Observations of post-explosion dust samples from an experimental mine.

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Abstract
Coal dust explosions are routinely conducted within the full-scale experimental mine at the National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory's (PRL) Lake Lynn Experimental Mine (LLEM) to meet the needs of numerous safety and health research programs. Many of these explosion tests over the years involved igniting different coal dust and limestone rock dust mixtures (up to 80% by volume rock dust). Following four more recent tests, floor dust samples have been collected and analyzed using the alcohol coking test and scanning electron microscopy (SEM) and the results compared to estimate the flame travel.

Introduction

Serious accidents and injuries from fires and explosions have decreased considerably over the last 100 years in the underground coal mining industry [1, 2]. However, they still occur today and often result in many fatalities, for example, the Sago mine, WV, 12 fatalities from explosion of gas and dust; the Darby mine, KY, 5 fatalities from explosion of gas and dust; and the Aracoma mine, WV, 2 fatalities from fire [3-5].

All mining related accidents in the United States are investigated by the Mine Safety and Health Administration (MSHA). For fire and explosion accidents, one area of such investigations usually involves implementing a mine dust survey to establish the flame travel by the fire or explosion, i.e., where it terminated. This can be done by close examination of solid residues left by a fire or explosion.

Specific Objectives

This paper describes how flame travel in a coal dust explosion can be assessed by conducting a number of coal dust explosions in an experimental mine and analyzing the post-explosion residue samples in a laboratory using two very different techniques – alcohol coking test and scanning electron microscopy.

Experimental Mine and Test Procedures

Mine Explosion Tests

All the explosion experiments were carried out at the LLEM [6]. The experimental mine has 4 parallel tunnels (A, B, C and D) each approximately 20 ft (6.1 m) wide, 7 ft (2.1 m) high, and over 1600 ft (488 m) long [7]. The first three explosion experiments were conducted in tunnel 'D' and last one in tunnel 'A'.

Pulverized Pittsburgh coal (PPC) was used in the explosion experiments. The coal was mined from PRL's Safety Research Coal Mine near Pittsburgh, PA and then ground and pulverized at an on-site facility. PPC and limestone rock dust are fine powders (80% <75µm or -200 mesh). Half of the coal dust and limestone rock dust mix was scattered onto the floor of the mine in the "dusted zone" and half deposited onto shelves suspended 1.5 ft (0.5 m) from the roof.

The dust explosions were initiated with a 10% methane-air explosion at the closed end of the tunnel. Gas samples were taken for subsequent analysis in a gas chromatograph in order to verify the methane concentration actually used. The gas zone forming this primary explosion varied from 12 ft (3.7 m) for LLEM #473 to 40 ft (12.2 m) for LLEM #401 and LLEM #511. The gas explosions were ignited using electric matches. A list of the explosion experiment parameters are summarized in Table 1. After each explosion test, dust samples were collected along the middle of the tunnel at regular intervals. Only floor samples were taken, starting from the closed end of the tunnel. Dust was brushed from a known collection area, 2 ft by 2 ft (0.6 m by 0.6 m) sample area) from the dry concrete mine floor; this dust sample collection process was repeated for several sample areas at the same relative location if insufficient quantities of dust were collected from just one sample area at that location.

Alcohol coke test

The alcohol coke test was carried out by adding approximately 1 g of -20 mesh (<0.8 mm) post-explosion sample into a test tube containing about 15 mL of denatured ethyl alcohol [8]. The sides of the test tube were then washed down with about 5-10 mL of alcohol.

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Table 1 Summary of LLEM explosion parameters, including rock dust content and dusted zone locations.

Explosion test ID	**Tunnel**	**PPC : limestone rock dust mix**	**Total incombustible content, TIC (%)**	**Coal dust*, g/m³**	**Dusted zone, ft and (m)**
LLEM #401	D	20:80	82	200	40 - 460 (12.2 – 140.2)
LLEM #471	D	35:65 and	68	150	27 - 205 (8.2 – 62.5)
		20:80	82	150	205 - 445 (62.5 – 135.6)
LLEM #473	D	35:65	68	200	12 - 250 (3.7 – 76.2)
LLEM #511	A	35:65 and	68	150	40 - 250 (12.2 – 62.5)
		20:80	82	150	250 – 580 (62.5 – 176.8)

* Equivalent coal dust per unit volume inside the tunnel in the dusted zone only.

The test tube was set aside to allow time for the more dense particles to sink to the bottom. After 5 minutes the sample was classified according to the chart shown in Figure 1.

