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Methane-coal dust hybrid fuel explosion properties in a large scale cylindrical explosion chamber

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ABSTRACT

The fires and explosions caused by flammable hydrocarbon air mixtures are a major safety concern in the chemical and processing industries. The thermo-physical and chemical properties of the flammable fuels in a hybrid form appear to have a significant impact on the combustion process. This usually occurs due to substantial changes in the flammability concentration regimes. The aim of this study is to investigate the fire and explosive properties of hybrid fuels in the chemical and process industries. In addition, it examines the impact of the ignition energy and vessel geometry on the magnitude of the pressure rise and flame propagation velocity. The experimental work was conducted on a cylindrically shaped explosion chamber constructed as part of this study at The University of Newcastle, Australia. The chamber was made of mild steel and was 30 m in length and 0.5 in diameter. It included a series of high resolution pressure transducers, a pyrometer, as well as a high speed video camera. Methane and coal dust were used as fuels and chemical igniters with a known energy were used to ignite the fuels.

The results obtained from this study showed that both the ignition energy and the diluted combustible fuel dust have significant impacts on the Over Pressure Rise (OPR) in an explosion chamber. The significant findings included that the OPR doubled when 30 g m^{-3} of coal dust was added to a 6% methane/air mixture, and it increased by 60% when 10 kJ was used instead of a 1 kJ ignition source. The initial ignition energy was observed to considerably enhance the speed of both the pressure wave and the flame front, where the pressure wave speed doubled when using a 5 kJ instead of a 1 kJ ignition source. However, the pressure wave speed increased by five times when a 10 kJ was used instead of a 1 kJ ignition source. Additionally, the maximum flame front velocity observed for the ignition source with 5 kJ energy was twice the flame front velocity for the 1 kJ ignition source. Finally, it was observed that the time needed for the initial methane ignition was reduced by about 50% when using a 10 kJ instead of a 1 kJ ignition source.

1. Introduction

The accidental fires and explosions caused by hybrid natural gas/combustible dust continue to occur in chemical and processing plants. In the last two centuries, over 2000 worldwide incidents were caused by combustible dust alone (e.g., petroleum coke and metal) Yuan et al. (2015). Metal and wood are involved in about 46% of all dust accidents worldwide, food and plastic account for 34% and coal dust about 10%, as referred by Joseph (2007). In the United States, between 1980 and 2005, 109 fatalities occurred as a result of 197 accidental dust fires (Joseph, 2007). In China, between 1981 and 2011, there were 106 coal mine accidents, as reported by Xing and Yu (2012). However, since 1976, over 25 methane/coal dust hybrid explosions have been recorded (Zipf et al., 2013). Having a deep understanding of the controlling mechanisms of hybrid fuel fires and explosions will assist in reducing accidents from occurring in the future. One of the limitations in this research stems from oversimplifications of the potential fire and explosion sources. The explosion characteristics of coal dust and methane are commonly investigated independently, without due consideration of the transformed characteristics which occur when both methane and coal dust are present as mixtures.

Bartknecht (1981), one of the earliest researchers in this area, gave attention to the hazards of coal dust and methane mixtures

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and introduced the term "hybrid mixture" for a mixture consisting of both a combustible dust and a flammable gas. In the work published by Bartknecht et al., the pressure developed from exploded combustible dust and flammable gas was reported for confined and unconfined vessel. It was found that there is a relation between the pressure developed and the cubic root of the vessel volume. Nagy and Mitchell (J Nagy and Mitchell, 1963) did experimental work on coal dust and flammable gas mixture explosions. These two previous studies show that the presence of a combustible dust with a flammable gas could produce a more violent mixture, and was easier to ignite than the individual gas or dust alone.

Developing from this initial work, many researchers attempted to understand the explosion characteristics of hybrid mixtures (coal dust and methane). Cashdollar (Cashdollar and Hertzberg, 1985; Cashdollar and Zlochower, 2007; Cashdollar, 2000, 1996; Cashdollar et al., 1992) reported in a number of papers which investigated the explosion characteristics of coal dust and hybrid mixtures. The experiments were carried out using a 20 L explosion vessel, where the ignitors were located in the centre of the chamber. Cashdollar et al. clearly stated that the hazards of combustible dust and flammable gas mixtures are determined by the Over Pressure Rise (OPR), deflagration index (K_{st}), flammability limit, Minimum Oxygen Concentrations, Minimum Explosion Concentration (MEC) and Minimum Ignition Energy (MIE). Cashdollar et al. also showed the explosive concentration region for coal dust and how only a 2.5% concentration of methane increased the risk of explosion. In other experimental work using the same apparatus as used by Cashdollar et al., Torrent (Torrent and Fuchs, 1989) found that the OPR of coal dust increased by 33% when only a 3% concentration of methane was added. Additionally, Amyotte et al. (2012) used a quantified approach to show the influence of particle size reductions on the maximum explosion pressure and the deflagration index in hybrid mixtures. The conclusion reached was that avoiding mixing combustible dusts with their gases reduces risk in the processing industry. Amyotte et al. also reported in a number of papers on preventing and evaluating the hazards of combustible dust (Amyotte et al., 2007; Yuan et al., 2015, 2013).

Li et al. (2012) showed how the presence of a 5% concentration of methane added to 125 g m^{-3} coal dust could increase the K_{st} from 22 bar m s^{-1} to 62 bar m s^{-1}. Another laboratory scale experimental work was carried out on a different setup (i.e., 6 L) (Xu et al., 2012) for methane concentrations ranging from 4% to 12.5% mixed with coal dust concentrations ranging between 70 g m^{-3} to 700 g m^{-3} Landman (1995) also investigate the OPR and K_{st} for a hybrid mixture by using a 40 L explosion chamber. The concentrations of coal dust ranged between 50 g m^{-3} and 600 g m^{-3}, and the methane concentration was ranged between 1% and 10%. Landman et al. addressed two important factors. Firstly, the ignition source and the geometry of the explosion chamber have an influence on the ignition of the hybrid mixture: and secondly, a higher ignition source reduces the required minimum explosion concentration, thus increasing the risk of fire and explosion.

In addition to the explosion characteristics, some of the researchers tried to understand the flame properties and the propagation through the hybrid mixture. Chen (2007) conducted research on an open ended vertical chamber (0.5 m height, 0.08 m by 0.08 m square section) using spark ignitors and a thermocouple to measure the temperature. The outcomes of this study could be summarised as follows: the presence of methane in a coal dust cloud/air mixture or the presence of a coal dust cloud in a methane/air mixture increases the flame speed and the temperature of the front flame; in the temperature time profile, two peaks were observed, the earliest peak due to the methane and the volatile combustion, and the later peak due to the solid carbon combustion; and finally, the coal particles were completely combusted in 3–7 ms. Bai et al. (2011) investigated the flame propagation, flame structure and OPR produced by methane and hybrid mixture explosions. A horizontal cylindrical closed 10 m^3 vessel (3.5 m length by 2 m diameter) with five pressure transducers located at 0.25 m, 0.5 m, 0.75 m, 1.3 m and 1.8 m and a 40 J electrical ignitor were used. The coal dust was dispersed through five dust chambers by 11 bar pressurised air. Bai et al. divided the explosion into two stages: the pressure rise stage, when the pressure starts to increase until reaching the maximum pressure value: and the pressure attenuation stage, when the pressure starts to decrease gradually until no OPR value is detected. In terms of the OPR, there were two significant observations. Firstly, the position of maximum OPR was reported after 0.5 m. Secondly, the pressure rise stage of a hybrid mixture (8% methane, 25 g m^{-3} coal dust concentration) started earlier, by 200 ms, than for methane gas alone. In terms of the flame structure and propagation, the fireball flame consisted of three regions. The outer region corresponded to methane combustion, the middle region corresponded to volatile and dust composition combustion, and the luminous fireball centre region corresponded to carbon combustion. These observations were in agreement with Chen (2007).

