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

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ABSTRACT

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

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

1. Introduction

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

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

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

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

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

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

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

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

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

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

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