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The flame deflagration of hybrid methane coal dusts in a large-scale detonation tube (LSDT)

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ABSTRACT

To gain a deeper understanding for the influences of coal dust on methane flame deflagrations in chemical plants, a LSDT has been established at the University of Newcastle, Australia. The initial ignition source was delivered by the ignition of 50 mJ chemical ignitors. This study focuses on the influences of dilute coal dust concentrations (below 30 g m^{-3}) on the deflagration of methane in a hybrid form. The work addressed the characteristic of hybrid flame deflagration behaviour including the flame velocity, pressure profile, dynamic and static pressure. Two concentrations of coal dust were introduced to the methane deflagrations, which were 10 g m^{-3} and 30 g m^{-3}. The results revealed that the presence of a diluted coal dust of 10 g m^{-3} significantly enhanced the flame travelling distance of a 5% methane concentration, from 12.5 m to 20.5 m. Introducing a 30 g m^{-3} coal dust concentration also enhanced the flame travelling distance of a 5% methane concentration, from 12.5 m to the EDT (End of Detonation Tube, 28.5 m). This enhancement was associated with boosting the flame velocity and the over pressure rise. For a higher methane concentration (i.e., a 7.5% methane concentration), the flame of the methane reached the EDT. Introducing 10 g m^{-3} coal dust to a 7.5% methane explosion increased the flame intensity signal, from 1 V to the maximum reading value (10.2 V), and enhanced the flame velocity at the EDT by about 14 m s^{-1} and finally, increased the stagnation pressure at the end of the detonation tube from 1.25 bar to 4.6 bar.

1. Introduction

In a medium consisting of a sufficient reactant and air, the particles combust in a wave form travelling away from the ignition source. The high energy released from the combustion of the reactants could cause a huge change in the gasdynamic and the thermodynamic states. The hazards of the presence of combustible dust in a flammable gas environment was highlighted in the early 1960s [1,2]. The hazards of flammable gas in reducing the lower flammability limit of coal dust has been revealed by a number of scholars [3–13].

Bartknecht et al. [14] particularly emphasized the consequences of mixing coal dust in a cloud form with methane gas. The experimental work of both Nagy et al. [15]. and Bartknecht et al. [14]. showed that the lower flammability limits of methane/coal dust hybrid mixtures are lower than the lower flammability limits of methane or coal dust individually, the lower flammability limit is defined as the lower fuel mixture that can be ignitied by an ignition source and cause a flame to travel from the source of ignition to the wall of the container [16]. A number of researchers later examined the hazards and flammability limits of hybrid mixtures using laboratory scale apparatus.

Landman et al. [17] undertook an experimental and theoretical examination of the lower flammability limits of methane coal dust mixtures. The concentrations of coal dust were between 40 g m^{-3} and 600 g m^{-3} and the concentrations of methane were between 1% and 10%. Two types of ignition sources were employed, chemical ignitors (15 J) and electrical sparks (1 J). The explosive/non explosive regions for the two types of coal dust (particle mean size 20 μm) were classified as high volatile matter (32%) and low volatile matter (22%). The results showed that the minimum explosion concentration for a high volatile coal dust ignition was 75 g m^{-3}, while the minimum explosion concentration for a low volatile coal dust was

Abbreviations: DDT, Deflagration to Detonation Transition; DPR, Dynamic Pressure Rise; EDT, End of the Detonation Tube; ID, Internal Diameter; LSDT, Large Scale Detonation Tube; OPR, Over Pressure Rise; PW, Pressure Wave; RS, Reactive Section; SPR, Static Pressure Rise; VAM, Ventilation Air Methane.

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150 g m^{-3}. Cashdollar et al. [18] also investigated the explosion hazards of coal dust in the co-presence of methane gas. The coal dust proximate analysis was as follows 1% moisture, 37% volatile, 56% fixed carbon and 6% ash, the particle size was below 74 μm. A 20 L apparatus was used and the mixture was ignited by a 2.5 kJ chemical ignitor. The lower flammability limit of the hybrid mixture was investigated for coal dust concentrations of 30, 50, 75, 100 and 125 g m^{-3}, and the methane concentrations of 1%, 2.5% and 4.5%. Two types of coal dust where used, Pittsburgh and Pocahontas. In good agreement with Landman et al. [17] the minimum explosion concentration was 75 g m^{-3} for high volatile matter coal dust. Consequently, the area of the explosive region was larger.

Amyotte et al. [19] studied the flammability and ignitability of hybrid methane coal dust explosions in a 26 L explosion chamber. A single methane concentration (2%) and a wide range of coal dust concentrations were investigated. The coal dust proximate analysis was as follows; 1.7% moisture, 30.3% volatile, 54% fixted carbon and 14% ash, the mean particle size was 30 μm. The hybrid mixtures were ignited with varied sources of energy, ranging from 50 J to 10 kJ. The authors highlighted a number of outcomes. Firstly, the lower flammability limit was reduced with increasing ignition energy. The actual lower flammability limit was measured by using a 5 kJ ignition source. A methane concentration of 2% reduced the lower flammability limit of the coal dust, and the influence was more significant when using a low, rather than high, ignition energy source. Finally, the composition of the coal dust also played an important role in the lower flammability limit, especially the volatile matter and the average mean diameter. Amyotte et al. [12,19] later investigated the influences of igniters on hybrid explosions.

Ajrash et al. [20,21] experimentally and analytically investigated the flammability of hybrid methane and coal dust explosions in a 20 L explosion chamber. The methane concentrations were in the range of 1.25–5%, and the coal dust concentrations were in the range of 10 g m^{-3} to 100 g m^{-3}. The coal dust proximate analysis shows 1.1% moisture, 31.7% volatile, 56.9% fixted carbon and 11% ash, the particles mean size was 29.91 μm In agreement with Amoytte et al. [12,19] and Cashdollar et al. [16,17] Ajrash et al. [20,21] found that the initial ignition energy could reduce the lower flammability limit of methane and/or coal dust. Additionally, the presence of 10 g m^{-3} coal dust resulted in a significant over pressure rise for a 5% methane concentration [20,21]. On the other hand, Gang et al. [22] explicitly described the influence of coal dust on methane ignition using a low energy ignition source generated from friction in a 29 L explosion chamber. The results indicated that introducing coal dust did not promote methane ignition [22].

The influences of coal dust and premixed methane/air on flame front velocities (burning velocity), velocity of the flame at the front corresponding to the flow of unburnt mixture ahead of the flame [23,24], were investigated by Xie et al. in a laboratory scale apparatus [25]. The authors found that coal dust particles in the size range of 53–90 μm, and in the concentration range of 10–300 g m^{-3}, decreased the methane front flame velocity. In contrast, coal particles with sizes below 25 μm increased the front flame velocity of the methane. It is important to note that the study investigated methane concentration at an equivalence ratio in the lean mixture range of 7–8.5.

Xu et al. [26] undertook an experimental investigation on the over pressure rise of explosions of hybrid methane coal dust mixtures. A vertical explosion chamber (0.6 m high, 0.1 m × 0.1 m square cross-section) was employed. The coal dust concentrations were in the range of 100 g m^{-3} to 800 g m^{-3}, and the methane concentrations were 3%, 5% 7% and 9%. The maximum pressure rise was about 0.5 bar at a 500 g m^{-3} coal dust concentration [26]. Chengjie et al. investigated the explosion pressures of methane in a closed both end pipe with and without coal dust deposited. The pipe was 2.4 m long and 0.1 m diameter [27]. The results showed that the over pressure rises of the methane were higher when coal dust was present at all the methane concentrations tested (6%, 7%, 8%, 9.5% and 11%). The maximum difference was at 9.5% methane concentration, where the over pressure rise of the methane was 4.1 bar, and was boosted to 4.7 bar in the presence of coal dust [27].

