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

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HIGHLIGHTS

- $10\,g\,m^{-3}$ coal dust increase the wrinkling and the burring rate in methane front flame.
- Flame velocity of 5% and 7.5% methane boosted by introducing the dilute coal dust.
- Pressure wave velocity of 9.5% methane decelerate by introducing $30\,g\,m^{-3}$ coal dust.

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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 enhanced the turbulence 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

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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 m^3 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 0–368 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 Fig. 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.

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

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 Sections 1 and 2. Each section of the tube includes two coal dust injectors (see Fig. 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 Fig. 3). The injection of coal dust starts 1000 ms before the ignitor activation.

The reactive sections shown in Fig. 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)