To quantify the results, the categories of coke were assigned an arbitrary value which this paper terms the ‘alcohol coke index’ such that, very large = 15, large = 10, small = 4, trace =1 and none = 0. The ‘medium’ category shown in Figure 1 was not used in this study because it was difficult to differentiate this from the ‘large’ class. It should be pointed out that the terms ‘coke’ and ‘coking’ used in this paper do not relate to those used in the metallurgical world as the post-explosion coal residues are the result of rapid coal devolatilization and are more akin to char than actual metallurgical coke in both appearance and physical properties such as porosity and strength.

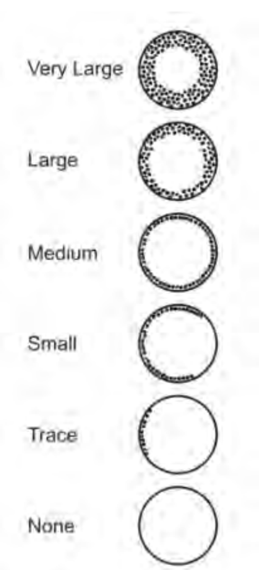

Figure 1 Alcohol coke test chart [8].

Scanning Electron Microscope Observations

The microscopic analysis of post-explosion particles was carried out using a Jeol 6400 scanning electron microscope. In order to obtain good images of the organic components of interest, the post-explosion samples were initially acid leached in 8M hydrochloric acid to remove all the limestone rock dust. This also removes some of the inorganic minerals from the coal. After this, a small amount of each test material was mounted onto a piece of adhesive tape which in turn was mounted onto a copper or aluminum disc which acted as a sample holder. These were then treated in a sputter coater under vacuum, which deposits a thin conductive layer of gold onto the sample via evaporative deposition to minimize charging effects by the electron beam [9]. For each explosion residue, digital photographs of at least 6 fields of view were recorded at relatively low magnifications (between x100 and x400) in order to obtain a reasonable number of particles per field of view for analysis.

The SEM micrographs were analyzed by eye to quantify the extent of coal decomposition. This was done by estimating the percentage of coal particles that had decomposed in each of the photographs and averaging the totals. This percentage was called the ‘SEM coke content’.

Low temperature ashing

The incombustible contents (IC) of the post-explosion floor dust samples were determined using a low temperature ashing furnace. About 1 g of each sample, sieved to -20 mesh, was weighed in a small ceramic crucible. This was heated over 1.5 hours to 515°C and held for 20 hours before cooling naturally. The total heating and cooling cycle was about 24 hours.

Results and Discussion

The laboratory analysis of the post-explosion dust samples showing alcohol coke index, along with the SEM coke content are summarized in Figures 2-5. The pre-explosion total incombustible contents (TIC) in the dusted zones are clearly marked. There was only one dusted zone in explosions LLEM #401 and LLEM #473 but two adjacent dusted zones in LLEM #471 and LLEM #511, the areas of which are outlined by the dashed lines. All the dusted zones started immediately beyond the closed end gas ignition zone which is located nearest the origin on the graphs and have been annotated for clarity.

For LLEM #401 (Figure 2), the single dusted zone explosion resulted in floor dust material which had very similar incombustible contents compared to the initial TIC of 82% except for one sample taken furthest away from the initial explosion. This suggests that only a small fraction of the coal has been combusted during the explosion. It is also possible that the some of the coal particles which have been largely consumed in the explosion are simultaneously ejected out along the tunnel. There is strong evidence that the coal near to the gas zone did burn according to both the SEM coke content and alcohol coke index data (Figure 2). The results show a very high level of coke from the SEM data and a high alcohol coke index in this region. In mine accident investigations, the presence of either large or very large quantities of coke in the post-explosion dust samples are indicative of an explosion flame [4]. It is also worth pointing out that although 1g of sample was used in the alcohol coke tests, the amount of combustible material contained in each of this set of samples was in fact quite small (approximately 0.2g or less).

The SEM coke content falls from 100% at around 200 ft (61 m) from the closed tunnel to a value of almost zero at 400 ft (122 m) and beyond. The alcohol coke index follows a similar pattern where it falls rapidly from a peak value of 15 at 100 ft (30.5 m) to 0 at 400 ft (122 m) where there was only a trace or no coke present in the samples. This is well before the end of the dusted zone which extended to 460 ft (140 m) and suggests the explosion did not travel beyond the dusted zone due to the high IC (82%) used in this experiment which effectively inerted the explosion.

