise below a concentration of 5% methane. The pressure rise values for all three experiment were in good agreement with findings of Cashdollar and Hertzberg, 1985.

3.4. Over pressure rise for hybrid mixture

Sudden liberation of energy from the air-methane and/or coal dust hybrid mixture reaction results in a rapid pressure and temperature rise in the process. If not treated properly by a proactive safety measure i.e. a venting system, it may lead to some unexpected consequences such as property damage or system failure.

Accordingly, a series of tests were carried out to examine the Over Pressure Rise (OPR) resulting from the explosions of hybrid mixtures of coal dust and dilute concentrations of methane in air (lean limit). In addition, the effect of ignition source energy on OPR was investigated.

Concentrations of 0, 0.75, 1.25, 2.5 and 5% methane gas in air were mixed with coal dust of concentrations of 0, 10, 25, 50 and 100 g m^{-3}. The hybrid mixtures were ignited using 1, 5 and 10 kJ chemical ignitors. The variation of OPR with coal dust concentrations at various methane concentrations for the different ignitor energies is shown in Fig. 6a, b and c.

The OPR for hybrid mixtures at 1 kJ ignitor energy is shown in Fig. 6a. No change in the OPR at 10 g m^{-3} was observed, and only a slight rise in OPR at 25 g m^{-3} was observed. On the other hand, a significant rise in OPR at 50 g m^{-3} occurred, especially for methane concentrations of 2.5% and higher. At 2.5% methane; the condition of the mixture changes from a non-explosive to explosive state. Lastly, at 100 g m^{-3} the OPR increases with methane concentration and reaches double the value at 5% methane.

For the 5 kJ ignitors (Fig. 6b), the OPR is slightly higher when 10 g m^{-3} of coal dust is added to the methane-air mixture. The OPR at 25 g m^{-3} of coal dust cloud increased significantly from 2.5% methane onwards and reached a value of 3 bar at 5% methane. At a coal dust concentration of 50 g/m^3, the observed OPR is approximately 0.3 bar in a dilute methane concentration of 0.75%. However, the OPR significantly increased to 3.8 bar at 1.25% methane.

From Fig. 6c, it can be seen that the OPR increases significantly with increase in coal dust concentration and methane concentration in all cases for the 10 kJ ignitors. The OPR increases at 10 g/m^3 of coal dust from 0 (at 1.25% methane) to 0.35 bar with 2.5% methane. At this level of methane the gas mixture is non-explosive; however, it becomes explosive in the presence of the coal dust. The influence of dilute methane is clearly evident when examining the three-fold increase in OPR from 1 bar at 0% methane to 3 bar at 0.75% methane for a coal dust concentration of 50 g/m^3.

The above results confirm that the energy of the ignitors have a significant effect on the explosion characteristics and this is in good agreement with previous studies (Hertzberg et al., 1988; Kuai et al., 2013; Yuan et al., 2012).

Further illustrations of the influence of methane concentration on the OPR for varying coal dust concentrations for different ignition energy sources are shown in Fig. 7.

For 100 g m^{-3} coal dust concentration, it can be observed that the OPR curve at 1 kJ overtakes the curves for the 5 and 10 kJ ignitors at a concentration of 2.5% methane. In spite of the fact that higher energy sources increase the OPR at the lean limit, it is also found that the rate of pressure rise declines as stoichiometric concentrations are reached (see Fig. 7). The higher energy ignitors produce lower OPR due to the fact that increasing amounts of fuel are consumed earlier in the reaction, during transport of the flame to the vessel wall (Hertzberg et al., 1988). Therefore, the consumption of fuel increases with increasing energy of the ignitor and results in less fuel remaining at the proceeding stoichiometric

