Analysis of post−explosion residues for estimating flame travel during coal dust deflagrations

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Abstract

Fine coal particles are produced in underground coal mines during the mining process. These particles can cause an explosion if they are entrained and ignited. However, this type of explosion hazard in underground coal mines can be reduced by applying generous quantities of incombustible rock dust to the entries, including the roof, rib, and floor areas. The National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR) has conducted a series of large−scale explosion experiments at the Lake Lynn Experimental Mine (LLEM) to investigate the inerting effect of limestone rock dust. Numerous experiments were conducted using a pulverized Pittsburgh coal dust (PPC) mixed with limestone rock dust to achieve total incombustible contents varying from 67 to 82%. These dust mixtures were entrained and were subsequently ignited, if insufficient incombustible was present, by the ignition of a methane−air zone located at the closed end of the entry.

Electronic flame sensors were positioned at regular intervals along the length of the entry to measure the flame travel. Post−explosion dust residue samples were taken along the entry after each explosion and analyzed to infer flame travel by measuring the thermal decomposition of limestone rock dust. Alcohol coking indices of the post−explosion residues were also measured. The alcohol coking test method is a forensic tool currently used by the Mine Safety and Health Administration (MSHA) in accident investigations.The determination of the extent of flame travel by these different measurement methods are discussed and compared. The rock dust solubility test described in this paper could assist accident investigators in more accurately establishing the flame limits of a dust explosion.

Keywords : coal dust, explosion, rock dust, forensic.

1. Introduction

In modern coal mines, improved safety practices such as rock dusting, methane control and monitoring, improved ventilation systems, use of permissible equipment, and roof bolting have led to a steady decline in the number of fatalities over the years and a dramatic decline in the number of explosions. Unfortunately, despite these measures, accidents still occur and lives are lost from fires and explosions1) 3). In the United States, underground coal mines are required to add sufficient rock dust to maintain an incombustible content of 65 percent in the intake and at least 80 percent in the return air courses4). (Note : In NIOSH Publication5), "Recommendations for a New Rock Dusting Standard to Prevent Coal Dust Explosions in Intake Airways", NIOSH recommends a new standard of 80% total incombustible content (TIC) be required in the intake airways of bituminous coal mines in the absence of methane.) If methane is present in either the intakes or returns, the amount of rock dust must be increased by 1.0 and 0.4 percent, respectively, for each 0.1 percent of methane.

In the United States, mine accidents are investigated by the federal agency, MSHA (Mine Safety and Health Administration). There are few specialized forensic techniques for investigating underground mine explosions. The alcohol coking index is one such tool normally used for this purpose. Accident investigators analyze dust samples for evidence of coking to map the extent of flame travel. Limestone can undergo thermal decomposition during an explosion[6], and this decomposition pattern (measured by its solubility) may track flame travel and may provide useful supplementary information to accident investigators.

In this paper, the flame travel during a series of experimental coal dust explosions is measured using the conventional alcohol coking test. Results from this test are compared to a newer method that involves measuring the rock dust solubility.

2. Experimental procedures

2.1 Lake Lynn Experimental Mine explosion tests

Pittsburgh–seam coal has been mined at the OMSHR Safety Research Coal Mine since the early 1900s. The coal is ground and/or pulverized on–site and has been used historically as a standard coal dust to which other coal dusts can be compared to determine explosibility. The coal, which contains about 8% incombustible material and 37% volatile matter (dry basis), was prepared to meet three basic size requirements for this research program : coarse dust which contained about 20% <200 mesh (75 μm) particles, medium dust which contained about 40% <200 mesh, and pulverized dust which contained about 80% < 200 mesh. The coal was initially ground to 100% below 20 mesh (850 μm), then pulverized to generate the finer–sized dust particles (PPC). The coarse and medium sizes were prepared by blending various amounts of the ground coal with the pulverized coal. The particle size distributions of the coals were measured by sieving in the laboratory. The size distributions of the three dusts used are summarized in Table 1.

Full–scale single–entry explosion experiments were carried out at the OMSHR Lake Lynn Experimental Mine (LLEM). Details of the experimental mine and the layout of the entries have been described elsewhere[7) 11]. The explosion experiments described in this paper were carried out in 'A' drift [Figure 1]. Normally there are seven open crosscuts connecting this entry with entries 'B' and 'C'. However, for these explosion experiments, crosscuts1 to 5 (X–1 to X–5), as sequentially numbered starting from the closed end, were blocked with reinforced concrete block structures, while crosscuts 6 and 7 (X–6 and X–7) were blocked with mortared solid block stoppings[10], thus creating a single–entry configuration.