Figure 3 shows the laboratory data for samples taken from explosion LLEM #471. The two dusted zones containing 68 and 82% TIC are clearly identified. The single floor dust sample taken from the first dusted zone had a relatively high incombustible content as expected but the subsequent floor dust samples had ICs very similar to the initial TIC of the second dusted zone of 82% which again suggests only a small fraction of the coal has been consumed. There is good agreement between the SEM coke content and the alcohol coke indices with both showing a steady fall in the amount of coke material from 200 ft (61 m) to about 450 ft (137 m) before reaching a minimum at 500 ft (152 m) and beyond. It appears that the coal dust explosion terminated near the end of the second dusted zone.

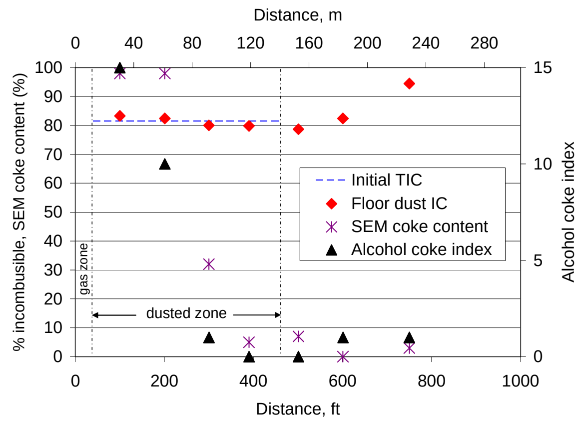

Figure 2 Analysis of post-explosion materials from LLEM #401 showing SEM coke contents and alcohol coke indices.

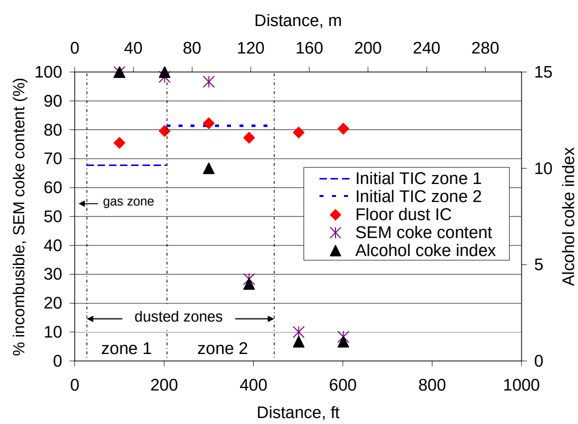

Figure 3 Analysis of post-explosion materials from LLEM #471 showing SEM coke contents and alcohol coke indices.

The floor dust IC for explosion LLEM #473 (Figure 4) follows a similar trend to LLEM #401 which also had a uniform dusted zone where the IC values almost match the original TIC, again indicating a low consumption of the coal. However, there is a significant difference in the SEM and alcohol coke data compared to the two other explosions described above. For LLEM #473, the SEM and alcohol coke data both start at lower values near the gas zone compared to LLEM #401 and LLEM #471. These indices fall rapidly and reach about 0 at 300 ft (91 m) which is only slightly further than the edge of the dusted zone. The reason for the smaller amounts of coke near the tunnel face (closed end) is probably due to the small gas zone, 12 ft (3.7 m), used in this experiment which would have resulted in a smaller initial explosion. Again, the explosion appears to have terminated at or near the end of the dusted zone.

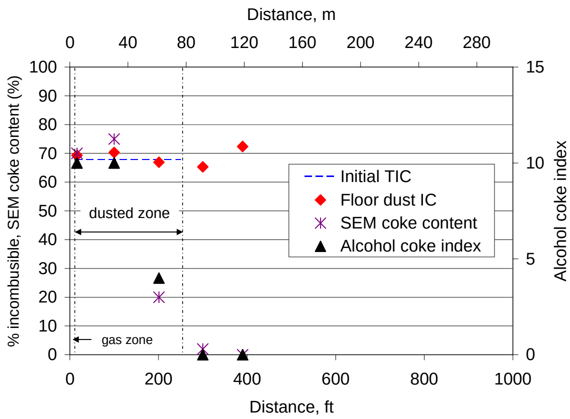

Figure 4 Analysis of post-explosion materials from LLEM #473 showing SEM coke contents and alcohol coke indices.