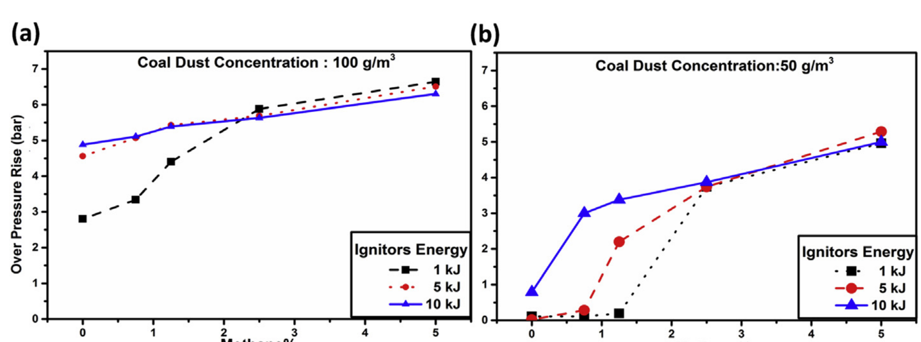

Fig. 7. OPR for hybrid mixture at various ignitors' energy for coal dust concentrations of (a) 100 g m^{-3} (b) 50 g m^{-3}.

region.

3.5. Deflagration index and explosion severity

The deflagration index is an important characteristic in the evaluation of dust explosions. It is dependent on the value of the maximum pressure of the explosion and the time at which this occurs for a fixed volume within the explosion chamber. The deflagration indices for the 1 kJ, 5 kJ and 10 kJ ignitors for different methane-air and coal dust mixtures are shown in Fig. 8.

For the 1 kJ ignitors, the value of the K_{st} increases steadily at 100 g m^{-3} of coal dust from 0 bar m s^{-1} in 0.75% of methane mixture to about 30 bar m s^{-1} in 5% methane. A slight change in K_{st} is observed at 50 g m^{-3} for higher methane concentrations. There is little change in K_{st} values for lower concentrations of coal dust (Fig. 8a).

For the 5 kJ chemical ignitors, the K_{st} value at 100 g m^{-3} coal dust cloud concentration increases significantly as methane concentration is increased and the value of K_{st} doubles from 1.25% to 2.5% methane. On the other hand, K_{st} values increase slightly for 50 g m^{-3} and 25 g m^{-3} of coal dust cloud as methane concentration is increased. However, the value obtained for 50 g m^{-3} is higher than for 25 g m^{-3} dust cloud (Fig. 8b). For the 10 kJ chemical ignitors, the K_{st} increased significantly when coal dust cloud concentrations of 100, 50 and 25 g m^{-3} were present in 0.75% of methane gas mixture (Fig. 8c).

The value of the K_{st} is an indicator of explosion severity. Explosion severity has been classified into different classes based on K_{st} values by Nifuku (Table 3) (Nifuku et al., 2000).

With reference to Table 3, the explosions presented in Fig. 8 were less than 200 bar m s^{-1} and the explosion severity is classified as weak.

3.6. Mechanism of explosions of hybrid mixtures

Analysis of the explosion characteristics is a key to understanding the mechanism of explosions. However, coal dust cloud explosions consist of a number of complex physical and chemical reactions. Generally, the mechanism of coal dust cloud explosions is similar to coal combustion which consists of homogenous and heterogeneous reactions (Li et al., 2012). The understanding may be facilitated by exploring the effects on OPR and K_{st} combined with visual observations. A high speed camera was therefore employed to observe the explosion behaviour of a 50 g m^{-3} coal dust cloud detonated by a 5 kJ ignitor at varying methane-air concentrations (see Fig. 9).

Two pressure lines have been identified in Fig. 9. The Ignitor Pressure Line refers to OPR resulting exclusively from ignition of the ignitor; the Explosion Pressure Line refers to the minimum OPR above which an explosion is considered to occur for the hybrid mixture. The time taken for the ignitor to energize (88 ms) is also indicated in Fig. 9.