The literature review has shown an absence of experimental work on the explosion of hybrid methane coal dust mixtures in large scale detonation tubes. Liu et al. [28] are some of the few researchers who have investigated the explosion characteristics of methane and coal dust in a large-scale detonation tube. The dimension of the detonation tube that Liu et al. used was 30.8 m long by 0.199 m diameter. The tube was equipped with twenty pressure transducers and photodiodes mounted along the tube. The proximate analysis of the coal dust used was 14.7% Ash, 40.47% Volatile Matter and 43.28% Fixed Carbon, and the sample was sieved through a 75 μm screen. The first seven meters from the closed end of the detonation tube were sealed by a plastic sheet. This section represented the initial explosion section. Ignition in the initial explosion section was achieved via an electrical spark (40 J) in an epoxypropane mist/air; the concentration of epoxypropane was a 394 g m^{-3}. The technical details are clearly described in [25,26].

The fuel in the detonation tube was first ignited by a high initial ignition source (7 m of an epoxypropane mist/air), resulting in the development of a shock wave (compressed wave formed ahead of the supersonic combustion wave) and quasi detonation just after a distance of 7.35 m from the end of the initial ignition source. However, the composition effects of the methane and/or coal dust on the over pressure rise and the flame front velocity of the detonations were obvious. The maximum pressure of the shock wave at 7.35 m was 17.8 bar for 268 g m^{-3} coal dust, although the front flame velocity of 750 m.s^{-1} was low. The lowest was 10 bar for the 5% methane/184 g m^{-3} coal dust mixture. The formation of the second stage started at a distance of between 8.5 m and 10 m from the closed end. The flame velocity ranged between 2000 m.s^{-1} to 2130 m.s^{-1}, and the maximum over pressure rise was 49 bar. The detonation was self-sustained in the third stage, and the fastest front velocity was achieved by the 9.5% methane mixture (1750 m.s^{-1}), while the slowest front flame velocity was recorded for the 368 g m^{-3} coal dust concentration. Liu et al. concluded that the deflagration to detonation transition occurred only in the range between 1.5 m to 3 m under a strong ignition source. However, when a weak ignition source was used, the distance needed for the deflagration to detonation transition was much longer.

In a previous work by Ajrash et al. [29], hybrid mixtures were investigated in a LSDT at the lower flammability limit of methane. The reactive section was 5 m long and three chemical ignition sources were used (1 kJ, 5 kJ and 10 kJ). The aim was to study the influence of the ignition energy on the over pressure rise and flame travel distance in the non-reactive section of the hybrid methane coal dust mixture. It was concluded that introducing the coal dust to the methane ignition at the lower flammability limit could increase the over pressure rise from 0.1 bar to 0.5 bar. Additionally, the flame travel distance increased from 10 m to 17.5 m from the ignition source. It is important to note the ignition source present in process industry could be generated by different forms such as hot spot, dust layer auto ignition, friction, electrostatic charge and spark [30–32].

A number of scholars have studied the flame deflagration and detonation of methane in LSDTs [33–42]. Another team focused on flame deflagrations and coal dust explosions in a LSDT

[31,43–45]. Hybrid mixtures of flammable gases fueled by a dust layer of combustible dust were also investigated experimentally by [46–48].

An LSDT system was built at the University of Newcastle in 2015 in order to give accurate insights into methane and/or coal dust explosions. This work aimed to address the influences of dilute coal dust concentrations ($10\ g\ m^{-3}$ and $30\ g\ m^{-3}$) on methane explosions and flame deflagrations. The influence of coal dust is explored in four dimensions. Firstly, the stagnation pressure and dynamic pressure rise (DPR) resulting from the hybrid methane coal dust explosion; the maximum pressure rise and pressure profile; the flame profile and flame travelling distance; and the influence of coal dust on the methane flame deflagration velocity.

2. Methodology and technique

2.1. LSDT

The LSDT used in this study consisted of 11 sections, with a total length of 30 m and an inside diameter of 0.5 m. The exit noise was minimized by an additional 6 m section (silencer) located at the EDT (see Fig. 1).

The pressure values were measured by thirty-three pressure transducers which were located radially around and along the DT at the rate of three pressure transducers per section. The pressure transducer measuring range was up to 60 bar, with an error of less than 0.25% and a response time of < 0.1 ms. The flame intensities were detected by thirty-three semiconductors (photodiodes) which were mounted in the same configuration as the pressure transducers. The photodiodes had the following specifications: an active area of 0.8 mm^2, a wavelength range of 200–1100 nm, a rise time of 1 ns and a reverse bias voltage of 10 V, the maximum voltage output is about 10.2 V.

The active section is represented in Sections l and 2 (see Fig. 4), and Sections 3–11 represent the non-reactive system (the grey sections in Fig. 4). The two blowers circulating the methane gas in the reactive section and the percentages were tracked by two methane monitors. The coal dust was dispersed to each section via two dust chambers at opposite directions. A high speed colour camera (type Phantom 4) was set at 2000 fps and a video camera was mounted at the EDT (type Bazlar, set at 255 fps) (see Fig. 3).

2.2. Hybrid mixture

The hybrid mixtures were achieved by using two steps, firstly by making a homogenous mixture of methane, and then the coal dust was injected 0.75 s before activating the ignitors (see Fig. 2).

Fig. 1. LSDT at UoN.

The homogeneity of the methane air mixture was achieved by two circulation systems along the tube. Each circulation system consisted of a blower (the volumetric flow rates for the first and second circulation blowers were 720 L/min and 1900 L/min, respectively), four pneumatic valves, a methane monitor, two flame arrestors and a rotameter. For each system there was a methane line connected to a methane cylinder via two pneumatic valves and a mass control flowmeter (see Fig. 4).

2.3. Coal dust properties

The coal dust samples used in the current work were collected from a coal mine located in NSW, Australia. The samples were stored in cool conditions (3 °C) to minimise any potential for oxidation. The proximate analyses and PSD are shown in Table 1.

3. Results and discussion

3.1. Stagnation, dynamic and static pressure rise

There are a number of capabilities which could be applied for explosion protection, such as: eliminating the fuel and ignition sources, design a mitigation system or by employing protective design measures. For chemical plants and the coal mining industries, which are dealing with flammable gases and combustible dusts (i.e., VAM Capture Duct), designing a suitable mitigation system and taking protective design measures are the favoured actions for explosion protection. However, the protective design measures do not prevent explosions, but they reduce the consequences of the explosion to an acceptable level by building the equipment and/or constructions to resist an explosion [49]. This process requires an accurate knowledge of over pressure rises and the consequences in a larger scale setup, especially when methane and coal dust are present in a hybrid form.

