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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