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A new shock tube configuration for studying dust-lifting during the initiation of a coal dust explosion

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ABSTRACT

The traditional defence against propagating coal dust explosions is the application of dry stone dust. This proven and effective safety measure is strictly regulated based on extensive international experience. While new products, such as foamed stone dust, offer significant practical benefits, no benchmark tests currently exist to certify their dust lifting performance in comparison to dry stone dust. This paper reviews the coal dust explosion mechanism, and argues that benchmark testing should focus on dust lifting during the initial development of the explosion, prior to arrival of the flame. In a practical context, this requires the generation of shock waves with Mach numbers ranging from 1.05 to 1.4, and test times of the order of 10's to 100's of milliseconds. These proposed test times are significantly longer than previous laboratory studies, however, for certification purposes, it is argued that the dust lifting behaviour should be examined over the full timescales of an actual explosion scenario. These conditions can be accurately targeted using a shock tube at length scales of approximately 50 m. It is further proposed that useful test time can be maximised if an appropriately sized orifice plate is fitted to the tube exit, an arrangement which also offers practical advantages for testing. The paper demonstrates this operating capability with proof-of-concept experiments using The University of Queensland's X3 impulse facility.

1. Introduction

Underground coal mines are immersed in coal dust, which is produced during the cutting, moving, and processing of coal in the mine (Harris et al., 2010). This dust, which can float through the mine many metres away from its source, settles onto horizontal surfaces such as walkways, work surfaces, shelving, overhead surfaces, and so forth. In the confined spaces of a coal mine, a coal dust explosion may occur when these fine particles of coal are raised into the air and in some way are ignited (Humphreys & OBeirne, 2000). The source of this ignition is termed the initiator.

The normal initiator for a coal dust explosion is the accidental ignition of methane, a gas which is produced during the mining of the coal, and like the coal dust itself, is ever-present in coal mines (Cybulski, 1975). A methane explosion can be responsible for both raising a dangerous cloud of coal dust, and at the same time, providing the heat required to ignite the dust cloud (Cybulski, 1975). Other potential initiators include shot firing, friction sparks, electrical arcing, and naked flame, although these must be coupled with a ventilation/wind source to initially raise the coal dust into the air (Cain, 2003). When a volume of methane ignites within the confined space of the mine, a shock wave is propagated ahead of the flame front. Air between the shock and the flame front has induced velocity which causes it to raise the coal dust, and mix it with air into explosive conditions. A propagating explosion begins when the trailing flame ignites the lifted coal dust. As Humphreys and OBeirne (2000), p. 1 note:

> "*Until there is a break in this cycle of raising then igniting coal dust, the explosion continues to propagate, generating destructive pressures and large quantities of irrespirable and toxic gases. Ultimately, a coal dust explosion could pass through the entire coal mine until it reached the surface.*"

Coal dust explosions fall under the more general category of dust explosions; Fig. 1 from Sichel, Kauffman, and Li (1995) details the stages involved in a dust explosion. It can be seen that in the most powerful dust explosions the pressure and temperature rise from the shock itself are sufficient to combust the coal dust/air mixture (Sichel et al., 1995), resulting in a detonating explosion, however it is thought that this mode has not occurred in any real-

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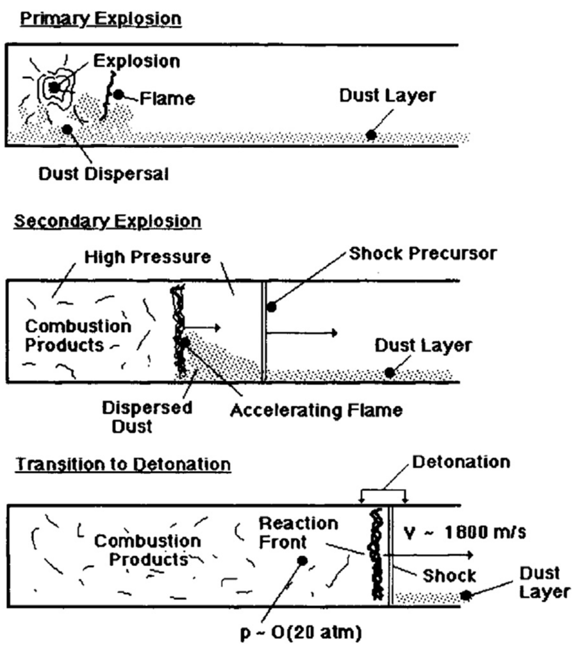

Fig. 1. Elements of a layered dust explosion (reproduced with permission from Sichel et al. (1995, Fig. 1)).

life coal mine explosions (Cybulski, 1975; Oberholzer, 1997). Even if the initial explosion of methane is a relatively minor event by itself, the propagating coal dust explosion which ensues may be a truly devastating event. "*Miners frequently survive gas explosions; they rarely survive explosions in which coal dust has a major involvement*" (NSW DPI, 2001, p. 4).

