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Impact of suspended coal dusts on methane deflagration properties in a large-scale straight duct

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Abstract

Knowledge about flame deflagrations in mixtures of methane and diluted coal dust assists in the prediction of fires and explosions, and in the design of adequate protective systems. This vital lack of information on the role of hybrid mixtures (methane/coal dust) is covered in this work by employing a novel Large-Scale Straight Duct (LSSD) designed specifically for this purpose. The hybrid fuel was injected along the first 8 m of the 30 m long LSSD. The results revealed that a 30 g.m⁻³ coal dust concentration boosted the flame travel distance, from 6.5 m to 28.5 m, and increased the over pressure rise profile to 0.135 bar. The over pressure rise (OPR), pressure wave velocity, flame intensity and the flame velocity were significantly boosted along the LSSD in the presence of 10 g.m⁻³ or 30 g.m⁻³ coal dust concentrations in the methane flame deflagrations. Finally, the high speed camera showed that the presence of the coal dust increases the wrinkling in the front flame. Consequently, the pressure wave and flame velocities were both increased when a 10 g.m⁻³ coal dust concentration coexisted with a 9.5 % methane concentration in the deflagration.

1. Introduction

Continuing problems with the flame deflagration of flammable gases and combustible dusts exist in the mining and process industries. The complexity of methane and coal dust deflagrations are still poorly investigated, although, numerous accidental fires and explosions have occurred in the coal mining industry [1–3]. Most of the previous research on methane and coal dust explosions has been conducted in laboratory scale experimental setups, due to the fact that large experimental setups have higher operational costs, higher capital costs and a longer time is required to achieve the tests.

The hazards of methane gas in the presence of coal dust during combustion is highlighted by Nagy [3, 4]. The conclusions that Nagy made were that coal dust-methane mixtures required less energy to ignite than either one alone, and that the explosion severity is higher. Bartknecht [5, 6] continued the investigation of hybrid mixtures, including methane coal dust mixtures. In agreement with Nagy, Bartknecht et al. found that a mixture of methane and a combustible gas could be ignited below their respective lower explosion concentrations, and he also developed a quadratic relation to predict the minimum explosion concentration for the hybrid mixture. The relation is in disagreement with the straight relation of Le Chatelier's mixing rule for flammable limits [7, 8]. The research findings by Nagy et al. and Bartknecht et al. are considered a good reference for hybrid mixture explosions. The behaviours of methane coexisting with coal dust in hybrid mixtures are important to examine for safety measures in the process industry [10–12].

The influences of coal dust on methane lowers the flammability limit were later investigated by Amyotte et al. [13,14], the authors clarified the influences of 1% and 2% methane concentrations on the coal dust explosion characteristics for several types of coal dust. No significant influence of methane on the Pressure Rise (PR) of a coal dust explosion when the concentration of the coal dust was over 500 g.m^{-3} [13,14]. Another experimental and theoretical study was performed by Landman [15] on methane coal dust lower flammability limits. In agreement with Bartknecht et al. and Cashdollar et al., he found that a coal dust concentration, even at 50 g.m^{-3} , reduced the lower flammability limit of methane.

The influence of coal dust on methane ignition delay was highlighted by Li et al. [16]. A 3.5 m length and 3.25 m diameter explosion chamber was employed for that purpose. The researchers concluded that the delay time of methane ignition may increase with decreasing coal particle size. No systematic correlation was observed between the coal dust composition and the delay time of the methane ignition. Xie et al. [17,18] experimentally examined the

interactions of coal dust with premixed methane flames at lean concentrations by employing a laboratory-scale dust burner equipped with a shadowgraph macro lens. The scholars concluded that particle sizes below 25 μm promoted the burning rate of the methane flame, even at low concentrations [18]. Rockwell [19] investigated the influence of coal dust on the burning rate of methane by employing a new laboratory apparatus called a Hybrid Flame Analyser. The author found that the size and concentration of the coal dust were key factors in enhancing the methane flame's velocity by increasing the burning rate. Particle sizes between 106 μm - 125 μm may enhance or reduce the turbulent flame velocity, depending on the coal dust concentrations; however, the laminar flame velocity was reduced. Particle sizes below 106 μm , and at concentrations of 74 g.m^{-3} and above, were found to enhance the burning rate of the flame [26, 27]. This was in line with the findings of Chen [21], where he observed that the presence of methane in coal dust explosions, or vice versa, enhanced the flame velocity of the mixture.