This experimental work gives an accurate insight into the explosion over pressure rises to assist in designing protective measures from the estimations of the explosion hazards of mixtures containing low coal dust concentrations and methane. In this section, over pressure rises are discussed from two perspectives, which are the maximum over pressure rise and the stagnation pressure. The stagnation pressure is represented by the summation of both the SPR and DPR, expressed as the following equation:

$$P_{Stag} = P_{St} + P_{Dyn} \tag{1}$$

In this work, the static pressure is determined from the pressure transducer mounted on the wall of Section 11, the DPR is detected via two pitot tubes located at Section 11, and the stagnation pressure is calculated according to Eq. (1).

In this section, the static, dynamic and stagnation pressures were addressed to give a precise description of the consequences of methane explosions in pipes that may occur in chemical plants and coal mines. For example, the prediction of the damage to structures, the prediction of the fluid velocity from the DPR, and a consideration of the impact of the stagnation pressure when designing both a structure and a mitigation system.

The stagnation, dynamic and static pressures for a 5% methane concentration explosion (lower flammability limit) are shown in Fig. 5. The results showed that the DPR was higher than the SPR at all conditions. When a $10\ g\ m^{-3}$ coal dust concentration was introduced, the stagnation pressure increased slightly, however, it is to be noted that at a 5% methane concentration, the DPR and SPR were mainly caused by the initial explosion at the first section. When a $30\ g\ m^{-3}$ coal dust concentration was introduced, the stagnation pressure increased by 3.6 times that when the system was free of coal dust. The significant increase in the stagnation pressure

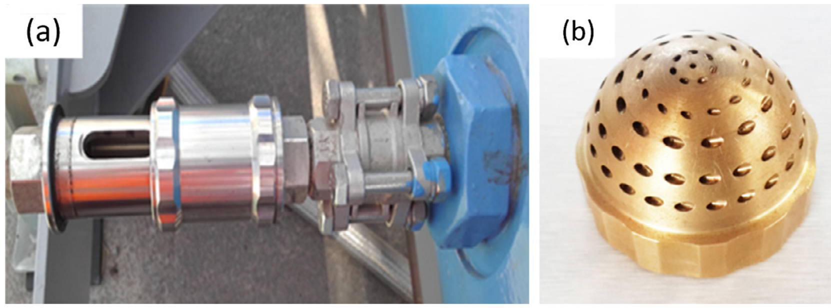

Fig. 2. (a) Coal dust injection chamber (b) nozzle inside the detonation tube.

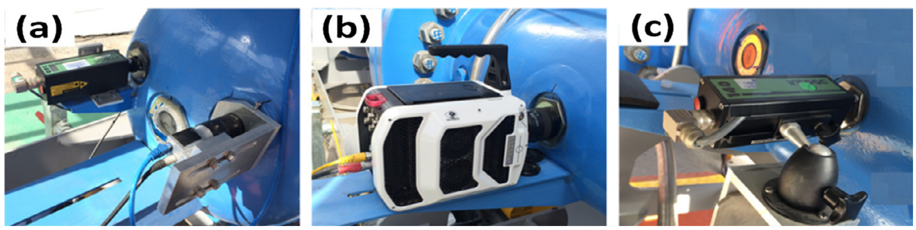

Fig. 3. (a) Pyrometer and video camera mounted at the beginning of tube (b) high speed camera mounted at the side view of section one and (c) pyrometer mounted at the side view of section six.

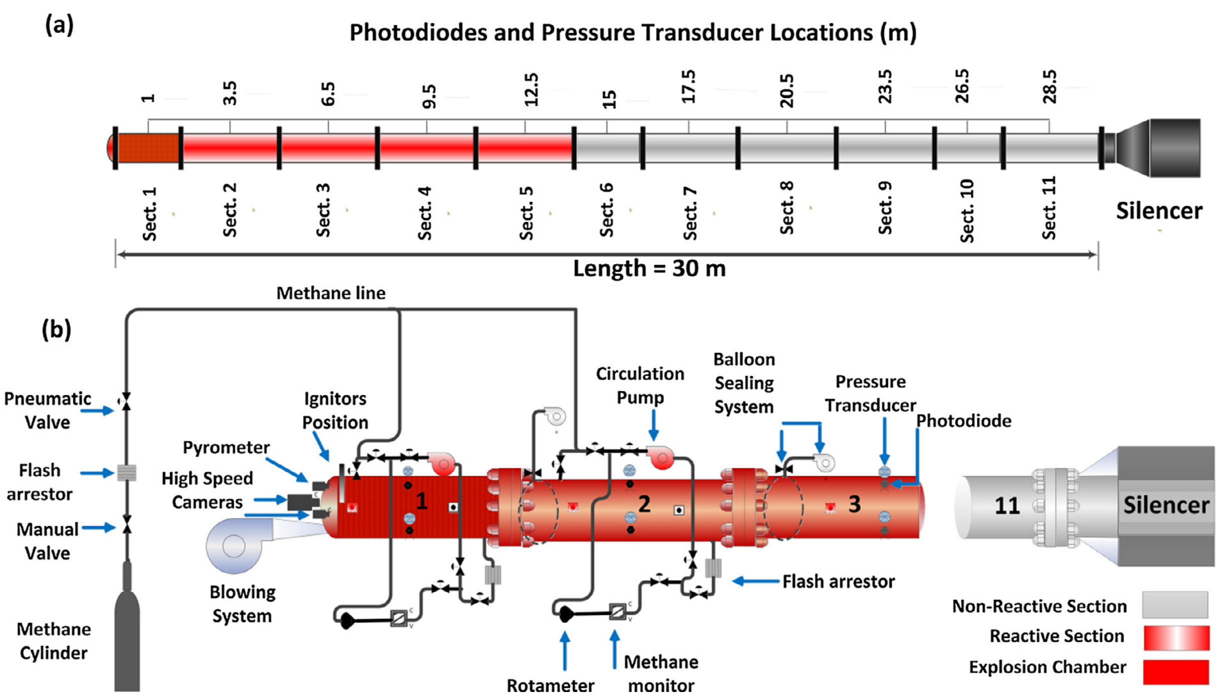

Fig. 4. Components of the detonation tube at UoN.

Table 1
Coal dust analysis (Proximate analysis and PSD).

Fixed carbon %	Total moisture %	Ash %	Volatile matter %	D_{90} (μm)	D_{50} (μm)	D_{10} (μm)
43.7	4.7	23.3	28.1	71.56	20.51	1.52

was a result of increasing both the DPR and SPR. The pressure boost was 0.375 bar and 0.268 bar, respectively, for the DPR and SPR.

The stagnation, dynamic and static pressures for a 7.5% methane concentration explosion are shown in Fig. 6. The DPR and SPR for the 7.5% methane concentration significantly rose as compared with the 5% methane concentration, where the DPR and SPR increased by 4.2 and 4.7 times, respectively. The results revealed that the stagnation pressure of a 7.5% methane

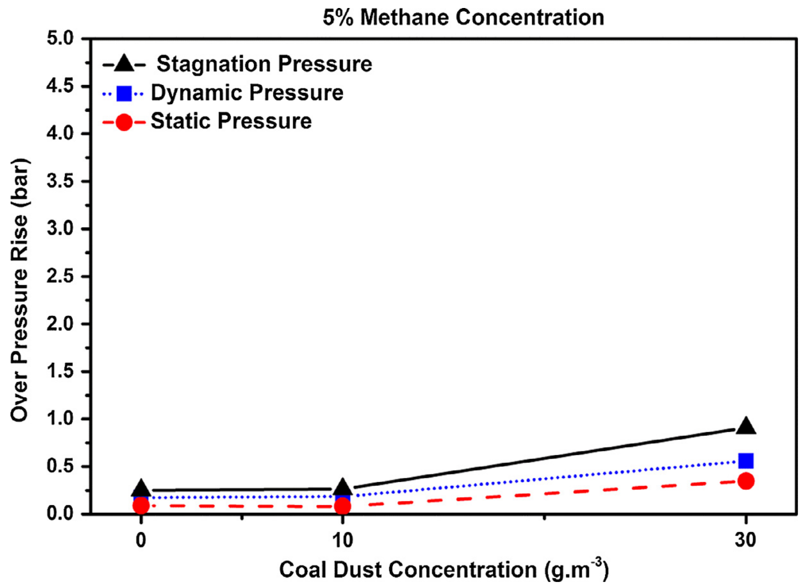

Fig. 5. Stagnation, dynamic and static pressures for a 5% methane concentration.