The 0% methane line (solid line) in Fig. 9 indicates changing OPR with time Pressures achieved are, however, not high enough to reach the explosion limit according to ASTM E1226 (ASTM Standard, 2014). It is believed that these changes in pressure occur instantaneously following the explosion of the ignitors and is due to the combustion of fuel during the travel of ignitor's explosion wave from the centre to the wall of vessel. Observation of the ignition process did not indicate any changes in ignition behaviour for 0% and 0.75% methane experiments with the same ignitor energy. In a mixture containing 0.75% of methane gas, the OPR increases from 0.16 bar to 0.3 bar, which may be related to increased total combustion due to the presence of a higher concentration of fuel.

Fig. 10 shows images of the frames captured for the ignition of the 0.75% methane hybrid mixture containing 50 g m^{-3} coal dusts. At about 3 ms after the ignitors were energized (88 ms), another illumination was observed coinciding with a rapid pressure rise.

This is due to the fuel burning during the propagation of ignitor flame (Hertzberg et al., 1988). The illuminated region started to reduce at about 100 ms and completely disappeared at about 108 ms (Fig. 10).

In the first and second cases (0% and 0.75% methane), the coal dust cloud did not lead to an explosion. However, in a 1.25%

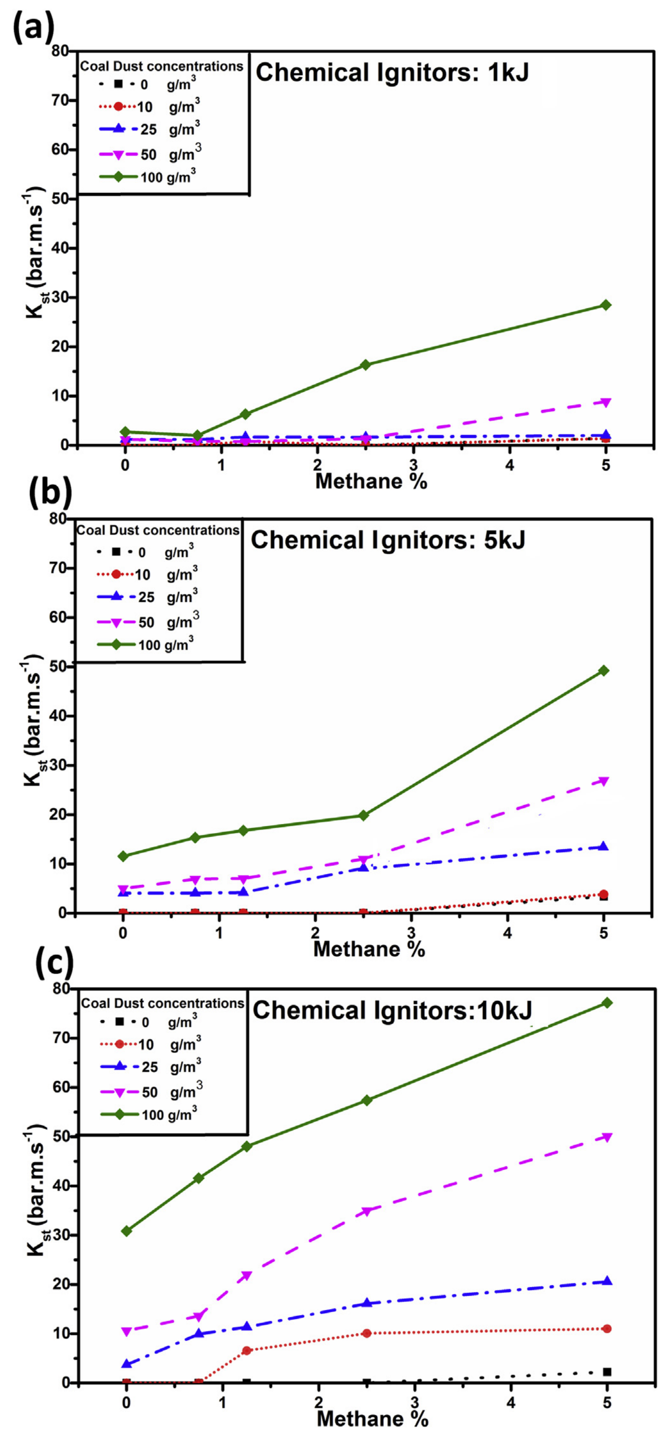

Fig. 8. Deflagration index for hybrid coal dust methane mixture using: (a) 1 kJ ignitors, (b) 5 kJ ignitors, (c) 10 kJ ignitors.

Table 3
Explosion severity (Nifuku et al. (2000)).

Explosion class	K_{st} (bar.m.s^{-1})	Explosion severity
St 0	0	non explosive
St 1	1–200	weak
St 2	201–300	strong
St 3	>300	extreme

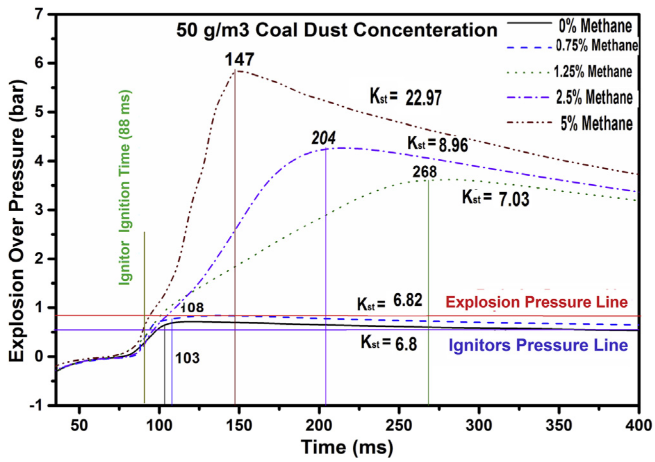

Fig. 9. Explosion behaviour for 50 g m^{-3} by using 5 kJ chemical ignitors.