The explosion characteristics of hybrid mixtures at diluted concentrations of methane and coal dust were illustrated by Ajrash et al. [29, 30]. A 20 L explosion chamber and three initial ignition types (1, 5 and 10 kJ) were used to illustrate the explosion characteristics of the lower explosion limit as a function of the initial energy. The coal dust concentrations were between 10 g.m^{-3} to 30 g.m^{-3} , and the methane concentrations were between 0.75% to 5%. At the methane Lower Flammable Limit (LFL) concentration (5%), the influence of 50 g.m^{-3} on the methane explosion was obvious at all three initial ignition energies. However, a 25 g.m^{-3} coal dust concentration significantly boosted the severity of the methane explosion when using 5 kJ and 10 kJ as the initial ignition source. Finally, with a 10 kJ initial ignition source, 10 g.m^{-3} coal dust enhanced the PR of methane from 0.8 bar to 1.7 bar, and enhanced the pressure rise rate from 2 to 9 bar.s^{-1} . Ajrash et al. [24] later clarified the influences of diluted coal dusts of 10 g.m^{-3} and 30 g.m^{-3} concentrations on the methane flame velocities in a 1 m^3 cylindrical explosion chamber. The researchers showed that at a 6% methane concentration, the ignition was delayed by 25 ms with the introduction of a 30 g.m^{-3} concentration to the mixture. Hybrid mixtures of flammable gases, including propane and combustible dusts, were also experimentally investigated by [25–29].

To date, there are few experimental studies which have investigated the flame deflagration and explosion characteristics of methane coal dust mixtures in a large apparatus.

Bai et al. [30] employed a 10 m³ cylindrical explosion chamber (2 m diameter and 3.5 m length). The researchers found that the maximum pressure for methane explosion was 6 bar and that it appeared at a distance of 0.75 m. However, the presence of coal dust in a hybrid form in a methane explosion increased the value of the maximum pressure and reduced the distance required to reach the peak pressure. Liu et al. [31] employed a Large Scale Straight Duct (LSSD), 30.8 m long by 0.199 m diameter. A high energy initial ignition source was used to drive the explosion in the detonation tube, which was delivered in a 7 m explosion chamber fuelled by epoxypropane mist/air [39, 40]. The fuel mixtures in the LSSD consisted of methane in the range of 2.5% - 9.5% concentrations and coal dust in the range of 0 to 368 g.m⁻³. Due to the strong initial ignition conditions and sufficient fuel and flame deflagration distances, the phenomena of deflagration to detonation transition (quasi donation) was formed in methane coal dust compositions, other scholars have studied flame deflagrations and detonations of methane [34–44]. Another team focused on deflagrations and coal dust explosions in a LSSD [45–48].

The literature review has shown that methane coal dust explosion properties have been well investigated in small and confined laboratory-scale explosion chambers. However, not much research was found for the methane-coal dust explosions at an industrial scale in the open domain. The presented findings for these limited number of studies are also very scattered and in some cases do not comply with the real case scenarios. For instance some of assumed or decided initial conditions or fuel concentrations hardly can occur in real operation conditions. This work is an attempt to investigate the properties of methane gas and coal dust deflagration under conditions pertinent to coal mines or extractive industries. To achieve the broad objectives of this study a comprehensive experimental and theoretical investigation conducted on LSSD designed and constructed at the University of Newcastle, Australia.

2. Methodology and Techniques

The LSSD used in this study consisted of eleven spools with a diameter of 0.5 m, a total length of 30 m, and a 6 m silencer attached at the end of the LSSD, together with a dual wall sound mitigation enclosure to reduce the noise of the explosions (see Figure 1). Three tracking sensors for measuring the pressure and flame (pressure transducer and photodiodes) were mounted on the middle of each section along the LSSD. Three high response pressure transducers (<0.1 ms) were mounted in the middle of each section to track the pressure changes, with a reading range of up to 60 bar and an error reading of less than 0.25%. Three

photodiodes (with an active area of 0.8 mm^2 , a wavelength range 200 - 1100 nm, a rise time of 1 ns and a bias of 0.6 V) were also mounted in the middle of each section to track the flame travelling.

Figure 1: The Large Scale Straight Duct (LSSD) at the University of Newcastle, Australia

Two pyrometers were employed to detect the temperature changes at Section 1 and Section 6. The front flame and explosion behaviour were recorded by a Phantom 4 camera (high speed camera, 2000 frame/second), see Figure 2.