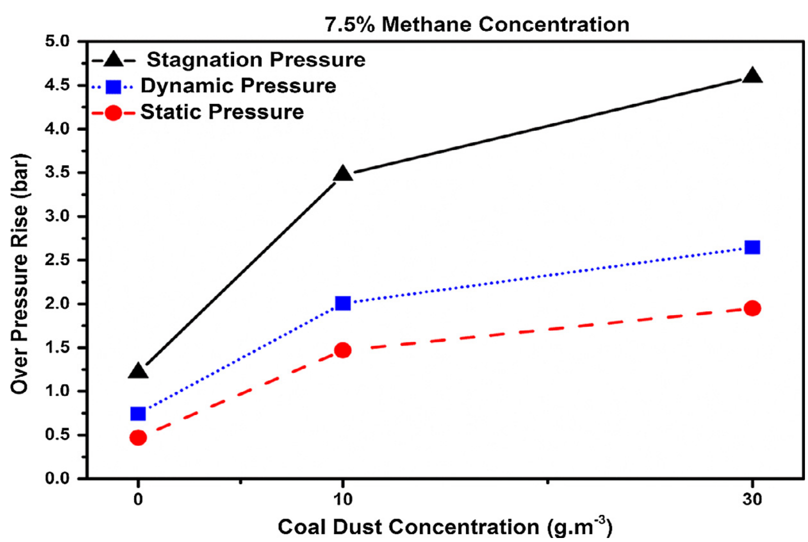

Fig. 6. Stagnation, Dynamic, Static pressures for a 7.5% methane concentration.

concentration explosion is more sensitive when introducing 10 g m^{-3} coal dust concentration than the 5% methane concentration in which the developed stagnation pressure reached 3.5 bar. When 30 g m^{-3} coal dust was introduced, the stagnation pressure further increased and reached about 4.6 bar. This fact emphasizes the explosion hazards of the hybrid form of 10 g m^{-3} coal dust mixed with a 7.5% methane concentration, which significantly increased the stagnation, dynamic and static pressures. To sum up, the hazards of diluted coal dust concentrations in a hybrid form are related to the methane concentration at the lower methane flammability concentration limit. Coal dust concentrations of 30 g m^{-3} have a pronounced influence on the stagnation, dynamic and static pressures. However, no significant pressure rise was recorded in the stagnation, dynamic and static pressures when adding 10 g m^{-3} coal dust to a 5% methane concentration. Additionally, a hybrid of 10 g m^{-3} coal dust added to a 7.5% methane concentration significantly increased the stagnation pressure, DPR and SPR by about threefold.

3.2. Pressure wave (PW) tracking

The pressure wave (PW) is important for safety audit applications in chemical plants. During the phase of flame propagation, the products of the combustion expand behind the flame. This expansion boosts the temperature ahead of the flame. As a result, the flame is accelerated and the gases expand with the PW. According to Gugan [50], 60% of explosions result in a severe PW causing vast damage at long distances. From the mechanism of PW development, it could be extrapolated that the properties of the PW are dependent on a numbers of factors, including the types of fuel, the concentrations, the initial ignition, the initial condition and the geometry of the container [11,45–47]. This section shows the properties of pressure waves as functions of two variables, the coal dust concentrations and the methane concentrations. The PW profile is determined by measuring the peak of the over pressure rise in each section during the phase of the explosion, the over pressure rise represents the magnitude of pressure that increased over the normal conditions (in this work, the normal conditions represent the atmospheric pressure).

The PW profile for a 5% methane concentration and a 5% methane/coal dust mixture is shown in Fig. 7. The results revealed that at a 5% methane concentration, the PW travelled at about 0.5 bar for 17.5 m, then gradually reduced, reaching about 0.2 bar. As mentioned earlier, these values were mainly produced by the initial explosion in Section 1. These results almost matched the PW profile for the 5% methane concentration and 10 g m^{-3} coal dust and were in agreement with results for the stagnation pressure, DPR and SPR. Adding 10 g m^{-3} coal dust to a 5% methane mixture did not show significant effects on the over pressure rise. The influence of 30 g m^{-3} coal dust and a 5% methane concentration in the hybrid form was obvious along the detonation tube, where the PW profile showed a distinct behaviour compared with the PW profile of the 5% methane concentration and the PW profile of the hybrid form of the 5% methane concentration with 10 g m^{-3} coal dust. The first distinct behaviour of the PW was that the pressure rise in the first 6.5 m reached 0.9 bar, compared with about 0.45 bar for both the 5% methane concentration and the hybrid form of 5% methane concentration with 10 g m^{-3} coal dust. Secondly, the peak pressure of the PW rose by 0.96 bar from 9.5 m to 20.5 m, then diminished gradually at 23.5 m (see Fig. 7). The PW profiles of the 5% methane concentration and the 7.5% methane/coal dust mixture are shown in Fig. 8. The PW profile of the 7.5% methane concentration showed recognizable differences compared with the 5% methane concentration. In the case of no coal dust, the PW of the 7.5% methane concentration travelled at relatively high pressure from the first section (1.5 bar) for 6.5 m, then at 9.5 m the PW started to develop slightly to 1.73 bar, and the maximum over pressure rise was recorded at 23.5 m, which was 1.4 times higher than the over rise of the PW at the beginning of the detonation tube (see Fig. 8). It was noted that when a methane coal dust hybrid form is generated, the PW travelled at almost the same pressure for about 15 m, then a significant development in the over pressure rise of the PW was noticed.

The development of the PW after 15 m is dependent on the amount of coal dust introduced into the system, and the highest over pressure values appear always at the end of the tube. It is believed that the significant pressure rises at the EDT was due to the fast deflagration of the flame, which may have progressed to a detonation phenomenon if the L/D ratio were higher. The pressure developed at the EDT was 1.1 and 2.27, respectively, for no coal dust and for 30 g m^{-3} coal dust.

To sum up, the PW profiles showed a distinct behaviour for methane explosions and methane/coal dust hybrid explosions. The reason behind this distinct behaviour is attributed to the fact that part of the coal dust instantaneously combusted with methane, which increased the amount of product behind the flame front, and eventually increased the over pressure rise in the system. The maximum over pressure rise of the PW was about 0.52 bar for both the 5% methane concentration and for the hybrid 5% methane concentration and 10 g m^{-3} coal dust. For the 5% methane with 30 g m^{-3} coal dust concentration, the over pressure rise of the PW was significantly enhanced, reaching 0.96 bar. In spite of the enhanced over pressure rise of the PW when adding coal dust, the profiles were similar, or may develop slightly then diminish at the EDT. However, the PW profiles showed a different behaviour for the 7.5% methane concentration, where the hybrid mixture developed a significant PW at the EDT, which was attributed to the fast deflagration of the flame and the PW.