methane mixture, an explosion did occur in the presence of the coal dust cloud (Fig. 9). This is evident by the increase of OPR from 0.3 bar to 2.2 bar, and slight increase in K_{st} from 6.81 bar m s^{-1} to 7.03 bar m s^{-1} (Fig. 9).

The explosion behaviour for the third case is as follows (as shown in the high speed camera images Fig. 11). Ignitor explosion causes brightness at 88 ms and continues for about 3 ms, followed by methane combustion which extends the brightness until about 120 ms. Coal dust combustion begins after 200 ms with maximum OPR being reached after 268 ms. The coal dust combusts earlier (OPR earlier by 64 ms) when 2.5% of methane is added instead of 1.25% of methane. In the case of adding 5% of methane, the OPR of coal dust combustion reached the maximum value at 147 ms (57 ms earlier). The explosion frames captured for a 2.5% and 5% methane and 50 g m^{-3} coal dust are shown in Fig. 12.

Increasing concentrations of methane gas accelerate the combustion period of the coal dust cloud resulting in reducing overall combustion time and increasing both OPR and K_{st} values (Fig. 9). In summary: in cases one (0% methane) and two (0.75% methane) the ignitor ignition and methane combustion do not provide enough energy for coal dust cloud particles to combust. In case three (1.25% methane) the energy was high enough to explode the coal dust cloud. In cases four (2.5% methane) and five (5% methane), the higher methane concentration provides excess energy to combust the coal dust cloud more rapidly.

3.7. Explosive regions for coal dust and hybrid mixtures

Coal dust cloud and methane mixtures could reduce the MEC of dust or the LFL of methane. The result is an explosive mixture of unknown lower energy (Amyotte et al., 1991; Chatrathi et al., 1994). In this study, the lower limits of explosions are addressed for coal dust and dilute methane mixtures as a function of the ignitors' energy. Fig. 12 identifies regions in which hybrid mixtures become explosive.