Figure 2: (a) pyrometer at Section 1, (b) high speed camera mounted at the side of Section 1, and (c) pyrometer mounted at Section 6

The hybrid mixtures were achieved in two stages, firstly by injecting the methane at the ultimate concentration and waiting until the methane was well mixed with the air via two circulation systems. The homogeneity of the methane was observed using two methane monitors at Section 1 and Section 2. Each section of the tube includes two coal dust injectors

(see Figure 4). The injectors could be engaged or disengaged to participate in the experimental work according to the experimental plan. Each injector consists of two parts: i) dust chamber and ii) nozzle head. For each experiment the coal dust was injected into the tube by compressed air and dispersed uniformly via a customised nozzle head (see Figure 3). The injection of coal dust starts 1000 ms before the ignitor activation.

Figure 3: coal dust injection nozzle

Figure 4: Components of the LSSD at the University of Newcastle, Australia

The reactive sections shown in Figure 4 represent the part of the tube filled with methane and coal dust (i.e. spools 1, 2 and 3 in this figure). No fuel was injected in the non-reactive sections. The reactive sections were isolated from the non-reactive sections by using a balloon sealing system. Isolating balloons were placed in the predefined locations and then inflated to the point at which the reactive and non-reactive sections separated and sealed from each other. The coal dust samples were collected from Australian mines in NSW, and the samples were stored under a cold condition (3°C) to preserve the chemical properties from

oxidation. The proximate analyses and particle size distributions (PSDs) of the coal samples are shown in Table 1, the PSD was measured by using a Malvern instrument.

Table 1: Coal dust properties

Carbon %	Moisture %	Ash %	Volatile Matter %	D ₉₀ (μm)	D ₅₀ (μm)	D ₁₀ (μm)
43.7	4.7	10.3	28.1	71.56	20.51	1.52

Where, D₉₀, D₅₀ and D₁₀, respectively represent particle size percentages that are less than 90%, 50% and 10%.

3. Results and discussions

3.1 Pressure Profile

The combustion of premixed methane air mixtures causes rapid increases in the pressure. The most dangerous combustions occur in long tubes. The explosion hazards can be exacerbated in case of the travelling wave of combustion causing damage to the infrastructure, or the travelling wave pressure may couple with the pressure wave of a secondary explosion and cause a piling pressure. The combustion of the fuel travels in a flame form, and the continuously travelling flame not only keeps the momentum of the pressure wave, but can also increase the magnitude of the pressure wave on some occasions. Eventually, the deflagration to detonation phenomenon may occur if the travel distance is adequate, as well as the L/D ratio and fuel.

This section clarifies the influences of the diluted coal dust (i.e., 10 and 30 g.m⁻³ concentrations) on the wave PR and the flame intensity signal of the methane deflagration in a large-scale detonation tube. The wave PRs of the methane coal dust mixtures are shown in Figure 5. The wave PR of a 5% methane concentration (see Figure 5 (a)), revealed that at 5% methane (the lower methane flammable limit), a slight pressure wave formed which varied between 0.05 bar and 0.08 bar along the detonation tube. This was in consonance with previous studies, including the PRs of methane concentrations at the lower flammability limits [37, 55, 56]. 10 g.m⁻³ coal dust in the methane ignited at the LFL had no consequence on the pressure wave (see Figure 5 (a)). These findings were in line with a previous study using a 20 L explosion chamber [22]. Adding 30 g.m⁻³ coal dust increased the wave PR in the range of 0.1 bar to 0.135 bar. In spite of the PR boost, the mixture didn't reach the explosion

criteria defined by [51], where the PR should reach or cross over 0.3 bar. This result disagreed with previous work [22], where only 25 g.m⁻³ coal dust concentration boosted the PR of a 5% methane concentration to about 2 bar. The discord between this work and the literature review is attributed to several main facts. Firstly, the differences in the coal dust compositions and in the 20 L explosion chamber. Also, it had been experimentally proven that a 5 kJ initial ignition source over drives the explosion [52], and scaling the explosion chamber up could reduce the pressure rise and the developed temperature [59, 60].