3.3. Flame tracking

Initiating an ignition in a flammable mixture generates a flame deflagration in a series of combustion reactions out of the ignition source. The deflagration velocity of the flame in a smooth pipe is controlled by the burning rate at the flame front and the expansion ratio of the flame produced behind the flame front that causes the PW, as described earlier in Section 3.2. In pipes, the flame propagates in both directions in the case of both end open pipes, however, in this experimental work, the flame was initiated at the closed end of the pipe, and it propagates firstly in a spherical laminar velocity toward the open end of the pipe. The expansion ratio of the products behind the flame exerted a pressure on the flame front as the travelled distance increased. Consequently, in the expansion pressure case, the wrinkling and instability of the front flame led to the turbulence, and the turbulence of the flame increased the surface area of the flame front that resulted in an increased burning rate and, eventually, an increased flame velocity

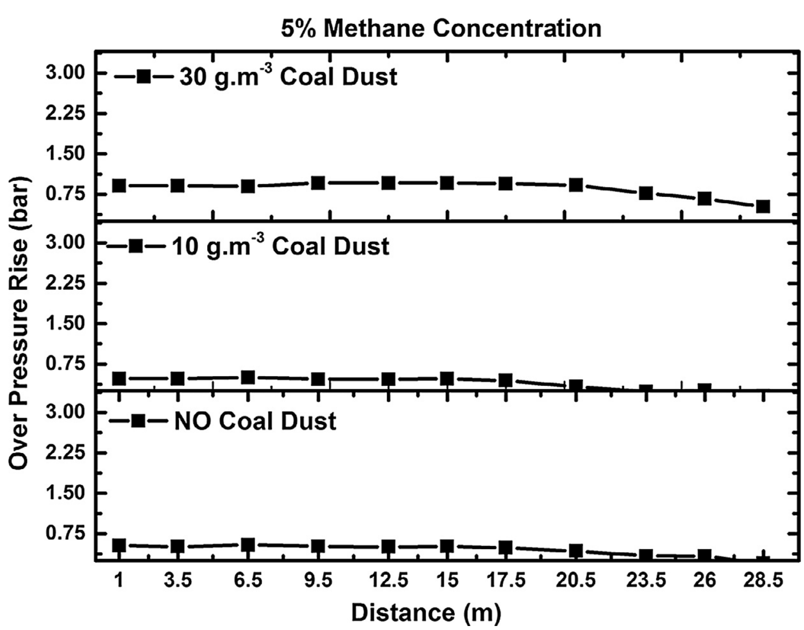

Fig. 7. PW profiles of a 5% methane concentration with different coal dust concentrations along the detonation tube.

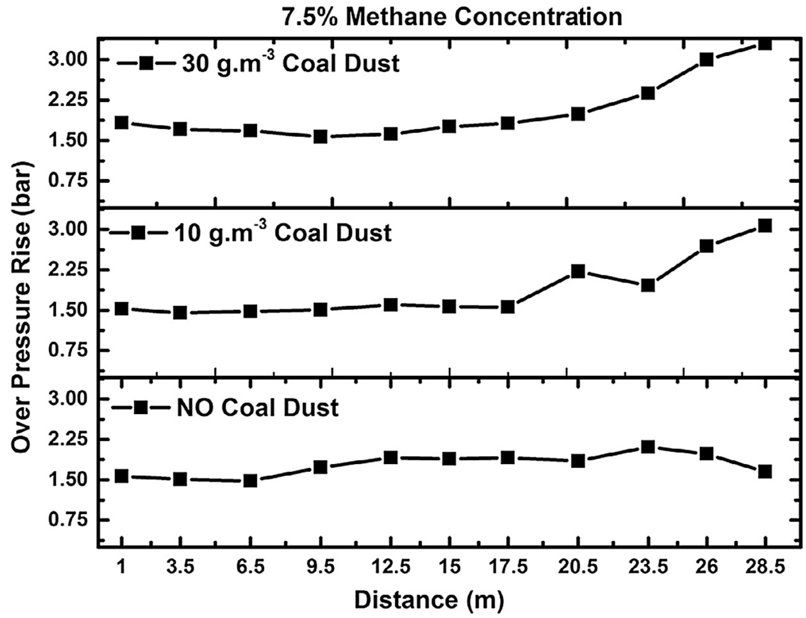

Fig. 8. PW tracking of a 7.5% methane concentration with different coal dust concentrations along the detonation tube.

to fast flame acceleration. A fast flame acceleration may develop further and initiate a shock wave [51]. This section explores the influence of the coal dust on the methane flame's development in the detonation tube. The flame was tracked in two aspects, which were the photodiode output voltage (flame intensity signal) and the flame deflagration velocity. Addressing the flame intensity in pipes is mainly important in order to detect the flame then activate the alarm and flame mitigation systems. The variations of the flame intensity are dependant not only on the type of fuel but also on the fuel concentration, as well as the velocity of the flame in some cases. The flame intensities of a 5% methane concentration with different coal dust concentrations along the detonation tube are shown in Fig. 9. The results revealed that the maximum flame intensity signal was about 1.2 V for the 5% methane concentration. The photodiode output voltage readings indicated that the flame intensity gradually declined until it disappeared at about 12.5 m. The results also revealed that the coal dust concentrations had a pronounced influence on the flame travel distance for the 5% methane concentration. Adding 10 g m^{-3} coal dust to a 5% methane concentration caused the flame intensity signal of the explosion to increase from 1.2 V to 2.5 V at a distance of 1 m, and the maximum flame intensity signal recorded was about 4.4 V at about 3.5 m. Additionally, the flame intensity signal revealed that the addition of 10 g m^{-3} coal dust to a 5% methane concentration extended the flame travel distance from 12.5 m to about 20.5 m. Increasing the coal dust concentration in the hybrid form of 30 g m^{-3} coal dust enhanced both the flame intensity and the flame travel distance.

The results showed that the flame travel distance increased from 20.5 m to the end of detonation tube when using 30 g m^{-3} coal dust instead of 10 g m^{-3} coal dust in a hybrid form with a 5% methane concentration. The flame was also detected until the

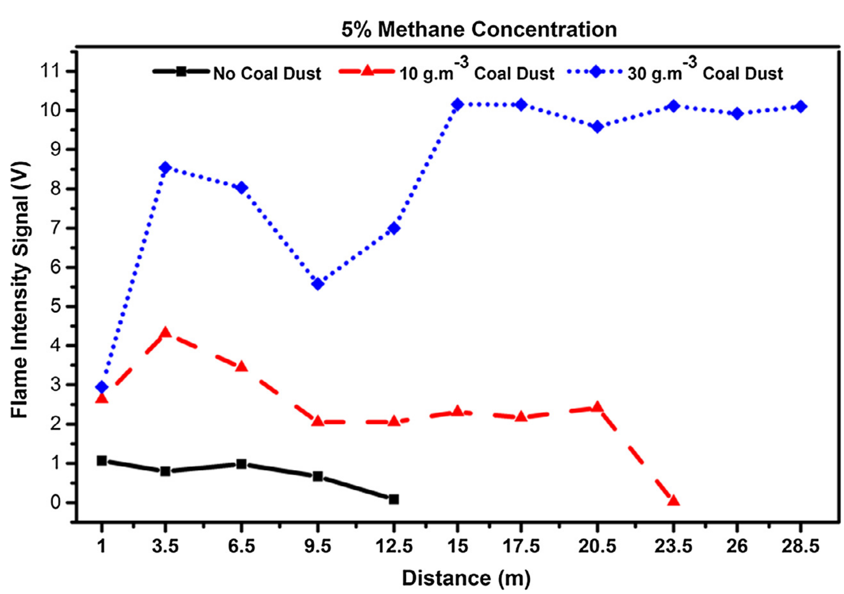

Fig. 9. Flame intensity signal of a 5% methane concentration with different coal dust concentrations.