Cashdollar (1996) reported values of lower explosion limits for hybrid mixtures of 2.5% and 1.5% methane with 40, 50, 75 and 100 g/m^3 coal dust using 2.5 kJ ignitors. The study has been extended to include three different types of ignitor's energy and a wider range of dilute methane concentrations of the hybrid mixtures. The literature values shown in Fig. 12 are in good agreement with existing literature values (Cashdollar, 1996). It is clear that increasing the ignition energy increases the range of the explosive mixture concentrations. The MEC of the pure dust cloud decreases from 100 g m^{-3} to only 50 g m^{-3}. Moreover, a 25 g m^{-3} of coal dust cloud becomes explosive by adding 0.75% of methane where both 25 g m^{-3} of coal dust and 0.75% of methane are independently far from the explosive ranges. Finally, even at low energy (1 kJ) a 50 g m^{-3} coal dust cloud becomes explosive when mixed with 2.5% of methane, while they are both far from the explosive ranges when considered separately.

The curves distinguishing between the explosive and non-explosive regions could be predicted theoretically based on the fuel concentration in a hybrid mixture and the LFL for gases and dusts. Le Chatelier's Law indicates that the weight fraction of gas and dust are related to the LFL (as referred in Landman, 1995), according to the following formula:

$$LFL_{hybrid} = \frac{100}{\frac{X_{gas}}{LFL_{gas}} + \frac{X_{dust}}{LFL_{dust}}} \tag{3}$$

where:

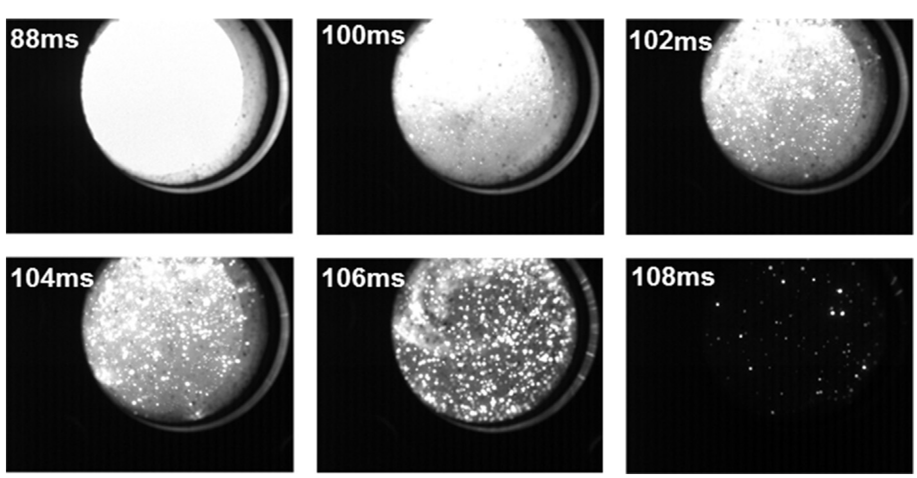

Fig. 10. Frames captured of a 0.75% methane and 50 g m^{-3} coal dust concentration mixture Ignition.