Liu et al. (2013) examined the influence of suspended coal dust in methane gas on the flame propagation and Delegation to Detonation Transition (DDT), by using a horizontal detonation tube (30.8 m long and 1.99 m inner diameter). The ignition chamber was 7 m long and was fed by an epoxy-propane mist/air mixture. He observed the maximum wave speeds, as shown in Table 1.

The non-hybrid flame speed, flame propagation, flame pressure and DDT have been investigated by various researchers for coal dust (Jolla, 1978; Gardner and Barbara, 1986; Lebecki et al., 1995; Liu et al., 2010, 2009; Nettleton and Stirling, 1973; Spencer and Cliath, 1972; Wolanski, 1991; Zhang et al., 2001), and methane gas (Jacobus, 2014; Peraldi et al., 1988; Shepherd, 2009; Taylor et al., 2007; Wei et al., n.d.; Zhang et al., 2011; Zipf et al., 2013) using detonation tubes.

The effects of the initial ignition source on the explosion and flame properties were investigated using laboratory and large scale explosion chambers. Cashdollar (1996) was one of the earlier researchers who highlighted the influence of ignitor energy on the explosion characteristics by using a 20 L apparatus. Ajrash et al. (2016), reported that for methane (1%)/coal dust (500 g m^{-3}) the explosion is sensitive to chemical ignitors rather than the spark ignitors. The explosion initiated by spark ignitors is 250 ms slower than the explosion initiated by chemical ignitors, with no significant difference in the maximum pressure. Going et al. (2000), in the matter of the ignitors energy effects on the flammability limit of a coal dust, used pyrotechnic chemical ignitors with energies of 0.25, 0.5, 1, 2.5, 5 and 10 kJ in a Fike 1 m^3 explosion chamber and a 20 L explosion chamber. It was revealed that an energy of 2.5 kJ caused an overdriven explosion for the 20 L explosion chamber, while for 10 kJ no overdriven explosion was observed in a Fike 1 m^3. Zhang et al. (2012) did experimental work to investigate the influence of spark duration on the explosion parameters of methane/air

Table 1
Wave speed velocity for methane/coal dust/air mixtures in a detonation tube (Liu et al., 2013).

Test No	Methane (v/v%)	Coal dust (g.m^{-3})	Wave velocity(m/s)
1	No methane	368	2000
2	9.5	No methane	2050
3	2.5	92	2100
4	5	184	2200

mixtures in 20 L and 5 L explosion chambers. For weak spark ignitions in the range between 54 mJ and 430 mJ, the spark duration had little impact on the explosion parameters. Other experimental work has proven that the ignitors' energy plays an important role in the flammability limit of dust clouds (Ajrash et al., 2016; Kuai et al., 2013). Finally, other studies investigated the effects of delays in the ignition in a DT on hydrocarbons fuels (Nagaboopathy et al., n.d.; Petersen, 2009).

The goals of this experimental study are to examine the Over Pressure Rise (OPR) and investigate the pressure wave and flame profile along the DT length for a mixture of methane/coal dust/air filled in a 1 m^3 (Reactive system) cylindrical explosion chamber.

2. Experimental setup and methodology

To avoid fires and explosions in industrial processing plants, such as in mining industries where combustible substances may be present in different states (i.e., methane and coal dust), the concentrations of flammables were kept well below the lower flammability limit. For the fugitive methane gas, for example, it is lowered to values between 0.5% and 1.25% volume percentages. During abnormal operational conditions, the concentration is subjected to rises which introduce and elevate the level of risks. In addition, the deposited combustible dusts may act as a secondary explosion and substantially support the flame propagation and develop a layered detonation when dispersed in the air. As little as a few millimeters of coal dust can achieve the minimum explosion concentration when dispersed into a dust cloud (Harbaugh et al., 1995; Hartmann, n.d.; Klemens et al., 2006, 2002).

The second important factor in determining the explosion properties is the initial ignition energy. The initial ignition may exist in many forms, including hot surfaces, exothermic reactions, electrical static and discharge static energy. The energy of the initial ignition was varied from mille joules (weak ignition source) to a number of joules (strong ignition source). The DT used in this study, however, consisted of eleven sections with a diameter of 0.5 m, a total length of 30 m and a 6 m silencer attached at the end of tube to reduce the noise of explosion (see Fig. 1(a)).

The pressure wave value and velocity were measured and tracked through 33 pressure transducers and were mounted to the system at the rate of three pressure transducers for each section. The pressure transducers reading was up to 60 bar, the error reading was less than 0.25% and the response time was <0.1 ms. The flame intensity and velocity were measured and tracked through 33 photodiodes, and were mounted to the system at the rate of three pressure transducers for each section. The photodiode had the following specifications: an active area of 0.8 mm^2, a wavelength range 200–1100 nm, a rise time of 1 ns and the bias voltage was 10 V. To give an accurate, more reliable reading, and to reduce the measurement error, the photodiodes and pressure transducers of each section were located at the middle cross-sectional line with a difference of 120° between each photodiode and pressure transducer (see Fig. 1), the frequency of both pressure transducers and photodiodes is set up to 100 kHz.

The active section is presented in Sections l and 2 (see Fig. 1(b)), Sections from 3 to 11 present the non-reactive system (the grey sections in Fig. 1), the reactive section consists of two methane circulations pumps, a methane monitor, the ignitor systems and the methane injection line.

The coal dust is spread to the DT through 22 dust injection chambers, at the rate of two dust injection chambers in each section. The reactive sections are isolated from the non-reactive sections through a balloon insulation system. A blowing system at the beginning of the tube is used to refresh the air inside the tube. The temperature of the reactive system is recorded by a pyrometer at a frequency of 100 kHz through a sapphire window. A high speed black and white camera (type Phantom 4) was set at 2000 fps and a video camera was mounted at the end of the tube (type Bazlar, set at 255 fps (see Fig. 1(b)).

Methane (99.99% purity) was supplied from a gas bottle located outside the Detonation Tube area and circulation fans were used to ensure the methane-air mixture was well mixed. The coal dust sample was obtained from a coal mine located in NSW, Australia. The sample was kept in air-sealed containers and stored in cool conditions (1–3 °C) to reduce further oxidation. Representative sub-samples were despatched to third party laboratories for proximate and PSD analyses. The results are shown in Table 2.

The ignition was initiated from chemical ignitor sources with different energy levels of 1 kJ, 5 kJ and 10 kJ. Instrument air was used to minimize the effects of moisture and any impurities associated with the air on the coal dust-methane hybrid mixture's explosive properties.