end of the detonation tube and the flame travelled at a high intensity (about 10.2 V, maximum photodiode signal reading) instead of at about 2.5 V (see Fig. 9). The flame intensity signal for a 7.5% methane concentration with different coal dust concentrations along the DT is illustrated in Fig. 10. The maximum flame intensity signal of the 7.5% methane concentration was about 1.6 V at about 6.5 m, then the flame travelled at an almost fixed value of flame intensity signal (1 V). The flame intensity signal revealed that adding 10 g m^{-3} coal dust to a 7.5% methane concentration increased the flame intensity signal in the first section, from 1 V to about 2.5 V. The flame intensity signal then significantly increased, from 3 V to about 10.2 V at 9.5 m, and the flame travelled from 9.5 m to the end of detonation tube at the same intensity signal (10.2 V). No significant change in the flame travel intensities were observed when increasing the coal dust concentration in the hybrid form to 30 g m^{-3} instead of 10 g m^{-3}, except at distances of 3.5 m and 6.5 m, where the flame intensities signals increased, respectively, from 2.5 V and 3.5 V to about 8.4 V and 8.5 V (see Fig. 10).

To sum up, the coal dust played an important role in both the flame travel distance and the flame intensity signal along the detonation tube. Adding 10 g m^{-3} coal dust to a 5% methane concentration increased the flame travel distance by 62%, and also increased the maximum flame intensity signal from 1.32 V to 2.5 V. The flame, however, was detected even at the end of the detonation tube and the flame intensity signal reached 10.2 V when 30 g m^{-3} coal dust was added to a 5% methane concentration. The flame intensity signal of the 7.5% methane concentration travelled to the end of detonation tube at about 1 V. The presence of coal dust (10 g m^{-3} or 30 g m^{-3} coal dust) in a 7.5% methane concentration caused the flame intensity signal to rise from 1 V to 10.2 V at a distance of 9.5 m, and the flame travelled along the tube for the hybrid mixtures at a flame intensity signal of 10.2 V.

The destructive force of an explosion propagates in pipes depending on the over pressure rise and the impulse generated from the flame deflagration [52]. A detailed record of methane flame deflagration velocities are not only required to determine pressure impulses and explosion developments, but also to design an effective flame mitigation system. The flame velocity helps to estimate the distance and time required between the flame detectors and the location where the flame mitigation acts. The term 'flame velocity' is conventionally defined as the velocity of the flame relative to a stationary point; the researchers assumed that the boundary of the gas velocity ahead of the flame is identical to the first indication of the flame reaching the photodiode. Another group of researchers measured the relative flame velocity from a stationary point to the first point of increased temperature, where the assumption was that the first point of increased temperature is asymptotic to the point of the gases ahead of the flame [24,53,54], mathematically describing the flame velocity as:

$$S = U + u_g$$

where S is the flame velocity, U is defined as the burning velocity, the velocity of the flame front relative to unburnt gas, and u_g is the velocity of the unburnt gas.

In this study, the flame velocity is calculated relative to the first sign of the flame's light being detected (0.03 V). According to the stagnation pressure, pressure profile and flame intensity, the influence of the coal dust was significant for the 5% methane concentration when mixed with 30 g m^{-3} coal dust, and for the 7.5% methane concentration when mixed with 10 g m^{-3} coal dust. Consequently, this section highlighted the influence of coal dust on the flame velocities at the referred concentrations.

The flame velocity of both the 5% methane concentration and the hybrid form consisting of 5% methane concentration/30 g m^{-3} coal dust are shown in Fig. 11. The results showed that the coal dust had an obvious influence on enhancing the methane flame's profile. The flame, as mentioned earlier, quenched at a distance of 12.5 m for the 5% methane concentration, and Fig. 11(a) shows that the flame reach the distance of 9.5 m at a velocity of 37 m s^{-1}. However, the flame reached the distance of 1 m at a velocity of 12 m s^{-1}. With the addition of 30 g m^{-3} to the 5% methane concentration (see Fig. 11(b)), the flame travelling distance was not extended, however the flame velocity increased at 1 m, 3.5 m and 6.5 m, respectively, by 50%, 58% and 54%. It is to be noted that the flame velocity for the hybrid form smoothly increased until reaching the end of the detonation tube, where the maximum flame velocity recorded was 131 m s^{-1} at a distance of 28.5 m. The flame velocities of both the 7.5% methane concentration and the hybrid form, consisting of 7.5% methane concentration/30 g m^{-3}coal dust, are shown in Fig. 12. The flame velocity of the 7.5% methane concentration continually increased along the detonation tube, and the maximum flame velocity at the end of the detonation tube was 132 m s^{-1}.

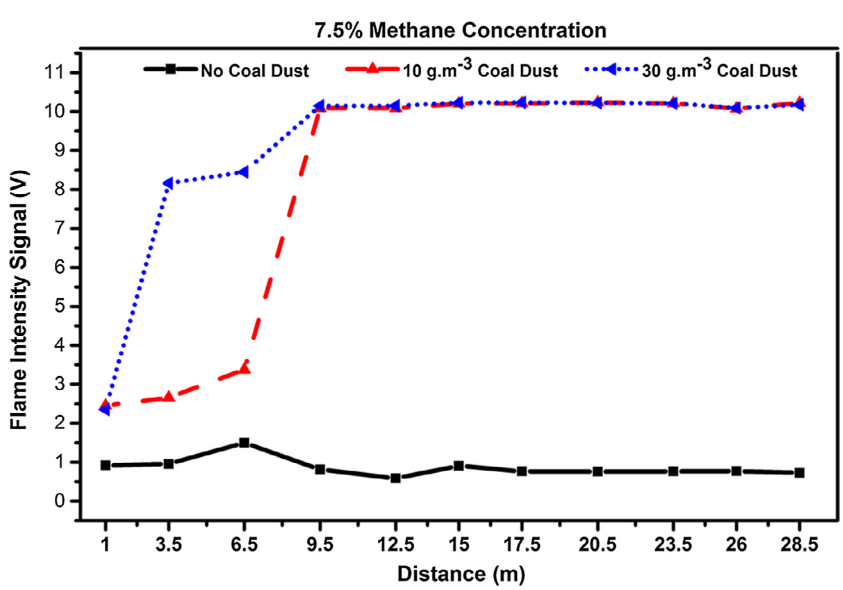

Fig. 10. Flame intensities signal of a 7.5% methane concentration with different coal dust concentrations.