The results given in this paper are part of a much larger research investigation which examined the size of coal dust found in modern underground mines and the effect of coal particle size on rock dust inerting requirements[5]. A summary of the dust mixtures used in these 2008 explosion experiments is given in Table 2. For each of these experiments, the coal and rock dusts were first individually weighed to ensure that the correct total incombustible content (TIC) was met ; then the dusts were mixed together using a barrel tumbler. The coal and limestone rock dust mixtures were deposited in the mine by hand to ensure a uniform loading of the dust. To enhance the dispersion, half of the dust mixture was loaded onto shelves suspended from the roof and the other half on the floor[12]. The explosion experiments were initiated by the spark ignition (12–m long) of methane–air mixtures at the face, and the dynamic pressure generated by the methane–air ignition entrained the adjacent dust mixture.

Table 1 Coal particle size distributions (sieving data).

Particle size 〔μm〕	Coarse Pittsburgh coal, wt%	Medium Pittsburgh coal, wt%	Pulverized Pittsburgh coal, wt%
212 850	57.2	28.8	0.2
150 212	9.0	7.7	0.8
106 150	8.2	10.7	5.9
75 106	5.7	13.6	13.5
53 75	5.9	14.2	22.8
38 53	3.7	7.5	17.2
<38	10.3	17.5	39.6

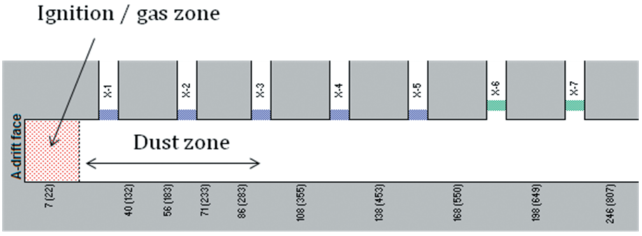

Fig. 1 Diagram of LLEM A drift showing flame sensor locations (indicated by numbers at the bottom). The numbers are also the distances in meters (and feet) from the face. The positions of the seven crosscuts (X1 X7) are also marked.

Table 2 Coal and rock dust mixtures tested in the LLEM explosion experiments using a 12 m (40 ft) long ignition zone ("a" and "b" indicate two adjacent zones of different mixtures of coal and rock dust).

LLEM test no.	Dust zone, m 〔ft.〕	Coal dust loading, g/m^3	Coal size, wt% <200 mesh	Total incombustible content wt%
511	64^a(210) & 100.5^b(330)	150	80	^{a}67.8, ^{b}81.5
512	91.4(300)	200	80	77.0
513	91.4(300)	200	80	81.5
514	91.4(300)	200	20	67.0
516	91.4(300)	200	20	71.5
517	91.4(300)	200	40	74.0
518	91.4(300)	200	40	76.4
520	91.4(300)	200	40	71.0

2.2 Electronic flame sensors

Electronic optical sensors with 0–5 volt outputs were used to track the flame arrival times as the explosion propagated down the entry. An optical flame sensor was installed within a data gathering panel (a steel box flush mounted into the rib) at ten locations within the entry[10], which in turn was connected into the underground instrument room. The data were then relayed to the control room located outside of the mine. The sensors were positioned at the following distances from the face : 7, 40, 56, 71, 86, 108, 138, 168, 198, and 246 m (22, 132, 183, 233, 283, 355, 453, 550, 649, and 807ft). These sensors were located mid−height on the right outby rib, as shown in Fig. 1. Flame was considered to have arrived when the sensor signal was greater than or equal to 1.0 volt.

2.3 Alcohol coking measurements

After each explosion experiment, a series of dust samples were collected along the entry from locations between 33 m (108 ft) and 245 m (807 ft). The alcohol coking test was carried out by adding approximately 1g of <20 mesh (<850 μm) post−explosion dust into a test tube containing about 15 mL of denatured ethyl alcohol (ethanol). The sides of the test tube were then washed down with another 5−10 mL of alcohol. The test tube was set aside for 5min to allow time for the more dense particles to sink to the bottom. As part of this process, coal and incombustible material sink to the bottom and coke floats to the top[13]. The samples were classified visually like previous studies[12]. Using alcohol for the test has two advantages : it is a better wetting agent than water and has a lower density, which expedites the sink/float separation process.