Methane explosions at a 7.5% concentration showed a high sensitivity to the diluted coal dust (i.e., 10 g.m⁻³ and 30 g.m⁻³ coal dust). The wave PR of a 7.5 % methane concentration is shown in Figure 5 (b). The explosion of pure methane (7.5% concentration) formed a pressure wave travelling along the LSSD at a magnitude of between 0.42 and 0.75 bar. The presence of a 10 g.m⁻³ coal dust concentration significantly increased the value of the PR along the LSSD, where the pressure wave travelled at a magnitude of between 0.84 bar and 1.1 bar. Adding a higher coal dust concentration (30 g.m⁻³) to the explosion of a 7.5% methane mixture increased the maximum PR by 69%. The maximum value of the PR was located at 17.5 m distance for a pure 7.5% methane concentration and a methane coal dust mixture. The behaviour of the methane explosions at stoichiometric concentrations showed a distinct response to the diluted coal dust concentrations (10 g.m⁻³ and 30 g.m⁻³) from the 7.5% and 5% methane concentrations. The wave PR of a 9.5% methane concentration are shown in Figure 5 (c). The wave PR of pure methane travelled at a magnitude of between 1.06 bar to 1.54 bar, similar to a 7.5% methane concentration, and the maximum PR was achieved at a distance of 17.5 m. This indicated that the flame velocities were accelerated, causing an exertion of pressure ahead of the flame and an increased turbulence of the flame. Introducing 10 g.m⁻³ coal dust to the methane explosion produced a severe pressure wave travelling between 1.24 bar and 3.75 bar. Figure 5 (c) shows that the pressure rise for 9.5% methane and 10 g.m⁻³ coal dust is significantly higher at the first half of the tube length (up to 12.5 m). This indicates that the concentration of the hybrid fuel reaches its optimum value “stoichiometric”, where maximum pressure produced. The pressure wave rises then gradually declines as the flame moves toward the end of the tube where there is a limited fuel supply. In the case of increasing the coal dust concentration to 30 g.m⁻³, instead of 10 g.m⁻³, the wave PR reduced by 50% compared to the wave PR of 9.5% methane/10 g.m⁻³ coal dust mixture explosions. The decrease in the wave PR was due to the excess of fuel in the system, resulting in the decreased pressure rises and burning rates of the fuel.

(a) 5% Methane

(b) 7.5% Methane

(c) 9.5 % Methane

Figure 5: pressure wave of methane with coal dust deflagration (a) 5% methane concentration, (b) 7.5% methane concentration, (c) 9.5% methane concentration

3.2 Flame deflagration at a 5% methane concentration

The behaviour of methane ignition at the LFL is very important for safety in the process industry. The previous section showed that the flame significantly developed with the addition of 30 g.m^{-3} coal dust to a 5% methane concentration. Getting an insight into the flame deflagration along the LSSD is important for increasing the knowledge of the influences of coal dust on methane ignition at the LFL. The pressure transducer, photodiode and pyrometer readings for a 5% methane/ 30 g.m^{-3} coal dust mixture are shown in Figure 6.

Figure 6: Flame deflagration of 5% methane/ 30 g.m^{-3} coal dust, F.V. referring to flame velocity

The pressure reading at 3.5 m distance showed a slight pressure rise at 13 ms, resulting in the ignition of the ignitors and the combustion of the methane, and at about 37 ms the pyrometer detected the combustion of methane. The photodiodes, however, firstly detected the flame at about 285 ms. The gap between the first detection of the pressure and the photodiode is attributed to the ignition of the coal dust particles. The delays in the coal dust explosions at the LFL (255 ms) was varied according to the methane percentage, coal dust and the energy of the initial ignition source [29, 31]. The flame reached 3.5 m distance from the ignition position at a velocity of 12.5 m.s^{-1} . The flame velocity then developed by about 55% and reached the maximum value 9.5 m from the ignition source. The data profile (Figure 6 (c)), supported the concept of the methane being consumed just after the reactive system and the coal dust disperse in the axial direction of the flame propagation. This was due to the expansion of the product, where at 20.5 m the temperature was detected at the same time as the flame intensity signal. Finally, the pressure wave didn't appear clearly along the detonation tube, where it fluctuated in the range of 0 to 0.16 bar.