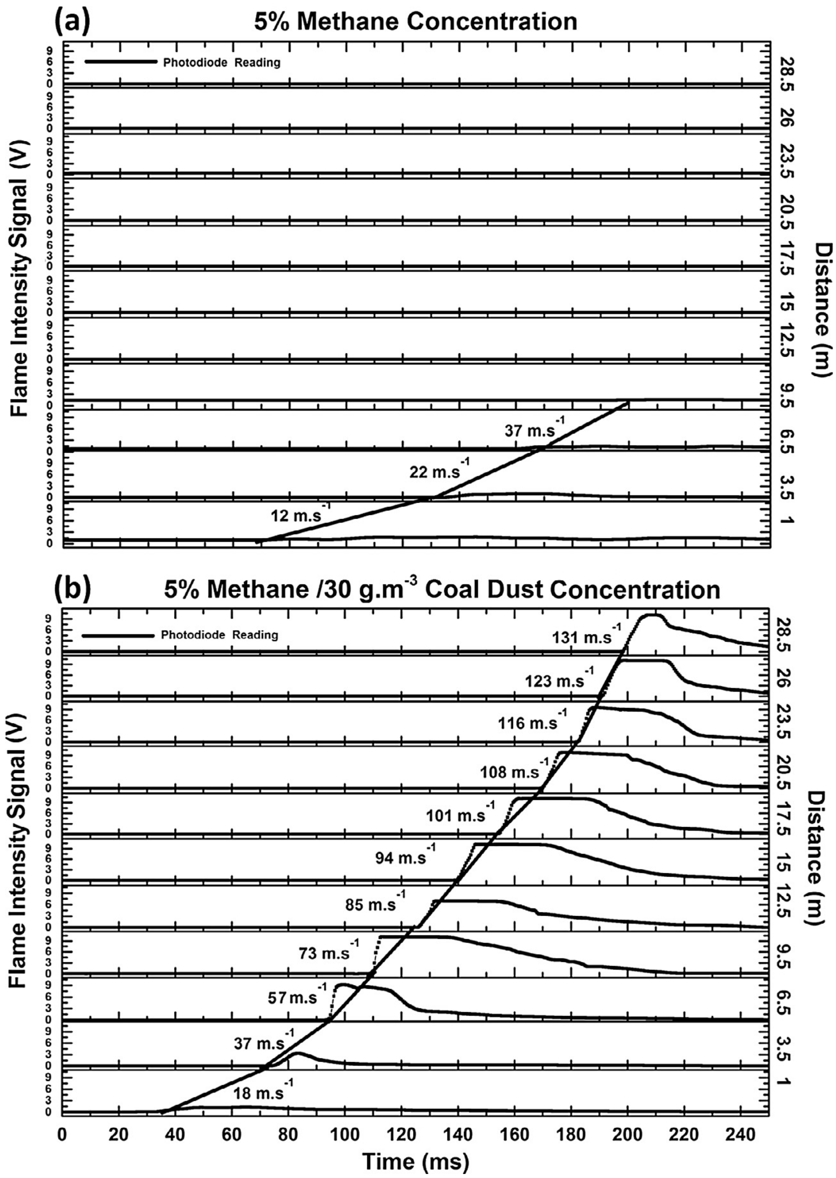

Fig. 11. Flame velocities for (a) 5% methane concentration, (b) hybrid 5% methane concentration/30 g m^{-3} coal dust.

Adding only 10 g m^{-3} coal dust to the 7.5% methane concentration significantly enhanced the flame velocity along the detonation tube. The average enhancement of the flame velocity by the addition of 10 g m^{-1} coal dust was about 16.6%, and the maximum flame velocity was 146 m s^{-1} (see Fig. 12(a)). It was observed that the methane flame velocity was enhancement by introducing coal dust, supporting the fact that the presence the coal dust in hybrid form with methane increased the flame front velocity by increasing the rate of the combustion reaction [55]. Increasing the flame front velocity also led to an increase in the pressure behind the flame front, which accelerated the velocity of the unburned gases ahead of the flame, all these factors combined to increase the flame velocity.

To sum up, the flame velocities continually increased along the detonation tube, irrespective of the values of the photodiode output voltage. A diluted amount of coal dust present in methane deflagration caused an enhancement in the flame velocity. At the lower flammable methane concentration (5%), the average flame velocity increased by 50% for the first 3 sections; for the 7.5% methane concentration, the addition of 10 g m^{-3} coal dust showed a pronounced influence on the flame velocity along the detonation tube; and the maximum flame enhancement reached 55% in the first section of the tube and the average increase in the velocity was 16.6% along the detonation tube.

The over pressure rise, PW velocity, flame velocity and DPR of this work were compared with relevant work in Table 2. The data published by Liu et al. [28] for flame deflagration was over driven with high initial explosion conditions which formed a DDT associated with high magnitude of both over pressure rise and flame velocity. Lebecki et al. [31], used low coal dust concentration (50 g m^{-3}), however, no data regarding the over pressure rise and flame front velocity were reported, but the author confirmed there was a flame deflagration developed along the LSDT. Obviously, the DPR was not highlighted in the relevant work exempting the work published by Wei et al. [57], where the DPR of 9% methane was about 1.4. This indicates that the hybrid mixture of 7.5% methane and 10 g m^{-3} coal dust in the current work gave a high pressure value (DPR of 2) exceeding the equivalent pressure value of 9% methane (near stoichiometric ratio). The comparison is valid as the setups of both works were about 30 m long,