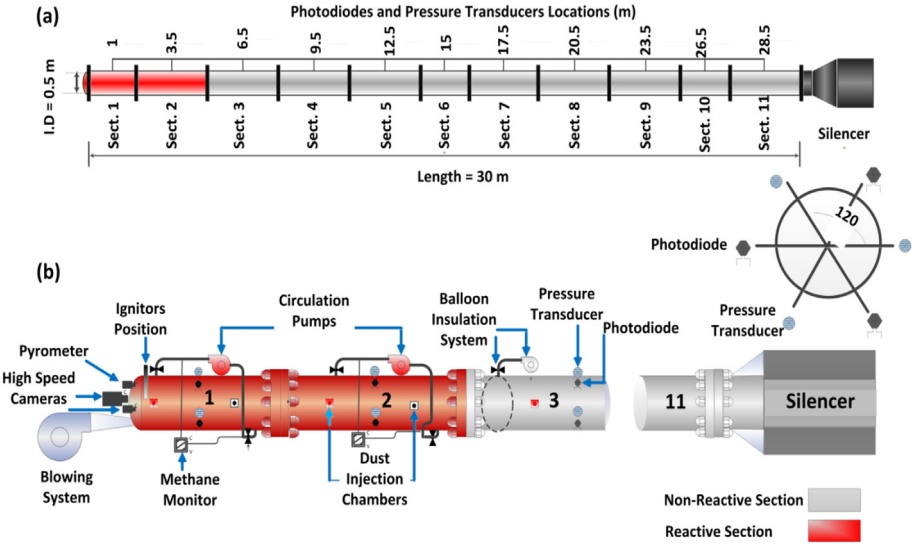

Fig. 1. Experimental set up of Detonation Tube (a) tube dimensions, photodiodes and pressure transducers, (b) active section components.

Table 2
Proximate and particle size distribution (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

The test procedure is summarized as follows: firstly, the system is purged with air to clear any residual methane that may have been left over from previous experiments. A balloon is inflated to seal the beginning of Section 2. This section is sealed off to isolate the reactive section from the non-reactive sections. Coal dust of a predetermined amount is loaded with an even distribution between the coal injection chambers located on either side of Sections 1 and 2. Then, loading the ignitors, the predetermined amount of methane concentration was introduced into Sections 1 and 2 for ignition purposes. The methane injection was achieved through a remote controlled computer located in the control room outside the detonator tube area. The ignition was activated just after the coal dust (if required) was introduced. All the sensors were activated at the time of ignition for the measurement of the pressure, temperature and the detection of flame. The data was automatically saved on the logging and control computer. Finally, the system was purged with air after the test was completed.

3. Results and discussion

3.1. Over Pressure Rise (OPR)

The destruction caused by the explosion of methane and/or coal dust are well known. An explosion is defined as a combustion process associated with a rapid increase in pressure. The definition clearly states that the OPR represents one of the most considerable factors in the explosion characteristics. Fig. 2 shows the OPR of a methane/coal dust air mixture according to three ignition energies.

The OPR data (see Fig. 2 (a), (b) and (c)) supports a number of observations. The OPR increased as the initial ignition energy increased in the semi-confined explosion chamber. This is in agreement with previous studies completed for confined and spherical explosion chambers (Cashdollar, 1996; Going et al., 2000; Zhang et al., 2012).

Fig. 2(a) shows the OPRs for methane/coal dust/air mixtures and a 1 kJ initial ignition source. At the methane range of 0%–2.5%, no rise in the OPR was recorded for all coal dust concentrations. A slight increase in the OPR at 5% of methane was observed, due to the high flammability of methane. On one hand, 10 g m^{-3} slightly boosted the OPR of the mixture (by about 0.05 bar), on the other hand, 30 g m^{-3} noticeably increased the OPR of the mixture (by about 0.2 bar), but still the mixture ignition did not satisfy the explosion OPR. At 6% methane, the OPR of the mixture crossed over the OPR explosion limit (explosion criterion) across all the coal dust concentrations (explosion criterion is defined by Yuan et al. (2014), when the OPR > 0.3 bar).

Fig. 2(b) shows the OPRs for methane/coal dust/air mixtures and a 5 kJ initial ignition source. In a similar behaviour, as compared to a 1 kJ initial ignition source (see Fig. 2(a)), no increase in the OPR was observed at a methane range of 0–2.5% at all coal dust concentrations when a 5 kJ initial ignition source was used. The OPR value crossed over the lower explosion pressure when 30 g m^{-3} of coal dust was added to a 5% methane concentration, which means the phase of combustion has moved from the flammable to the explosive region. In contrast, no change in OPR was noticed when 10 g m^{-3} was added. At 6% of methane, the methane/air mixture itself is an explosive mixture. Adding 10 g m^{-3} and 30 g m^{-3} of coal dust enhanced the OPR, increasing it by 0.2 bar when adding 30 g m^{-3} coal dust to a 6% of methane/air mixture.

Fig. 2(c) shows the OPRs for methane/coal dust/air mixtures and a 10 kJ initial ignition source. In a similar behaviour, when a 1 kJ and 5 kJ (Fig. 2(a) and (b)) was used, the OPRs in the methane concentration range of 0–2.5% increased by about 0.2 bar when a 30 g m^{-3} coal dust concentration was added due to the increased flammability of the coal dust cloud at that concentration. By increasing the methane concentration from 1.25% to 2.5% at a 30 g m^{-3} coal dust concentration, the OPR value was doubled.

To conclude, in a semi-confined vessel, the initial ignition energy significantly affects the OPR of the methane/coal dust/air mixture explosions. This is in good agreement with existing open literature for confined vessels. Fig. 2 indicates that the OPR rose as the initial ignition source was increased, i.e., the OPR for 6% methane/30 g m^{-3} coal dust/air mixture increased from 0.6 bar to 1.2 bar as the ignition source was increased from 1 to 10 kJ. In addition, the initial ignition source enhanced the ignition of the fuel from the flammable to the explosive condition, i.e., when a 1 kJ initial ignition source was used on a 5% methane/30 g m^{-3} coal dust/air mixture, the OPR was approximately 0.2 bar, which is a flammable state, however this increased to approximately 0.35 bar, an explosive state, when a 5 kJ ignition source was used.

3.2. The pressure wave and flame profile

The pressure wave is usually generated by a sudden release of energy, such as an explosion. The pressure wave characteristics are highly dependent on the physical and geometrical properties of the vessel in which the energy release was initiated (see Section 3.1). The explosion spaces are generally grouped in three types: fully confined (e.g., closed chamber), partially confined (e.g., tubes and ducts) and unconfined (e.g., open atmosphere). Fig. 3 presents the pressure wave profiles for these three types of spaces.

Where, (i) the pressure wave gradually diminishes once passed

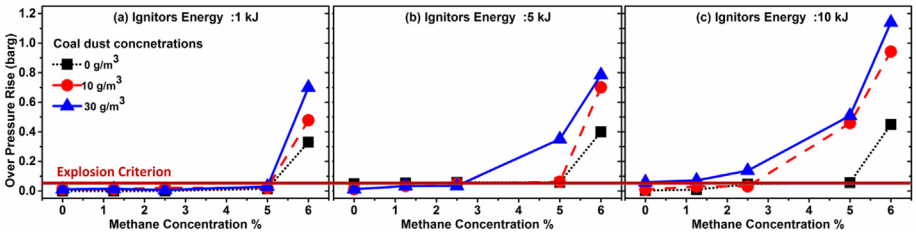

Fig. 2. The OPRs of methane/coal dust/air mixture explosions (a) 1 kJ, (b) 5 kJ, (c) 10 kJ.