3.3 Flame deflagration at a 7.5% methane concentration

The deflagration characteristics of methane coal dust explosions are mainly related to the fuel concentrations. The previous section illustrated hybrid explosions and flame deflagrations at methane LFL. However, this section clarifies the influence of 10 g.m^{-3} and 30 g.m^{-3} coal dust concentrations on the explosion of 7.5% methane concentrations. The pressure wave and the flame velocity for the methane coal dust are shown in Figure 7 and Figure 8 respectively. The data for the methane and methane/coal dust mixtures were precisely examined and analysed. The pressure wave velocity and flame velocity were calculated in accordance to the position of the initial ignition source as a stationary point. In spite of the fact that the pressure wave initially results from the combustion of the products of the flame, the pressure wave velocities of pure flammable gas or combustible dust are usually faster than the flame unless the phenomena of deflagration to detonation transition emerged [55–57]. The results of the 7.5% methane explosions totally agreed with the previous findings. However, it was found that the flame velocity developed and arrested corresponding to the pressure wave on different occasions. Figure 7 (i) illustrates the pressure waves and flame velocities of a pure 7.5% methane concentration. The pressure wave velocity, for most sections, was ahead of the flame. Notwithstanding, the flame velocity was faster than the pressure wave, and the reason is that the pressure wave was considered only when there was a 0.3 bar increase in the pressure.

Pressure Wave Velocity of 7.5% Methane Concentration

Figure 7: Pressure waves of a 7.5% methane coal dust mixture

Flame Velocity of 7.5% Methane Concentration

Figure 8: flame deflagrations of a 7.5% methane coal dust mixture

The pressure wave significantly developed after Section 2, and the flame was followed by the pressure wave along the detonation tube. This case was true in all of the 7.5 % methane and 7.5% methane coal dust explosions in this work. The gap between the pressure wave and flame velocity continued to increase from Section 2, and reach a maximum at Section 7, where the pressure wave velocity was ahead of the flame velocity by about 69.1 m.s^{-1} . The flame velocity then accelerated and reached the end of the LSSD, and was only 19.1 m.s^{-1} behind the pressure wave. The presence of 10 g.m^{-3} coal dust in a 7.5% methane combustion significantly accelerated the pressure wave and flame front velocities, as illustrated in Figure 8(ii), and the average enhancement of the flame's velocity along the LSSD reached about 32.4 m.s^{-1} . As a result of the flame velocity, the pressure wave was enhanced greatly, by about 57% in Sections 9, 10 and 11, as compared to the pressure wave of a pure 7.5% methane concentration. However, the enhancement in Sections 2 to 9 was about 15%. The gap between the pressure wave velocity and the flame velocity, in a similar behaviour to the explosion of a 7.5% methane concentration, reached a maximum value (60.8 m.s^{-1}) at Section 10. The pressure wave and flame velocity were enhanced by increasing the concentration of the coal dust to 30 g.m^{-3} . The average flame velocity was enhanced by about 52.2 m.s^{-1} , and the average pressure wave velocity significantly increased from Sections 2 to 11 by about 51% (see Figure 8 (iii)). The gap between the pressure wave velocity and the flame front velocity gradually increased until reaching Section 7, where the gap was 101.8 m.s^{-1} . The gap was then in the range of 108 m.s^{-1} to 88.1 m.s^{-1} for the remaining sections of the detonation tube.

3.4 Flame deflagration at a 9.5% methane concentration

The equivalence ratio is another important factor in developing the explosion and flame deflagration characteristics of methane air combustions. The maximum severity of the fuel/air explosion was established in the range of the stoichiometric concentration [58,59]. This section discusses the influence of 10 g.m^{-3} and 30 g.m^{-3} coal dust on the methane deflagration velocity at the stoichiometric concentration. The pressure wave and flame velocities were shown in Figure 8 for 9.5% methane concentrations. The pressure wave velocity reached the maximum value at the stoichiometric methane concentration and was in consonance of published work [58,59]. The pressure wave travelled at twice that of the 7.5% methane concentration after 26 m, with a 32% enhancement of the flame velocity as compared to the flame velocity at the end of the detonation tube. The other noticeable behaviour was that the average gap between the pressure wave velocity and flame velocity for the 9.5% methane