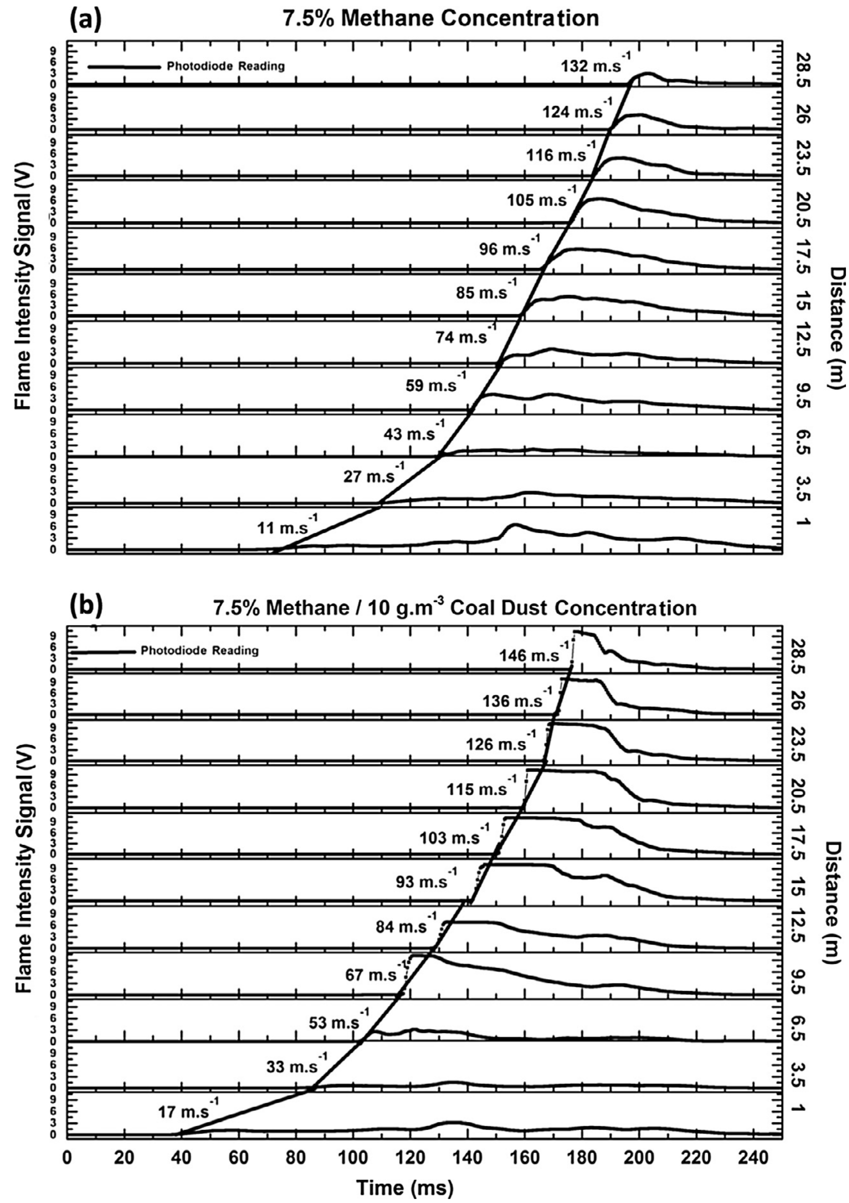

Fig. 12. Flame velocities for (a) 7.5% methane concentration, (b) hybrid 7.5% methane/30 g m^{-3} coal dust.

0.5 m diameter and the measurements were taken at the end of the tube.

4. Conclusion

The influences of diluted coal dust on methane explosions were investigated experimentally at two methane concentrations, 5% and 7.5%, by using a large scale detonation tube. The results showed that the addition of coal dust to a methane mixture has pronounced influences on the stagnation pressure, pressure profile, flame intensity and the flame velocity. The following outcomes were observed:

- The hazards of diluted coal dust appeared in the stagnation and dynamic pressures at the end of the detonation tube. Introducing 10 g m^{-3} coal dust in a hybrid form with a 5% methane concentration did not significantly influence the stagnation pressure or DPR. However, the dynamic pressure rise significantly increased by about 3.6 times when 30 g m^{-3} coal dust was added in a hybrid form with a 5% methane concentration. Also, 10 g m^{-3} coal dust in a hybrid form with a 7.5% methane concentration significantly increased the stagnation pressure by about 2.4 times.
- The work revealed that the addition of coal dust to a methane deflagration not only increases the risk of a methane explosion at the flammability limit, but also increases the pressure wave value along the detonation tube. This was attributed to the fact that the coal dust combustion produces additional gas products behind the flame that develop the pressure wave. According to the stagnation pressure results, 10 g m^{-3} coal dust does not make a significant impact on a 5% methane concentration in hybrid form. However, 30 g m^{-3} coal dust caused the PW to rise by over 0.9 bar along the detonation tube. The most hazardous results occurred for diluted coal dust in a hybrid form with a 7.5% methane concentration. In addition to the value of the pressure wave over pressure rise increasing, the data showed that the pressure wave significantly developed in the last two sections of the detonation tube, which was attributed to the fast

Table 2
Summary and comparison of the current work with the most relevant work in the literature.

Author	Methane conc. %	Coal dust conc. g m^{-3}	Coal dust PSD	LSDT	Initial ignition source	Propagation state	OPR	DPR	Flame velocity
Liu et al. [28]	/	368	Below 74 µm	Length: 30.8 m ID: 0.199 m One end open	Delivered via explosion of 7 m stoichiometric epoxypropane mist/air	DDT	47	/	2000
	9.5	/				DDT	49	/	2000
	7.5	92				DDT	47	/	2070
	5	184				DDT	33	/	2130
Liu et al. [44]	/	243–487	45–70 µm (36% Volatile)		Electrical spark, 40 J	Deflagration	0.58–0.72	/	380–436
	/	243	45–70 µm (36% Volatile)			Deflagration	0.72	/	436
	/	243	45–70 µm (32% Volatile)			Deflagration	0.61	/	417
	/	243	45–70 µm (26% Volatile)			Deflagration	0.49	/	395
Lebecki et al. [31]	/	50	65.5 wt% passing 60 µm sieve	Length: 200 m ID: 0.96 m	NA	No data available, the author confirmed there was flame propagation without acceleration			
	/	100				Deflagration	0.6	/	165
	/	150				Deflagration	4	/	330
	/	200				Deflagration	5.6	/	370
Ajrash et al. [29]	6	10	Below 74 µm	Length: 30 m ID: 0.5 m RS: 5 m	1 kJ Chemical Ignitor	Deflagration	0.49	/	/
	6	30				Deflagration	0.71	/	/
	6	10			5 kJ Chemical Ignitor	Deflagration	0.59	/	/
	6	30				Deflagration	0.8	/	/
	6	10			10 kJ Chemical Ignitor	Deflagration	0.94	/	/
	6	30				Deflagration	1.16	/	/
Bai et al. [56]	4.5	68.75	45–70 µm	Length: 5 m I.D: 2 m Closed Vessel	Electrical spark, 40 J	Deflagration	7.4	/	2–9.2
	5	62.5				Deflagration	7.56	/	2–9.2 –
	6.5	43.75				Deflagration	6.8	/	/
	8.5	25				Deflagration	6.75	/	
Wei et al. [57]	8.7	/	/	LSDT: 30 m ID: 0.5 m R.S: 13.3 m	50 mJ	Deflagration	2.6	/	/
	9	/			50 mJ	Deflagration	4	1.4	/
This work	5	/	Below 74 µm	Length: 30 m ID: 0.5 m RS: 14 m	Two meters of stoichiometric methane/air mixture ignited via 50 mJ	Deflagration	0.48	0.16	37
	5	10				Deflagration	0.47	0.18	/
	5	30				Deflagration	0.96	0.56	131
	7.5	/				Deflagration	2.1	0.74	132
	7.5	10				Deflagration	3.07	2	146
	7.5	30				Deflagration	3.3	2.65	/

deflagration of the flame that may have led to detonation if the tube were long enough to sustain this phenomenon.

- The hazards of the flame travel distance are boosted with the introduction of coal dust to the system, where the flame from the 5% methane concentration extended from a distance of 12.5 m to 20.5 m when 10 g m^{-3} coal dust was introduced in a hybrid form. The flame travelled to the end of the tube with the addition of 30 g m^{-3} coal dust in hybrid form with 5% methane concentration. These outcomes were observed from the photodiode readings along the detonation tube. Additionally, the photodiode output voltage of methane did not exceed 1.2 V. At 5% methane concentration, the flame intensity reached 4.5 V with the addition of 10 g m^{-3} coal dust in hybrid form. The photodiode output voltage reached a maximum value (10.2 V) with the introduction of 30 g m^{-3} coal dust as in hybrid form. The photodiode reading reached the maximum values for the hybrid forms for both 10 g m^{-3} and 30 g m^{-3} coal dust with 7.5% methane concentration as a result of burning the coal dust particles in the system.
- The flame velocity is the most concerning property in designing a safety system. The coal dust particles accelerated the flame velocity at both methane concentrations (5% and 7.5%), which were investigated in the current work. The flame velocity accelerated by about 1.4 times with the introduction of 30 g m^{-3} coal dust to 5% methane concentration. Moreover, the average flame velocities along the detonation tube accelerated by about 1.15 times with the introduction of 10 g m^{-3} coal dust concentration.

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