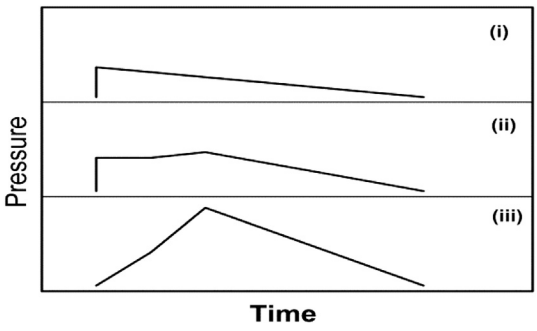

Fig. 3. Types of pressure waves (Bjerketvedt et al., 1997).

the reactive area, (ii) the pressure wave travelled with the same energy or gradually increased then diminished, (iii) the pressure wave generated a shock wave after a distance then diminished. These pressure wave profiles are affected by the energy of the explosion and the duct dimensions (Bjerketvedt et al., 1997). The shock wave pressure can be higher than the original explosion by about ten times. Furthermore, the pressure wave causes a dispersion of the layered coal dust and forms a cloud of coal which may explode at the presence of an ignition source.

As the volume and type of the space in this set of experiments are constant, a cylindrical explosion chamber and a partially confined space (see Fig. 1), the variation in the explosion characteristics are dependent on the initial ignition source, and the methane and coal dust concentrations. Fig. 4 shows the pressure wave profiles of a partially fueled DT. The fuel mixture is a methane/coal dust/air mixture and the explosion is initiated by 1 kJ, 5 kJ and 10 kJ ignition sources.

The first insight into the pressure wave profile results (Fig. 4) shows that the ignitor energy and the fuel concentration limited the pressure wave profile. The red dot represents the ignitor's position (0 m), which is located at the beginning of tube, 1 m before the first set of sensors. The pressure wave profile for the methane/coal dust/air mixture was initiated by a 1 kJ ignition source, as shown in Fig. 4(a). It was found that for a methane concentration in the range of 0%–2.5%, there was no pressure wave recorded for all the coal dust concentrations and the pressure change detected in Section one was due to the explosion of the ignitor. At about 5% methane, there was a slight rise in the pressure in Section one, but the pressure wave was not detected until after 3.5 m. Adding a 10 g m^{-3} coal dust concentration did not affect the pressure wave. However, the 30 g m^{-3} coal dust concentration caused a weak pressure wave, and the pressure reduced from 0.25 bar to 0.1 bar as the pressure wave travelled from 0 to 3.5 m, and it diminished at 9.5 m. For a 6% methane concentration, the pressure wave travelled along the tube at almost an identical pressure, only starting to decline after 20.5 m. For a 10 g m^{-3} coal dust concentration, the pressure wave was stronger, travelling at a pressure of about 0.43 bar and only starting to decline after 23.5 m. By increasing the coal dust concentration to 30 g m^{-3}, the pressure wave became stronger and travelled at about 0.79 bar, only starting to decline after 23.5 m.

The pressure wave profile for the methane/coal dust/air mixture initiated by a 5 kJ ignition source is shown in Fig. 4(b) for methane concentrations in the range of 0–2.5. For a mixture consisting of a 5% methane concentration and air, the pressure wave detected slightly increased after 3.5 m due to the flammability of methane. Adding 10 g m^{-3} of the coal dust concentration does not influence the travelling distance of the 5% methane pressure wave. A 30 g m^{-3} coal dust concentration caused an explosion in the reactive section, with a pressure rise of approximately 0.38 bar.

This explosion generated a pressure wave travelling to about 15 m, with an identical pressure (approximately 0.38 bar) before starting to diminish. For a 6% methane concentration, the pressure wave travelled along the tube both with and without coal dust. The only influence coal dust made on the system is that the pressure increased as the coal dust concentrations increased.

The pressure wave profile for the methane/coal dust/air mixture initiated by a 10 kJ ignition source is shown in Fig. 4 (c). No pressure wave was detected for a methane concentration of 0% at all coal dust concentrations. For a mixture consisting of 1.25% methane and a 30 g m^{-3} coal dust concentration, a slight pressure wave was detected in the reactive system. At 2.5% of methane, no pressure wave was detected. However, by adding 10 g m^{-3} of the coal dust concentration, a pressure wave was detected which travelled out of the reactive section to a distance of 9.5 m. Increasing the coal dust concentration to 30 g m^{-3} increased the pressure value, but the pressure wave also travelled for 9.5 m away from the first sensor sets. At a 5% methane concentration, the pressure wave travelled out of the reactive section to 12.5 m. Adding 10 g m^{-3} of the coal dust concentration caused a relatively strong wave pressure which travelled to the end of tube. The pressure value of the pressure wave dramatically decreased when it entered the non-reactive section (from 0.75 bar to 0.3 bar). Nevertheless, adding 30 g m^{-3} of coal dust to a 5% methane concentration produced a pressure wave which travelled for 20.5 m at the identical pressure value, before starting to gradually decrease after 23.5 m. At a 6% methane concentration, the behaviour was quite similar to when either a 1 or 5 kJ initial ignition source was used (see Fig. 4(a) and (b)).

Altogether, the diluted amount of the coal dust (i.e., 10 and 30 g m^{-3}) significantly enhances the travelling distance and the pressure value of a pressure wave. The energy of the initial ignition plays an important role in the travelling pressure wave. For example, for a 5% methane concentration, the pressure wave doesn't travel outside the reactive sections when using either 1 kJ or 5 kJ initial ignition sources, while for a 10 kJ ignition source the pressure wave travelled to 9.5 m. In an another example, for a 5% methane concentration with a 30 g m^{-3} coal dust concentration and a 1 kJ initial ignition source, the pressure value travelled for 9.5 m; although, for the same mixture using a 5 kJ instead of a 1 kJ initial ignition source, the pressure wave travelled to the end of tube.

The flame propagation depends not only on the properties of the explosive mixture, but also on the geometry of the system. In the DT, the flame front results from the combustion of the fuel. However, the products accelerate in opposite directions from the flame propagation, which causes an expansion in the rear side. As the DT has a closed end, the product expansion displaces the fuel particles forward. The result was a diffusivity of the flame in the non-reactive system. It was found that for no methane, 1.25% and 2.5% concentrations of methane, and under all the coal dust concentrations and ignitor energies, the flame did not travel further than 1 m from the ignitor source. Notwithstanding, the flame from the 6% methane concentration could travel up to 17.5 m from the ignition source (see Table 3).

To sum up, the flame travel distance from the reactive to the non-reactive sections is reliant on the amount of fuel dispersed to the non-reactive system due to the explosion severity in the reactive section. The severity is a function of the initial ignition source energy, and the methane and coal dust concentrations. Finally, at methane concentrations in the range of 5%–6% and coal dust concentrations in the range of 0–30 g m^{-3}, the flame travel distance was double the distance of the reactive system.