The alcohol coking index is obtained by quantifying the visual alcohol coking observations according to the amount of coke residue floating on top. The alcohol coking index classifies by way of the following 6 categories, representing amounts : very large=5, large=4, medium=3, small=2, trace=1, and none=0.

2.4 Rock dust solubility

The rock dust solubility test is based on the fact that calcium hydroxide has a much higher solubility in water[14] than calcium carbonate (limestone rock dust). Calcium carbonate undergoes some thermal decomposition in an explosion to form calcium oxide, which in turn can be hydrated to form calcium hydroxide[6].

The post−explosion dust samples were initially low temperature ashed (LTA) to remove all combustible material. This was carried out by placing about 2−3g of sample (<20 mesh or 850 μm) into a porcelain crucible and ashing the sample overnight in an oven at 400°C for 20 hr. This was followed by hydration of the residual inorganic material in order to convert any calcium oxide into calcium hydroxide. The hydration process was carried out for about 24 hr in a modified laboratory desiccator cabinet containing trays of water in place of desiccant material.

For the solubility experiments, 0.5 g of the hydrated, ashed sample was mixed with 300 mL of distilled water in a 500 mL beaker to allow the soluble component of the sample to dissolve. The beaker was placed in a water and ice bath for 2 hr. The mixture was then filtered using a pre−weighed piece of binder−free glass microfiber filter (2.16−in or 55−mm diameter) and a standard Büchner funnel and flask. The sample was left to dry in the laboratory for 48 hr then reweighed. The amount of material dissolved was calculated by comparing the amount of deposit on the filter and the amount of hydrated, ashed sample analyzed.

3. Results

Table 3 summarizes the extent of flame travel measurements from the mine explosion experiments using the alcohol coking test. Flame was assumed to be present where any coke was found. All the tests show a large concentration of coke in the dusted zones, but this concentration progressively decreases beyond 93 m (306 ft), which is near the end of the dusted zone. Some of the propagating explosions (LLEM tests #511, #512, and #520) show some coke at 182 m (600 ft), but for one test (LLEM test #514), the coke only extended to 153 m (502 ft). This distance was the same as that for one of the non−propagating explosion tests (LLEM test#513). The short flame travel for propagating explosion LLEM test #514 may be attributed to the relatively large particle size of the coal used during this test, which could have hampered the dust entrainment and travel. Conversely, the finer coal dust used in the non−propagating explosion (LLEM test # 513) resulted in a trace amount of coke at 153 m (502 ft), which is well beyond the edge of the 91 m (300 ft) dusted zone [Table 2].

Flame travel distances derived from the alcohol coking

Table 3 Alcohol coking indices of post explosion dust samples (5=very large, 4=large, 3=medium, 2=small, 1=trace, 0=none, n/d =no dust). The dust zone extended to 104 m (340 ft) from the closed end (face). Explosion result : P=propagating, N=non propagating.

LLEM test no.	Result	Distance from face, m 〔ft.〕							
		33 (108)	63 (208)	93 (306)	123 (404)	153 (502)	182 (600)	213 (699)	245 (807)
511	P	5	5	5	5	4	3	2	1
512	P	5	5	5	4	1	1	1	n/d
513	N	5	5	4	1	1	n/d	n/d	n/d
514	P	5	5	5	2	1	0	0	0
516	N	5	5	3	1	0	0	n/d	n/d
517	P	5	5	4	2	0	0	n/d	n/d
518	N	5	5	3	2	0	0	n/d	n/d
520	P	5	5	5	5	3	1	0	0

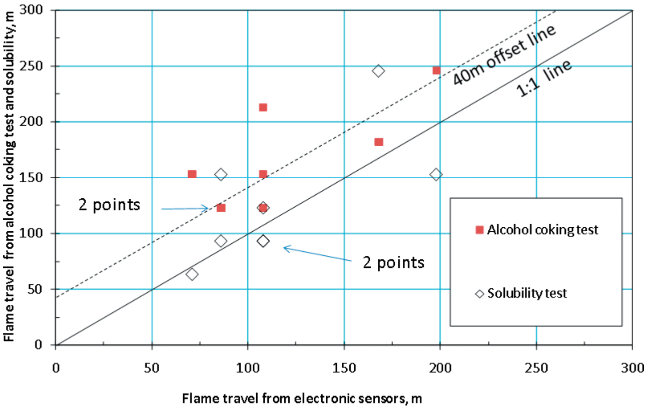

Fig. 2 Comparison of minimum flame travel distances using electronic sensors, alcohol coking test, and solubility measurements.

test have also been compared with the values measured using electronic sensors [Figure 2]. The results show a consistent correlation. However, the data also show that all the flame travel distances measured from the alcohol coking test are relatively high compared to the electronic sensor values. This suggests that the flame may not have traveled as far as where there were only traces of coke. Coke particles may have been carried by the air current from an explosion beyond where flame was actually present. The data appear to correlate better with an offset of 40 m. This may be attributed to the position of the flame sensors, and only the minimum flame travel, using the1 volt criterion, is reported in this paper. Additional flame sensors would be needed to determine the extent of flame travel more accurately.