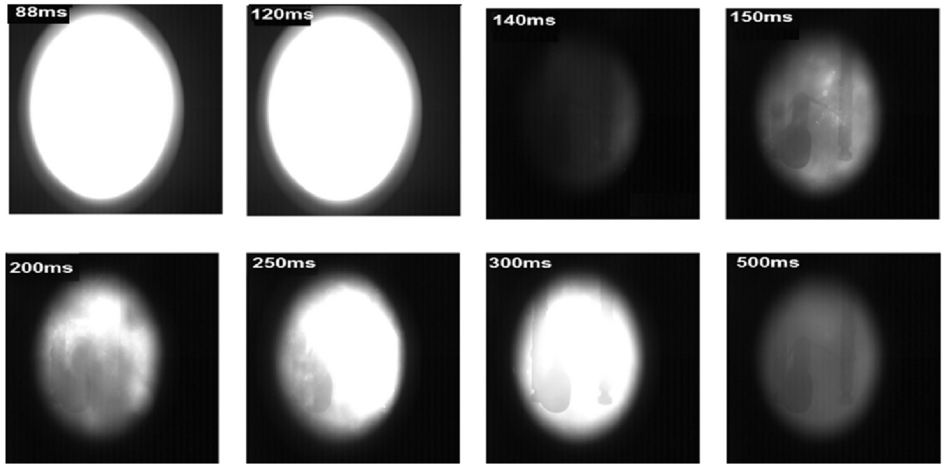

Fig. 11. Frames captured of a 1.25% methane and 50 g m^{-3} coal dust concentration mixture explosion.

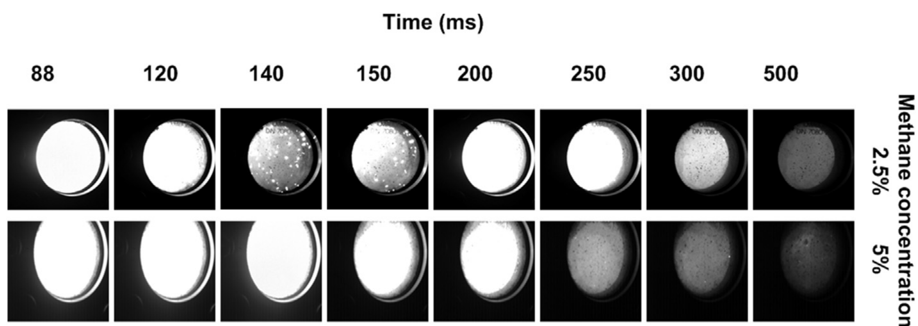

Fig. 12. Frames captured of 2.5% and 5% methane, added to 50 g m^{-3} coal dust concentration mixture explosion.

LFL_{dust} (g.m-^{3}) and LFL_{hybrid} (g.m-^{3}) are equivalent to MEC for dust in air and MEC in the hybrid mixture respectively; LFL_{gas} (v/v) is the lower flammable limit of flammable gas in air; X_{gas} is the mass fraction of flammable gas in air and X_{dust} is the mass fraction of dust in the air.

In a study done by W. Bartknecht, 1981, it has been found when adding methane or propane the MEC of dust decreases with gas concentrations more than that estimated by Le Chatelier according