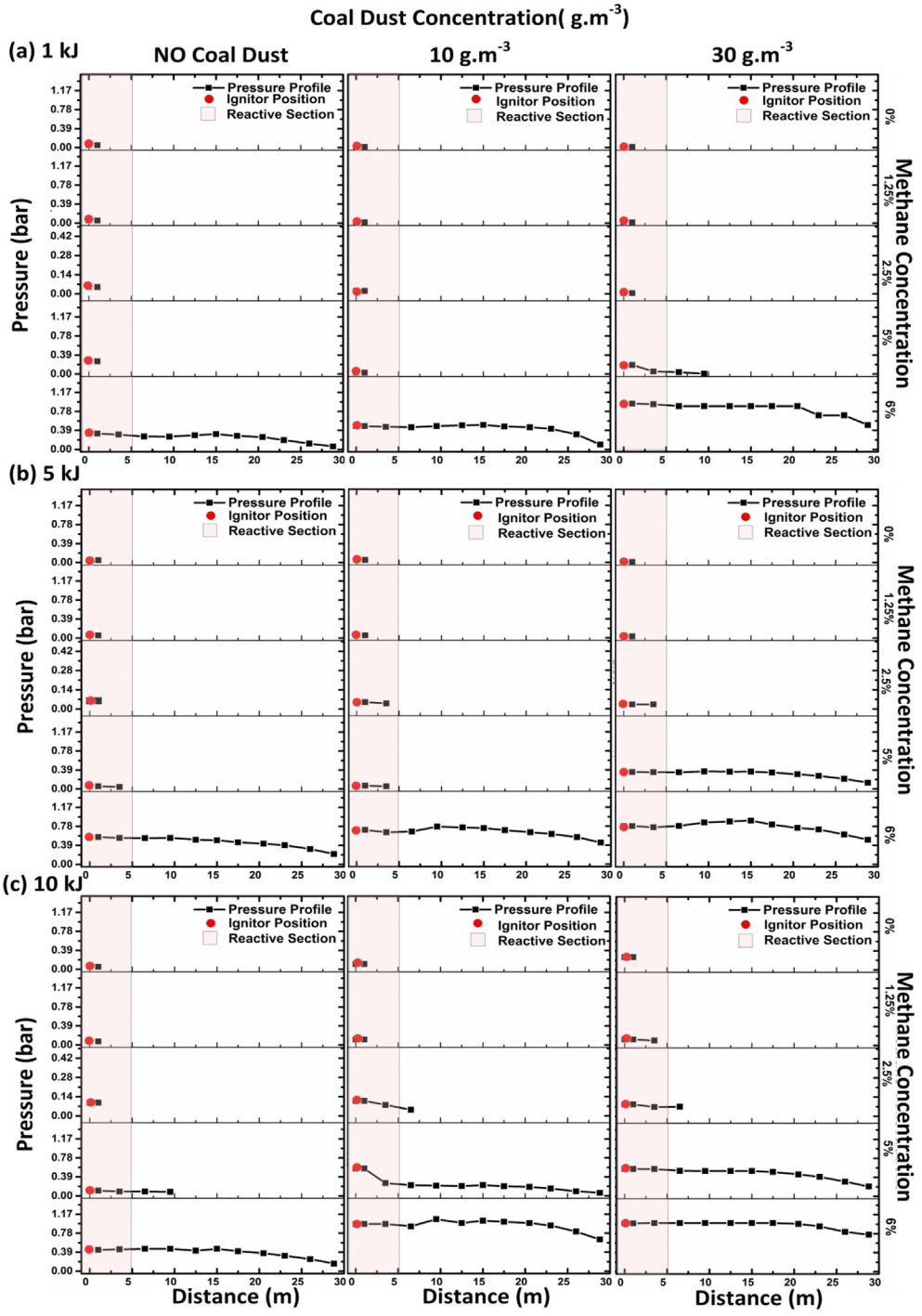

Fig. 4. Pressure wave profiles for methane/coal dust/air mixtures using (a) 1 kJ, (b) 5 kJ and (c) 10 kJ initial ignition sources.

Table 3
Flame travelling distance (m) for 5% and 6% concentrations of methane.

Methane%	Ignitor energy	Coal dust conc.		
		No coal dust	10 g m^{-3}	30 g m^{-3}
5%	1 kJ	1	3.5	10
	5 kJ	3.5	3.5	15
	10 kJ	3.5	10	17.5
6%	1 kJ	10	15	15
	5 kJ	12.5	15	15
	10 kJ	12.5	15	17.5

3.3. The effects of hybrid fuels on the flame and explosion intensities

To get an accurate insight into the hazards and limitations of coal dust on methane in partially confined space explosions, the mechanisms of the explosions must be understood clearly. It has been shown in previous studies that the explosion of methane/coal dust/air mixtures consists of two distinguishable phases. The initial methane explosion is followed by the coal dust explosion. It has also been proven that the combustible dust could reduce the minimum explosion limit of the flammable gases (Benedetto et al.

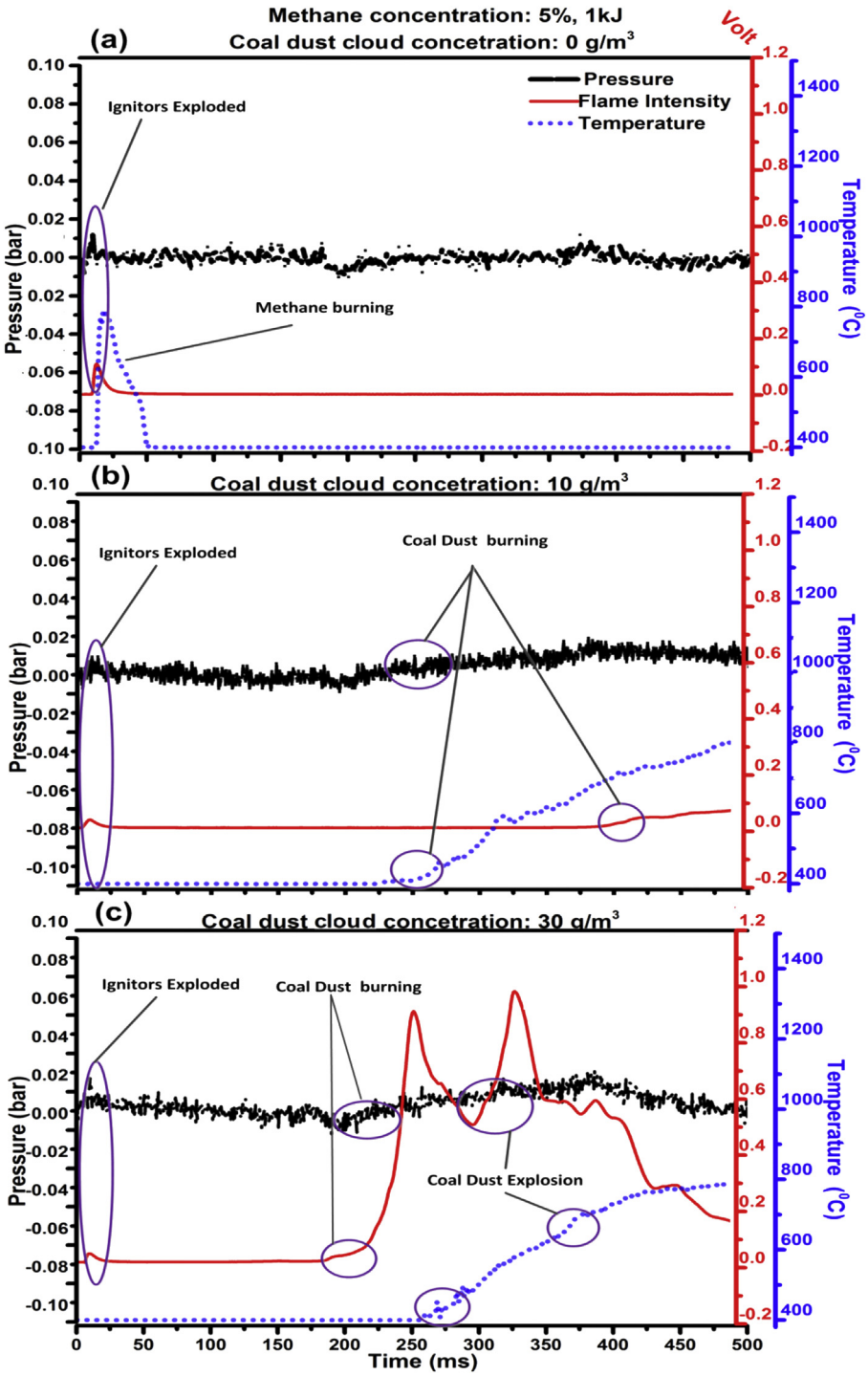

Fig. 5. Ignition analyses for the reactive section for 5% methane/air mixtures with (a) 0 g m^{-3}, (b) 10 g m^{-3} and (c) 30 g m^{-3} coal dust concentrations.