The rock dust solubility results are summarized in Table 4. As shown, there is a significant amount of soluble material in all the post−explosion samples near the ignition zone. For each explosion, the amount of soluble material decreases with distance away from the initial gas (ignition) zone and decreases very quickly for the non−propagating explosions (LLEM tests #513, #516, and #518). The data indicate that propagating explosions produced at least 5% soluble material along the entry, and this peak value occurs often but not always next to the ignition zone. A minimum solubility value of 0.5% was adopted as the criterion for the determination of the flame travel based on the repeatability of this analytical test.

The data from the electronic flame sensors are compared to measurements from the rock dust solubility experiments in Fig. 2. These two methods used for determining the extent of flame travel during the LLEM explosion tests resulted in a good correlation. Unlike the comparison with the alcohol coking test, the solubility data show little bias, with half the data points above the trend line and half below it.

4. Conclusions

OMSHR researchers have conducted a series of large−scale explosion experiments at the Lake Lynn Experimental Mine (LLEM) to investigate the inerting effect of limestone rock dust and determine, through various methods, the extent of the explosion flame travel.

A series of electronic optical sensors were used to detect the flame travel within the LLEM and provide a reliable measurement as to the minimum extent of flame travel. It is not realistic to install these types of sensors in mine entries to measure flame travel in the unlikely event of an explosion. However, conducting various tests on post−explosion dust samples collected by accident investigators can provide the necessary evidence to deduce the extent of explosion flame travel. Typically, alcohol coking tests are conducted on dust samples to make this determination.

In these experiments, the alcohol coking results produced high amounts of coke in the dusted zone and lower amounts away from the ignition zone. Precise flame travel distances were difficult to establish by the use of the alcohol coking test due to the limited amounts of post−explosion dust available in some areas, especially for those sample areas furthest from the methane−air ignition zone. The data also show that all the flame travel distances measured from the alcohol coking test were relatively high compared to the electronic sensor measurements. This suggests that the flame may not have traveled as far as the distances containing only traces of coke particles, which may be subject to dynamic effects such as airflow and turbulence. Therefore, the flame sensors can only be used to measure the minimum flame travel. Since the sensors used in these tests were separated by long

Table 4 Solubility of low temperature ashed post explosion dust samples 〔n/d=no dust〕.

LLEM test no.	Solubility, wt%							
Distance from face, m 〔ft.〕	33 (108)	63 (208)	93 (306)	123 (404)	153 (502)	182 (600)	213 (699)	245 (807)
511	15.3	15.6	5.6	5.0	3.1	0.4	0.2	0.3
512	7.0	4.2	1.3	0.0	0.0	0.0	0.0	n/d
513	3.3	1.7	0.0	0.0	0.0	n/d	n/d	n/d
514	10.8	6.0	0.9	0.0	0.0	0.0	0.0	0.0
516	5.2	2.8	0.6	0.0	0.1	0.0	n/d	n/d
517	6.9	4.5	0.6	0.6	0.4	0.0	n/d	n/d
518	4.1	1.9	0.7	0.6	0.9	0.0	n/d	n/d
520	5.0	8.7	5.8	7.1	3.7	2.3	1.5	1.6

distances, it is likely that the actual flame was extinguished in between a set of sensors. In addition, the force of the explosion may have carried coke particles beyond the flame path.

A newer forensic tool involving rock dust solubility measurements of the dust samples may aid investigators in more accurately determining the extent of the flame travel during explosions. Post−explosion dust samples collected just outby the LLEM methane−air ignition zone resulted in the highest rock dust solubility values. Dust samples collected after propagating explosions gave higher rock dust solubilities than those samples collected after non−propagating explosions. There was a good correlation for the extent of flame travel when comparing the electronic sensors and the dust sample solubility measurements. However, it should be pointed out that these are only preliminary results and more data would be required to develop this experimental technique into a forensic tool for use in explosion investigations.

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