concentration was higher, by about 59 m.s^{-1} , as compared to the 7.5% methane concentration. Due to the limitation of the fuel in the LSSD (8 m reactive sections), the flame velocity declined at 28 m. Consequently, a huge decline in the pressure wave velocity of about 62 m.s^{-1} occurred. The decline in the flame velocity reduced with the introduction of coal dust to the methane explosion. It was noticed for the deflagration of the 9.5% methane/10 g.m^{-3} coal dust, the decline of the pressure wave velocity was reduced to 25 m.s^{-1} . The decline was not present with the introduction of the 30 g.m^{-3} coal dust to the methane mixture, where the pressure wave velocity and the flame velocity continued to increase as a symptom of sufficient fuel being in the mixture (see Figure 9). These outcomes were consonance with the previous LSSD study [24]. The data revealed that introducing 10 g.m^{-3} coal dust to a 9.5% methane concentration boosted the pressure wave velocity and the flame velocity (see Figure 9 (b)). In addition to the PR, as discussed previously in Section 3.1, the enhancement of the pressure wave velocities and flame velocities from Sections 2 to 11 were 8.9% and 10.7%, respectively. The gap between the pressure wave and the flame velocity slightly reduced by 2 m.s^{-1} . The typical methane flame travels in a hemispherical shape, depending on the distance and the developing stage of the flame, due to the hydrodynamic instability across the tube [60]. The curve in the flame front increases the burning rate of the flame, which results in the flame accelerating into a finger shape while travelling. The flame images at a fixed distance (about 1.5 m from the ignition source) for the 9.5% methane concentration and 9.5% methane/10 g.m^{-3} coal dust mixture showed the flame of the 9.5% methane concentration travelled in a hemispherical shape with a slight oscillation due to the hydrodynamics and developments of the flame (see Figure 10 (b)). The presence of the coal dust, however, increased the oscillation and the wrinkling of the front flame and resulted in an increment in the burning rate and eventually increased the flame velocity [61,62]. The volume of the combustion products eventually increased. The images of the flame deflagrations also showed that part of the coal dust exploded after the flame front, by about 80 ms, which was in agreement with previous work on methane coal dust explosion behaviours [22]. A further increase in the coal dust concentration (i.e.30 g.m^{-3}) with the 9.5% methane concentration seemed to push the explosion further to the rich fuel region, where the explosion characteristics become less severe. The results revealed that the introduction of 30 g.m^{-3} coal dust to the 9.5% methane deflagration arrested the pressure wave velocity by about 58%, and the flame velocity by 2.5%.

Figure 9: Pressure waves and flame velocities of a 9.5% methane coal dust mixture

Figure 10: Images of flame deflagrations for a 9.5% methane concentration and a 9.5% methane coal dust mixture, the camera located 1.5 m from ignition source

4. Conclusion

Methane flame deflagrations in one end open tubes are highly affected by the presence of dilute coal dust concentrations, i.e., 10 g.m^{-3} and 30 g.m^{-3} . The large-scale experimental data in this study revealed that the influence of diluted coal dust on the premixed methane flame deflagration characteristics varied with the fuel concentrations in the tube between enhancement, arrestment and being unnoticeable. The presence of 10 g.m^{-3} coal dust in the combustion of a 5% methane concentration didn't show significant changes in the deflagration characteristics. In contrast, the presence of 30 g.m^{-3} coal dust increased the flame intensity signal from about 0.1 to 10 V and enhanced the flame travel distance, from 6.5 m to 28.5 m, and was associated with an increase in the PR up to 0.135 bar. In direct proportion, the diluted coal dust concentrations significantly enhanced the flame deflagrations for 7.5% methane concentrations. The presence of 10 g.m^{-3} coal dust increased the PR from the low range of 0.42 bar - 0.75 bar to the high range of 0.85 bar - 1.1 bar. The flame intensity signal also reached the maximum value, in addition to the enhancement of the average velocities of the pressure waves and the flame fronts, respectively, by about 6.1 m.s^{-1} and 32.3 m.s^{-1} along the LSSD (Sections 2 to 11). Increasing the coal dust concentration to 30 g.m^{-3} boosted the PR to the range of 1.29 bar -1.95 bar, and the pressure wave and flame front velocities increased to about 51.4 m.s^{-1} and 52.2 m.s^{-1} , respectively, along the detonation tube. The flame deflagration characteristics of the 9.5% methane concentration were enhanced by the addition of 10 g.m^{-3} coal dust, where the PR reached about 3.75 bar, and the pressure wave and the flame velocities were enhanced, respectively, by about 8.9 m.s^{-1} and 10.72 m.s^{-1} . The presence of 30 g.m^{-3} coal dust, however, arrested the average pressure wave velocity by about 58.5 m.s^{-1} with negligible influence on the flame front velocity, resulting in reducing the time gap between the pressure wave and the flame to about 34 m.s^{-1} instead of 90 m.s^{-1} , as compared to the deflagration of a 9.5% methane concentration only.

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