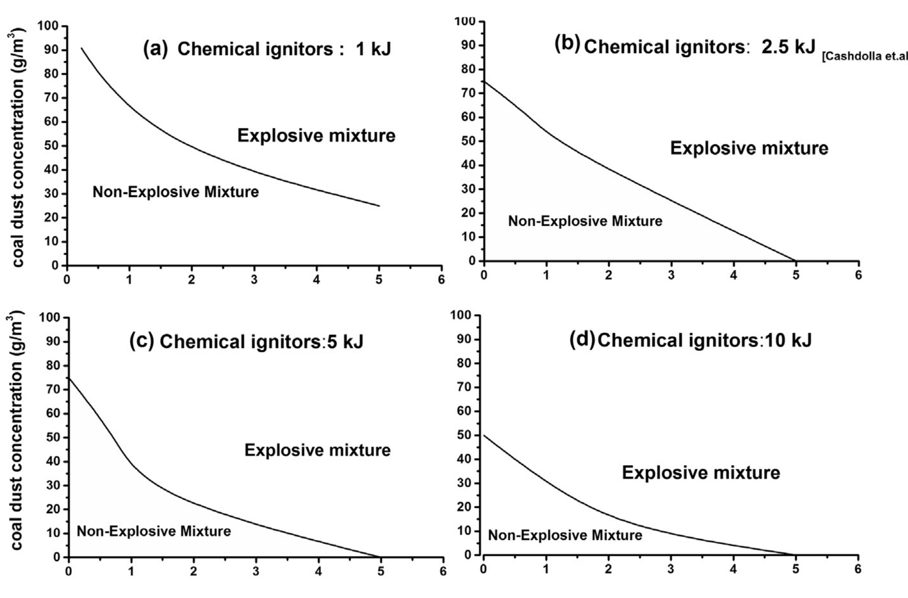

Fig. 13. Explosive and non-explosive regions for coal dust and methane hybrid mixtures at select ignitor energy of (a) 1 kJ, (b) 2.5 kJ (Cashdollar, 1996), (c) 5 kJ and (d) 10 kJ.

to the equation:

$$LFL_{hybrid} = LFL_{dust}\left[\frac{y_{gas}}{LFL_{gas}} - 1\right]^2 \tag{4}$$

These equations predict the change in MEC of hybrid coal dust-gas mixtures for a wide range of coal dust concentrations. However, the energy of the ignitors was not considered. Experiments were performed using spark ignitors, while others used chemical energy without referring to the energies of these ignitors.

To address the influence of ignitor's energy for the specific hybrid mixture (coal dust/methane/air) used for this study; a modification is made to the Bartknecht equation as follows:

$$MEC_{hybrid} = MEC_{dust}\left[\frac{y_{gas}}{LFL_{gas}} - 1\right]^2 \tag{5}$$

where y_{gas} is the volume percent of the flammable gas, MEC $_{dust}$ represent the Minimum Explosion Limit of the dust, and $MEC_{hybired}$ is represent the Minimum Explosion Limit of the dust in hybrid mixture.

The previous second order equation (Equation (5)) can be solved and simplified to its roots after dividing both sides by MEC_{dust} and rearranged as follows:

$$\frac{MEC_{hybrid}}{MEC_{dust}} = \left[\frac{y_{gas}}{LFL_{gas}}\right]^2 - 2\left[\frac{y_{gas}}{LFL_{gas}}\right] + 1 \tag{6}$$

For this study; two constants (a and b) are introduced to equation (6) as showing below:

$$\frac{MEC_{hybrid}}{MEC_{dust}} = a\left[\frac{y_{gas}}{LFL_{gas}}\right]^2 - b\left[\frac{y_{gas}}{LFL_{gas}}\right] + 1 \tag{7}$$

The optimum values for aforementioned constants (i.e. a & b) were determined from the experimental investigation performed in this study (see Fig. 14). Table 4 shows the a & b values corresponding to initial ignition energy.

A comparison between the results predicted from the Bartknecht, Le Chatelier equations and Equation (7) and the results of this study for ignitors' energy of 1 kJ, 5 kJ and 10 kJ is depicted in Fig. 13. The y-axis is determined by dividing the MEC of a dust in hybrid form (MEC_{hybrid}) by the MEC of the coal (MEC_{coal}), and the x-axis is determined by dividing the percentage of methane added to the hybrid mixture (y) by the LFL of methane.

The experimental results are significantly higher than the Le Chatelier predictions, but tend to be closer, and lower than, that predicted by Bartknecht. The Bartknecht curve shows better agreement when compared with the experimental data for the 10 kJ ignitor than for the 1 kJ and 5 kJ ignitors. Good correlation between the experimental results of this work and literature values are therefore apparent for higher ignitor energies.