(2012); Dufaud et al. (2008); Garcia-Agreda et al. (2011); Landman (1995)). Thus, the analysis covers two methane concentrations: the Lower Flammable Limit (LFL) concentration (5%), and a concentration above LFL (6%). The analyses also focused on the reactive sections and take into consideration the pyrometer, pressure transducer, photodiode reading and video recording camera.

3.3.1. Ignition at methane LFL (5%)

When the flame is able to travel from the ignition source to the wall of the container, the gas is considered flammable at that condition. In spite of the fact that the flammability condition of methane may has a low pressure increase (below 0.025 bar) (Seneca and Beaulieu (1998); W. Bartknecht (1993)), it is considered a major threat in industry for two valid reasons. Firstly, it increases the temperature of the system which makes a good environment for flash fires and/or a secondary explosion source. Secondly, it is considered to be a source of ignition which may travel far from the system. The goal of this set of experiments was to

address the hazards and behaviours of dilute coal dust concentrations in cloud form (10 g m^{-3} & 30 g m^{-3}) on the flammability of methane gas in a large-scale reactive section in a large DT.

Figs. 5 and 6 show the data analyses and video frames for the methane ignitions in the first section of the DT with a mixture consisting of 5% methane/air mixed with (a) 0 g m^{-3}, (b) 10 g m^{-3} and (c) 30 g m^{-3}, respectively, all ignited by 1 kJ chemical ignitors. The pressure and photodiode readings represent the first section in the DT. The Pyrometer is located at the beginning of the tube and is calibrated to detect the temperature at the cross-section of the first ring of the pressure transducers and photodiodes.

Fig. 5(a) shows the data analysis for a 5% methane/air mixture ignited by a 1 kJ initial ignition source. The results show that the ignitors exploded at about 6 ms, causing slight peaks in the pressure, flame intensity and temperature. The flame of the ignitor is associated with the methane combustion due to the fact that the 1 kJ source is considered a relatively high ignition source. This is observed from a comparison of the temperature profiles of this concentration experiment with the temperature profiles for the ignitors in a system free of fuel. The maximum temperature of the ignitors in a system free of fuel is 505 °C, and within a peak period of 4 ms, whereas the maximum temperature of this test was approximately 750 °C, within a peak period of 49 ms. In addition, Fig. 6(a) shows the blue flame at 10 ms, which is the result of the methane combustion. This phenomenon is characteristic of a high ignition source, where the explosion is overdriven by the energy of the ignitors.

Fig. 5(b) shows the data analysis for a 5% methane/10 g m^{-3} coal dust concentration/air mixture ignited by a 1 kJ initial ignition source. The photodiode and the pressure transducers detect the ignitor peak light intensity and pressure wave, however no temperature readings were detected in this case. This was owing to the coal particles blocking the way of the laser beams of the pyrometer. The first indication of coal dust burning is the temperature and pressure rises at about 225 ms. The combustion of coal particles is due to the methane flame travelling in the medium, which causes a high increase in the temperature and ignition of the coal particles (see Fig. 6(b)).

Fig. 5(c) shows the data analysis for a 5% methane/30 g m^{-3} coal dust concentration/air mixture ignited by a 1 kJ initial ignition source. The ignitor explosion was not detected by the pyrometer, however it was obvious in both the pressure and photodiode readings. Within 200 ms, the burning of coal dust was detected by the pressure transducers and photodiodes. The energy released by the methane flammability and the coal dust concentration were high enough to cause a weak explosion at about 300 ms. That explosion was detected first by the photodiodes and video camera (see Figs. 5(c) and 6(c)), reaching about 0.05 bar.

Altogether, at the methane LFL concentration, even diluted amounts of coal dust increased the hazard and the probability of fire and explosion. It has been found that the methane flame merged with the ignitor flame when using a relatively high energy ignition source (1 kJ). The total time of the methane combustion at a 5% methane concentration was about 45 ms. The coal dust concentration of 10 g m^{-3} ignited and travelled in the pipe at a speed of 6.7 m s^{-1}. Finally, increasing the concentration of coal dust to 30 g m^{-3} boosted the speed of the travelling combusted coal dust particles to 10 m s^{-1}. In addition, a weak explosion emerged after 300 ms from the time of the ignitor explosion.

3.3.2. Ignition above methane LFL (6%)

The results indicated that diluted coal dust concentrations (10 and 30 g m^{-3}) influence the explosion's characteristics, the pressure wave and flame propagation of a 6% methane concentration. However, the pressure wave and flame propagation initiated from an explosion in the reactive section illustrates that the mechanism of the initial generation of the explosion is important in reducing and eliminating the consequences of flame and pressure waves travelling along the tube.

Fig. 7 shows the data analyses and video frames for methane ignitions in the reactive system of the DT using a mixture consisting of 6% methane/air mixed with (a) no coal dust, (b) 10 g m^{-3} and (c) 30 g m^{-3}, respectively, and ignited by a 1 kJ chemical ignitor. The pressure transducer and photodiode readings represent the first section in the DT. The pyrometer was located at the beginning of the tube and was calibrated to detect the temperature at the same cross-section of the first set of pressure transducers and photodiodes.

Fig. 7(a) shows the data analysis for a 6% methane/air mixture ignited by a 1 kJ initial ignition source. The ignitor ignition occurs at 6 ms, as observed through the pyrometer and photodiode readings. Methane ignition is observed at 75 ms through the pyrometer readings, where the temperature started to rise to 950 °C at about 200 ms. However, the methane ignition was associated with a slight rise in both the pressure transducer (approximately 0.05 bar) and the photodiode reading (0.7 V). The slight rise in the photodiode reading is due to the fact that the methane flame ignition at a 6% concentration has a low wavelength.

Fig. 7(b) shows the data analysis for a 6% methane/10 g m^{-3} coal dust concentration/air mixture ignited by a 1 kJ initial ignition source. After the ignitor exploded at about 6 ms, the methane ignited at about 55 ms. No significant rise in the pressure and flame intensity was observed at this stage, which indicated that the rise in temperature was due to the methane ignition. At about 125 ms, the flame intensity significantly increased, indicating that the combustion of the volatile matter of the coal dust particles started. At 275 ms, the pressure, flame intensity and temperature increased again, which could be due to the combustion of the volatile matter released from the coal particles and the combustion of the non-volatile solids (active site) on the surface of the coal dust. At 500 ms, the remaining coal dust (larger size) was ignited.