Figure 5 shows the laboratory results from explosion experiment LLEM #511. Like LLEM #471 there were two adjacent dusted zones containing 68 and 82% TIC respectively but this time the dusted zone was extended 580 ft (176.8 m). As before, the floor dust IC samples almost follow that of the initial TIC values. The results also show a very high level of coke from both the SEM and alcohol coking tests from the tunnel face (closed end) to 400 ft (122 m) which is well into the second dusted zone. From this point the SEM coke content falls gradually but never reaches zero even at 800 ft (244 m). Unfortunately no samples were taken beyond this point but it is reasonable to believe from the data that the flame could have travelled to this region. Again, the size of the methane/air zone played an important role in the coal dust explosion both in terms with the amount of coke generated and the distance traveled along the tunnel in the mine.

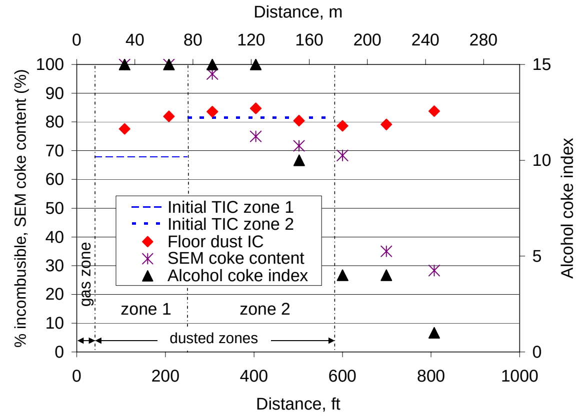

Figure 5 Analysis of post-explosion materials from LLEM #511 showing SEM coke contents and alcohol coke indices.

Conclusions

The alcohol coke test is a quick and simple test and has been shown to be a useful technique in an explosion research laboratory. Observations of partially burnt coal particles under a SEM at low magnification can also give similar quasi quantitative data which can forensically track the flame travel after a coal dust explosion. In this study, there appears to be a very good agreement between these two different laboratory methods.

Although the alcohol coke test is in itself a valuable tool in mine accident investigations, it may be supplemented with SEM coke analysis, especially in situations where the amount of sample is limited (to a few milligrams). However, SEM studies are time consuming and often not easily accessible.

Acknowledgments

The authors would like to thank Eric Weiss, Team Leader of Lake Lynn Laboratory, and the rest of the LLL team for conducting the explosion experiments; Donald Sellers, Physical Science Technician at LLL, for collecting the post-explosion dust samples; and to William Chisholm, Research Physical Scientist, and Diane Schwegler-Berry, Biologist, of NIOSH Morgantown for their assistance with the SEM.

References

1. Richmond, J. K., Price, G. C., Sapko, M. J., and Kawenski, E. M., “Historical Summary of Coal Mine Explosions in the United States, 1959-81”, U.S. Department of the Interior, Bureau of Mines Information Circular 8909, 1983.
2. Dobroski, H. Jr., Stephan, C. R., Conti, R. S., “Historical Summary of Coal Mine Explosions in the United States, 1981 to 1994”, U.S. Department of the Interior, Bureau of Mines, Information Circular 9440, 1996.
3. MSHA Report of Investigation, “Fatal Underground Coal Mine Explosion, Sago Mine, West Virginia, January 2, 2006”.
4. MSHA Report of Investigation, “Fatal Underground Coal Mine Explosion (Darby Mine No. 1), May 20, 2006”.
5. MSHA Report of Investigation, “Fatal Underground Coal Mine Fire, Aracoma Alma Mine #1, West Virginia, January 19, 2006”.
6. Triebsch,G. F.,and Sapko, M. J., “Lake Lynn Laboratory: A State-of-the-Art Mining Research Laboratory”, Proceedings of the International Symposium on Unique Underground Structures, Denver, CO, 1990, pp. 75-1 – 75-21.
7. Sapko, M. J., Weiss, E. S., Cashdollar, K. L., and Zlochower, I. A., “Experimental mine and laboratory dust explosion research at NIOSH”, Journal of Loss Prevention in the Process Industries 13:229-242, 2000.
8. Cashdollar, K. L., Weiss, E. S., Montgomery, T. G., and Going, J. E., “Post-explosion observations of experimental mine and laboratory coal dust explosions”, Journal of Loss Prevention in the Process Industries 20:607-615, 2007.
9. Ng, D. L., Cashdollar, K. L., Hertzberg, M., Lazzara, C. P., “Electron Microscopy Studies of Explosion and Fire Residues”, U.S. Bureau of Mines IC 8936, 1983.

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