2. Stone dusting

The primary defence against propagating coal dust explosions is stone (or rock) dusting. First employed in the early 20th century, this involves distributing a layer of stone dust, typically limestone, over working surfaces exposed to coal dust (Cain, 2003). During an explosion, the stone dust disperses into the air, mixes with coal dust, and prevents propagation of the explosion flame through the coal dust (Man & Teacoach, 2009).

Stone dust acts as a thermal inhibitor/heat sink (Man & Teacoach, 2009), absorbing energy from the system, blocking coal particles from radiation arising at the flame front (there by reducing preheating of the coal), and can reduce flame temperature such that devolatilisation no longer occurs in the coal particles (Cashdollar et al., 2010; Cybulski, 1975; Dastidar, Amyotte, & Pegg, 1997; Harris et al., 2010; Man & Teacoach, 2009). In sufficient quantities stone dusting will completely prevent explosion propagation (Cashdollar et al., 2010).

The amount of stone dust which is required to suppress the explosion of a cloud of coal dust can be defined in terms of the Total Incombustible Content (TIC) of the coal dust/stone dust mixture. The higher the TIC, the greater the stone dust content in the mixture. The minimum TIC to suppress an explosion depends on the explosibility of the coal dust, which varies with the type of coal (which itself is unique to each geographical mine site), and the condition of the coal dust (for example, the particle size, the internal surface area, moisture content, and so forth (Cain, 2003; Woskoboenko, 1988)). The explosibility of a given coal dust, and the minimum TIC to suppress its explosion, can both be established in the laboratory setting (Woskoboenko, 1988).

However, within a practical mine setting, sufficient stone dust must be applied so that the *raised dust cloud* has the required minimum TIC, not simply the aggregate surface dust, and this dust cloud must be adequately mixed. Fig. 2 shows an example of fine float coal dust resting on top of a thick layer of stone dust. Float coal dust refers to coal particles capable of floating through the mine workings, and are generally considered to consist of particles of coal smaller than 75 microns (NIOSH, 2006).

The Office of Mine Safety and Health Research (OMSHR) notes that *"layering of coal dust on top of rock dust can defeat all rock dusting efforts"* (OMSHR, 2014); even a thin layer of float coal dust, which can be raised by a relatively weak initiating explosion, can support a propagating coal dust explosion. For typical mine dust, in a typical mine setting, the minimum thickness of coal dust on the floor required to support an explosion may be as little as 0.05 mm (Cain, 2003; NSW DPI, 2001). However, considering a typical mine, foot prints in the coal dust would normally be unobservable until the dust was significantly thicker than 0.1 mm; visible foot prints indicate sufficient coal dust to propagate an explosion (Stephan, 1998).

A weak initiator, while capable of raising float coal dust, may only be powerful enough to scour just the upper surface of any underlying stone dust. Weak explosions associated with float coal dust are normally assumed to strip only a thin layer of floor dust away, typically 2–4 mm (Cain, 2003; Harris et al., 2010; Humphreys & OBeirne, 2000; NIOSH, 2006). To ensure sufficient inert content within the *raised dust cloud*, it is therefore necessary to repeatedly apply stone dust so that the top few millimetres of surface dust thickness (i.e. the thickness of dust that will actually be scoured by the explosion front) meets minimum TIC requirements. Referring to Fig. 2, most of the observed through-thickness stone dust is therefore unlikely to contribute to the suppression of a weak explosion.

The problem of float coal dust drives the stone dusting process within mines, and has significant practical implications on mining operations. The conventional method of distributing stone dust is to spray dry stone dust onto surfaces exposed to coal dust. To prevent exposure to airborne dust, personnel must be extracted while the dust remains airborne. As a result there can be large delays to production before the air clears (Mining Mirror, 2013).

Slurry (or wet) stone dusting involves mixing water with the stone dust before spraying it (OMSHR, 2014), and can avoid the production delays associated with dry stone dusting. Oberholzer et al. (2005) conducted a detailed review of slurry dusting and arrived at a number of conclusions, including the following:

- The slurry dust was effective at gathering and capturing existing coal dust. It was also much more effective than dry stone dust at adhering to inclined surfaces such as the walls and ceiling of the mine.

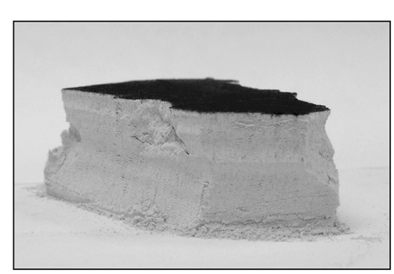

Fig. 2. 0.025 mm of float coal dust deposited on top of 20 mm of stone dust (reproduced with permission from NIOSH (2006)).