Fig. 7(c) shows the data analysis for a 6% methane/30 g m^{-3} coal dust concentration/air mixture. With similar behaviour to the previous ignitions (see Fig. 7(a) and (b)), the ignitors exploded at 7 ms (see Fig. 7(c)). The pyrometer indicated that the methane ignition starts at approximately 50 ms, and is followed by the combustion of the volatile matter liberated from the coal dust particles. At about 350 ms, another phase of combustion was

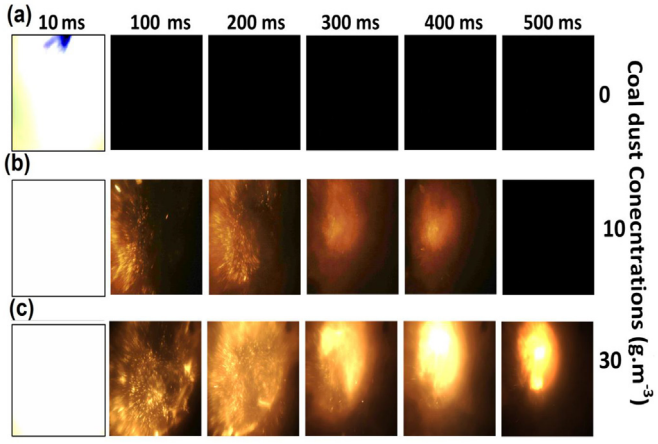

Fig. 6. Images of the reactive section for 5% methane/air mixtures with (a) 0 g m^{-3}, (b) 10 g m^{-3}, and (c) 30 g m^{-3} coal dust concentrations.

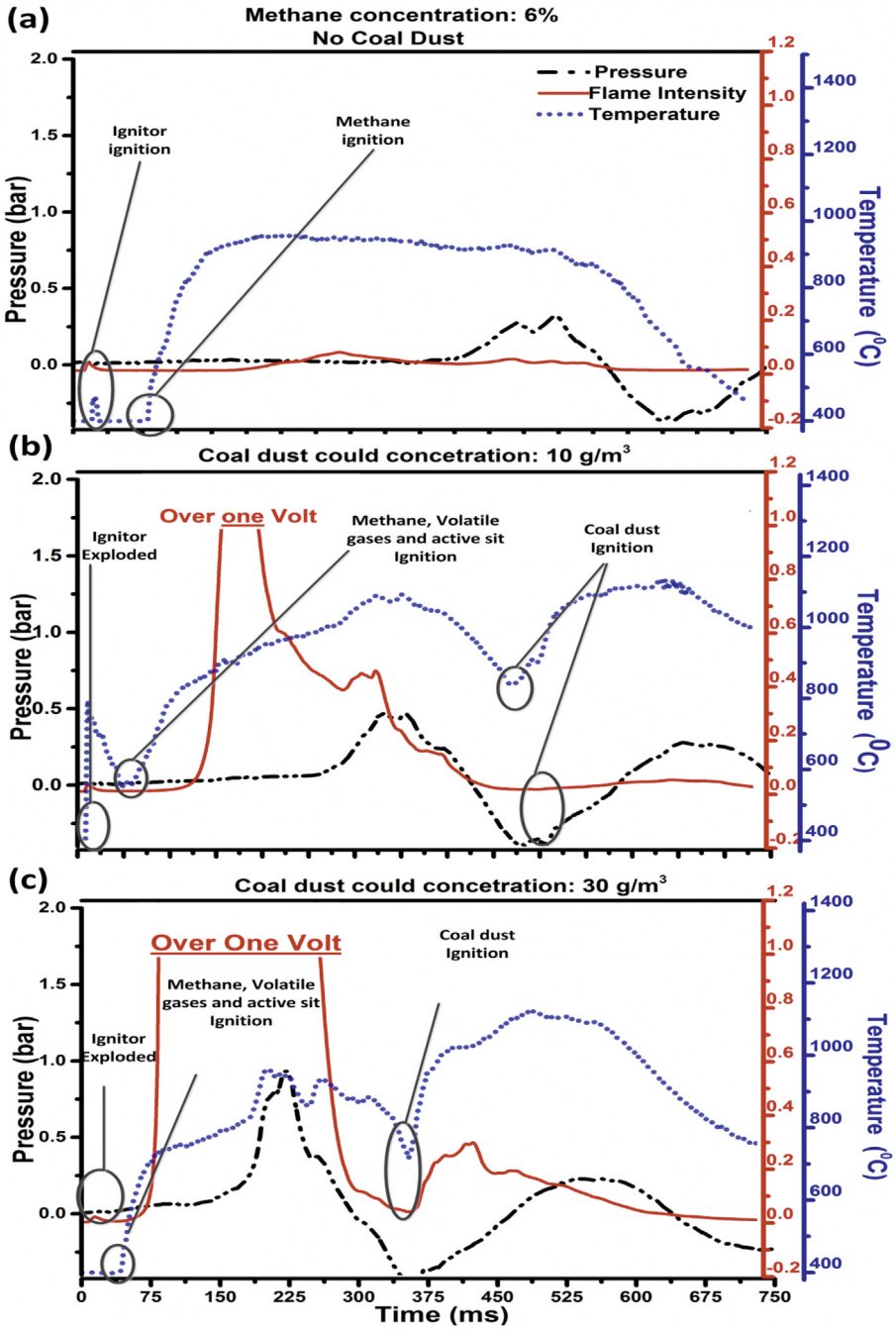

Fig. 7. Ignition analyses for the reactive section for 6% methane/air mixtures with (a) 0 g m^{-3}, (b) 10 g m^{-3} and (c) 30 g m^{-3} coal dust concentrations.

indicated, one corresponding to the combustion of the remaining coal dust particles.

The combustion of methane/coal dust/air mixtures consists of a number of processes and emits different forms of energy. In some cases (i.e., methane combustion at concentrations close to the lean limit), the methane combustion is revealed by the change in temperature, with no significant change in the pressure and a positive flame intensity readings. The pyrometer reading may not detect the change in the temperature in the case of using high coal dust concentrations, which may block the path of the pyrometer infrared beams. Hence, using the pressure transducer, photodiode, pyrometer and the visual recording system is important to reveal the methane/coal dust/air mixture combustion processes.

All in all, the presence of coal dust, even at a dilute concentration (10 g m^{-3}), in a 6% methane/air mixture enhances the acceleration of the initial methane ignition by 20 ms, while adding 30 g m^{-3} coal dust concentration to a 6% methane/air mixture accelerates the initial ignition of the methane by 30 ms. The hazards of coal dust not only increase the pressure peak of the explosion, but also bring up the times of the pressure peaks. The presence of a 30 g m^{-3} coal dust concentration brought up the peak pressure by about 125 ms for a mixture consisting of a 6% methane/10 g m^{-3} coal dust concentration/air mixture.

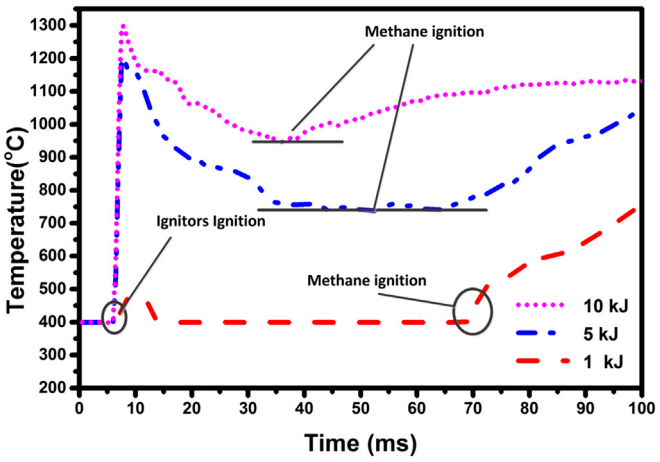

Fig. 8. Initiation of methane ignitions by 1 kJ, 5 kJ, 10 kJ and 50 mJ ignition sources.