4. Conclusion remarks

- It has been found that dilute concentrations of methane are able to change the explosion characteristics of dilute coal dust concentrations including decreasing the MEC, increasing the over pressure rise and increasing the deflagration index.
- The ignitors' energy affects the explosion characteristics and the boundaries of the explosive region.
- It has been found that coal dust/methane/air mixture explosions could be divided into three stages: ignitors, methane, and coal dust ignition. For a fixed ignitor energy and coal dust concentration, the time of the coal dust cloud combustion and the time

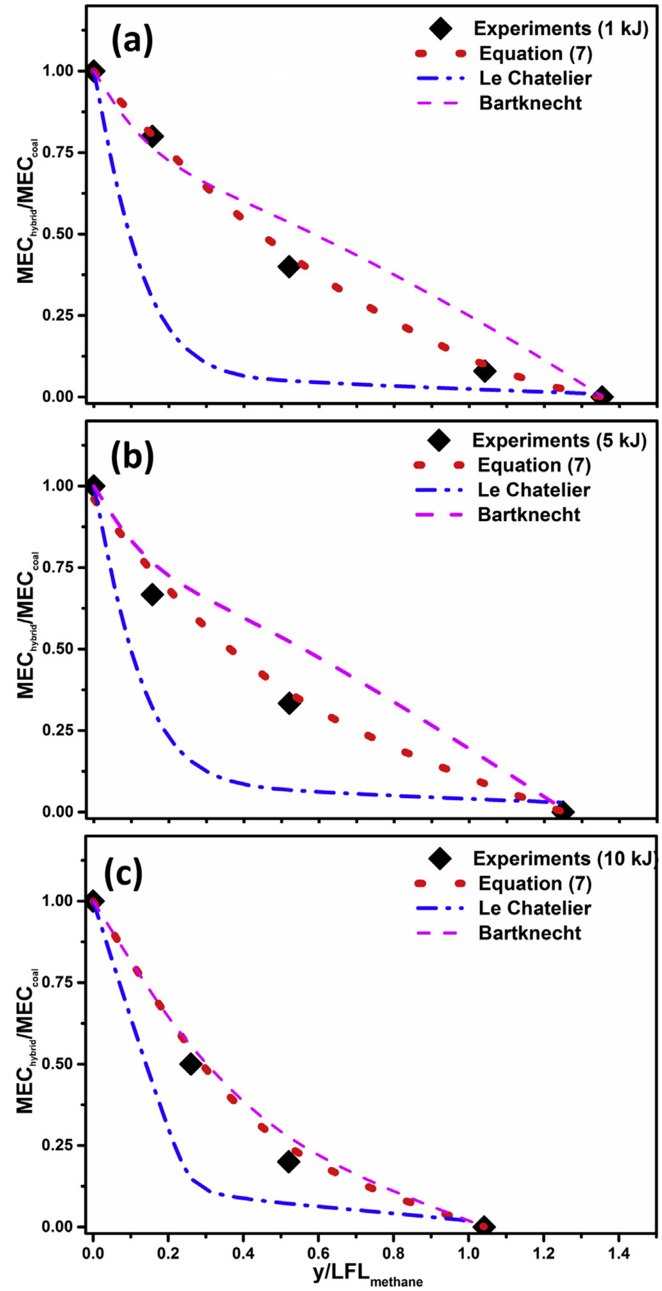

Fig. 14. Experimental and theoretical explosive region comparison for chemical ignitors: (a) 1 kJ, (b) 5 kJ, (c) 10 kJ.

until reaching the maximum pressure are reduced as the concentration of methane and/or coal dust concentration increase.
- For fixed methane percentage and coal dust concentrations, higher ignition energy sources will increase both the OPR and the Kst. At some point, for a hybrid mixture of methane and coal

Table 4
Constants a and b of equation (7).

Ignitors' energy (kJ)	a	b
1	0.487	1.398
5	0.677	1.614
10	1.134	2.14

dust in a confined vessel, the OPR trend from a lower energy ignition source will overcome the trend from a higher energy ignition source. This is due to the higher ignitor energy source consuming a larger amount of fuel during the initial travel of the flame and pressure wave from the ignitor toward the vessel wall.

- The explosive concentration range significantly increased as the energy of ignitors increased. Dilute concentrations of methane are capable of reducing the MEC of coal dust clouds and the MEC decreases with increasing energy of the ignition source.

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