3.4. Influences of the ignition source energy

3.4.1. Initiation methane ignition

This section discusses the influence of the ignition source energy on the initiation ignition of methane. Addressing the time between the ignition initiation and the ignition of the initial methane combustion is a crucial factor in designing a mitigation system. To illustrate the influence of the initial ignition source, the results from 1 kJ, 5 kJ and 10 kJ ignition sources were used as the initial ignition, for a mixture consisting of a 6% methane/air mixture, as shown in Fig. 8.

The results clearly indicate that the energy of the initial ignition source plays an important role in the time needed to ignite methane. Higher ignition sources liberated higher temperatures, which work on accelerating the methane oxidation process. It was found that 65 ms was needed to start the methane ignition when a 1 kJ initial ignition source was used. The time of initiating the methane ignition was reduced by 15% when using a 5 kJ instead of 1 kJ initial ignition source. Only 27 ms was needed to initiate the methane mixture when a 10 kJ was used as the initial ignition source (see Fig. 8).

3.4.2. Flame and pressure wave speeds

This section presents the influences of the ignition source energy on the pressure wave speed and flame velocity. Fig. 9(a) and (b) demonstrate the flame front velocity as well as the pressure wave speed caused by the ignition of a 6% methane/air mixture.

The results show that both the speed of the flame and the pressure wave were affected by the initial ignition source. The flame propagation reached approximately 22 m/s at 12.58 m distance from an explosion initiated by a 1 kJ initial ignition source. The flame speed development was doubled, reaching 46 m/s when a 5 kJ ignition source was used instead of a 1 kJ ignition source (see Fig. 9(a)). A higher flame propagation development (52 m/s) was achieved by using 10 kJ as the initial ignition source. It also has to be noted, the developed pressure wave speed (26 m/s) is slightly higher than the developed flame of the explosion initiated by a 1 kJ initial ignition source. However, for the explosions initiated by 5 kJ and 10 kJ initial ignition sources, the pressure waves developed at speeds considerably higher than the speeds of the flame. For example, for the explosion generated by a 5 kJ initial ignition source, the pressure wave speed was approximately twice the speed of the flame. The difference between the pressure wave and the flame speed was even increased when a 10 kJ initial ignition source was used, increasing it approximately fourfold.

To conclude, the initial ignition source has more influence on the pressure wave speed than on the flame speed. The speed of the developed pressure wave becomes approximately twice as fast as the flame speed when a 5 kJ ignition source is used instead of a 1 kJ ignition source. The speed of the developed pressure wave becomes approximately four times faster than the speed of the flame when a 10 kJ ignitor was used instead of 1 kJ ignitor.

4. Conclusion

In this study, the first two sections of the DT were used as a reactive system (a partially confined explosion vessel). A pyrometer, high speed video camera, 33 pressure transducers, 33 photodiodes and three types of ignitor energies were employed to study the explosion behaviours, pressure waves and the flame profiles of the methane/coal dust/air mixtures. The following outcomes were observed:

- For a methane explosion initiated in the reactive section of the DT tube, the diluted coal dust and initial ignition sources significantly affected the OPR, pressure wave and flame profiles.
- The OPR of methane in the lower flammable limit region (LFL) was significantly affected by the diluted coal dust concentration and the energy of the initial ignition source. The presence of a 10 g m^{-3} coal dust concentration increased the OPR from 0.09 to 0.55 bar in a 6% methane air mixture ignited by a 1 kJ initial ignition source. In addition, increasing the initial ignition source from 1 kJ to 10 kJ increased the OPR from 0.32 to 0.45 bar.

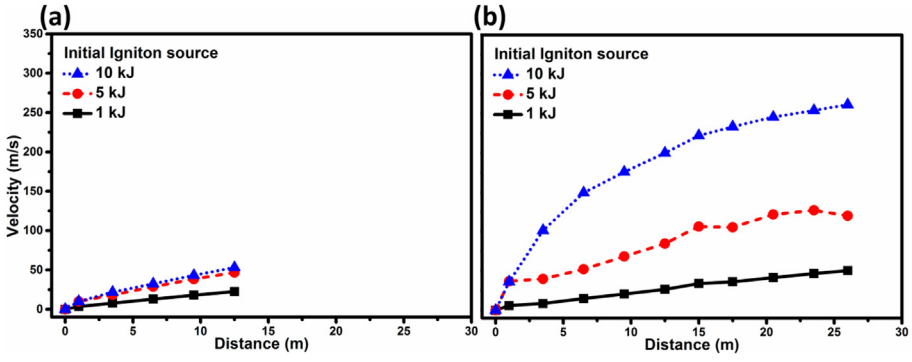

Fig. 9. (a) Flame front velocities and (b) Pressure wave speeds of a 6% methane/air mixture ignited by 1, 5 and 10 kJ ignition sources.

- The pressure generated from an explosion in the reactive section produced a pressure wave travelling along the non-reactive section. The severity of the travelling pressure wave was directly proportional to the OPR generated in the reactive system. Consequently, the travelling pressure wave had been affected by the energy of the initial ignition source and the presence of coal dust in the reactive system. The explosion of a 6% methane concentration resulted in a pressure wave travelling along the non-reactive system in the DT tube. The pressure wave of a 5% methane concentration ignition did not travel outside the reactive section unless a 10 kJ initial ignition source was used, which caused the pressure wave to travel to 9.5 m. The presence of 10 g m^{-3} of the coal dust with a 5% methane concentration did not travel outside the reactive section, unless using a 10 kJ initial ignition source, which generated a pressure wave travelling along the DT tube. The presence of 30 g m^{-3} of coal dust with a 5% methane concentration and initiated by 1 kJ ignition source generated a pressure wave which travelled for 9.5 m. When using either 5 kJ or 10 kJ initial ignition sources, the generated pressure waves travelled along the DT tube. The ignition of a 2.5% methane concentration resulted in a pressure wave which only travelled outside the reactive system when either 30 g m^{-3} or 10 g m^{-3} of the coal dust was present and a 10 kJ initial ignition source was used.
- The flame of methane has a poor intensity compared to the flame of coal dust. It was found that the flame of the methane and the hybrid mixture also travelled outside the reactive system, where the explosion and the pressure worked to disperse the particles to the non-reactive system. The longest distance (17.5 m) where the flame was detected for mixtures consisted of either 6% or 5% of methane/30 g m^{-3} coal dust concentrations initiated by a 10 kJ ignition source. In addition, the flame travelled to 12.5 m when a 6% methane concentration was ignited by either a 5 kJ or a 10 kJ ignition source, while the flame travelled for 12.5 m when a 1 kJ initial ignition source was used.
- The analysis shows that the presence of coal dust with methane not only increases the OPR, but also accelerates the time of the explosion. For example, the explosion grew at 25 ms earlier when 30 g m^{-3} of coal dust was added to a 6% concentration of the methane/air mixture.
- Increasing the initial ignition source also worked on accelerating the fuel ignition and increased the speed of both the pressure wave speed and the flame front velocity. Methane ignition occurred about 35 ms earlier when a 10 kJ ignitor was used instead of a 1 kJ ignition source. Moreover, the pressure wave speed at the end of the DT (28.5 m) increased from 50 m/s to 260 m/s when a 10 kJ ignitor was used instead of 1 kJ ignition source. Finally, the flame speed also increased from 22 m/s to 53 m/s at a 12.5 m distance when a 10 kJ ignitor was used instead of a 1 kJ ignition source.

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