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Floor dust erosion during early stages of coal dust explosion development

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Abstract

An ignition of methane and air can generate enough air flow to raise mixtures of combustible coal and rock dust. The expanding high temperature combustion products ignite the suspended dust mixture and will continue to propagate following the available combustible fuel supply. If the concentration of the dispersed rock dust is sufficient, the flame will stop propagating. Large-scale explosion tests were conducted within the National Institute for Occupational Safety and Health (NIOSH) Lake Lynn Experimental Mine (LLEM) to measure the dynamic pressure history and the post-explosion dust scour depth. The aim of this effort is to provide quantitative data on depth of dust removal during the early stages of explosion development and its relationship to the depth of floor dust collected for assessing the incombustible content most likely to participate in the combustion process. This experimental work on dust removal on is not only important for coal mine safety but also for industrial dust explosions.

Keywords

Underground; Coal dust; Explosion; Dust sampling

1. Introduction

A coal dust explosion in a mine entry can be initiated by a methane-air explosion that generates sufficient air pressure to disperse coal dust from the entry surfaces into the expanding combustion zone. Heat transfer to the coal dust particles results in the production of volatiles and tars from these particles. The combustible devolatilization products react with the oxygen in the air at elevated temperatures. Heat released from this exothermic reaction is converted into mechanical work of expansion of the semi-confined air. This fluidizes and disperses additional coal dust from the entry surfaces into the propagating coal dust explosion. The propagation of the combustion zone is limited by the turbulent mixing of the hot products at the leading edge of the combustion zone, the flame front, with the coal dust-air mixture.

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Rock dusting is the primary means of defense against coal dust explosions in U.S. mines. The purpose of the rock dust is to disperse with the coal dust and act as a thermal heat sink and to block radiant energy transfer to the coal particles to prevent sustained coal dust explosion propagation. 30 CFR 75.403, Subpart E (Combustible Materials and Rock Dusting) requires the use of rock dust in bituminous coal mines to abate the hazard of accumulated coal dust [1]. The regulations state that rock dust “shall be distributed upon the top, floor, and sides of all underground areas of a coal mine and maintained in such quantities that the percent incombustible content of the combined coal dust, rock dust, and other dust shall be not less than 80%.” When scoured and uniformly mixed with air, a dust containing 80% or more incombustible content will not be able to support combustion and flame propagation will stop. If the dispersed dust contains less than 80% incombustible content, the explosion is expected to continue to propagate as long as the dust is available.

In order to verify compliance with rock dusting regulations, Mine Safety and Health Administration inspectors collected dust samples according to established procedures at that time (2008) [2]. These procedures dictated that the band or perimeter method be used to collect a dust sample from the roof, ribs, and up to one-inch deep from the floor to create one homogeneous mixture. If the amount collected was more than required, the sample was thoroughly mixed and a portion taken for analysis. Underlying this sampling method was the assumption that in the event of an explosion, the coal and rock dust would disperse from all surfaces and would either enhance or inhibit propagation depending on the percentage of incombustible content.

Float coal dust is constantly produced as a consequence of active coal mining. However, abatement through rock dusting occurs intermittently. Over time this can result in a layering of coal and rock dust rather than creating a homogeneous mixture. When samples are taken for analysis, the rib, roof, and floor samples are mixed and this layering is lost. Previous work suggests that the top 2–4 mm of floor dust plays a prominent role in flame propagation. A layer as thin as 0.12 mm of pure float coal dust resting on top of an 80/20 rock and coal dust mixture will propagate an explosion [3]. Ideally, the sample taken from the floor of bituminous coal mines for purposes of measuring the incombustible content percentage should be taken to a depth similar to the depth of dust that would be eroded in the event of an explosion. This depth of dust should also reflect the portion lifted soon after the ignition of a float coal dust explosion. The dust interacting with the flame front will largely determine the explosion magnitude.

For rock dust to be effective it must be dispersible with the coal dust [4]. Singer et al. also found that the uniformly mixed beds always dispersed without separation, whereas in the case of coal dust layer deposited over a rock dust layer, only the coal dust is dispersed if the airflow velocity is in a range between the threshold dispersion velocities of the two dusts [5].

During large-scale dust explosion tests performed at the Lake Lynn Experimental Mine (LLEM) from (2007–2008), the depth of floor dust erosion during the early stages of explosion development was empirically measured [6]. The implications of this data on rock dusting and sampling procedures for explosion hazard assessment are discussed.

Two methods for predicting the depth of removal of uniform coal and rock dust mixtures from the floor dust deposit were used to compare predicted results with experimental determinations. These methods are also used to compare the surface erosion of float coal dust from the surface of a thick layer of dispersible rock dust.

2. Methods

The National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Mining Research Division (PRMD) conducted large-scale dust explosion tests in an experimental mine [6]. The gallery is approximately 488 m long, 2.1 m high and 6 m wide. Before each test, the gallery was thoroughly washed down, dehumidified air was passed through the gallery, and the gallery was allowed to dry several days before dust was loaded. As seen in Fig. 1, tests were started by the ignition of a methane air mixture.

For these experiments, the first 12 m section of the mine gallery starting at the face (closed end) was filled with a 10% methane in air mixture, roughly 15 m³ of natural gas. A plastic diaphragm was used to contain the methane-air mixture within the flammable gas mixture zone before ignition. The coal dust and limestone rock dust mixture was placed half on roof shelves made of expanded polystyrene and half on the floor as illustrated in Fig. 1. These roof shelves were suspended 0.5 m from the mine roof on 3 m increments throughout the dust zone which was 91 m long (i.e. spanning the 12–104 m distance from the face). The roof shelves were often damaged during the deflagration and resulting debris occasionally landed on the test bed causing easily identifiable gouges on its surface. The amount of the coal dust placed in the dust zone corresponds to a nominal dust loading of 200 g/m³. Ignition of the methane-air mixture alone would result in flame travel up to approximately 70 m from the closed end. The methane-air zone was ignited near the center of the face using electric matches grouped in a single location near the geometric center of closed end.

Approximately half of the coal dust and rock dust mixture was loaded on shelves suspended from the roof with the other half applied to the floor. The dust scour measurements were made between two 2.5-cm high by 2.5-m long parallel aluminum rails attached to the mine floor 61 cm apart. The dust was placed between the rails and leveled creating a 25-mm deep layer located 76 m from the face. In all of the explosibility tests, bi-directional probes were placed mid-entry near the trays to measure the local dynamic pressure. Dynamic pressure recordings were used for air velocity calculations. Measurements were made using 0–690 kPa strain gage pressure transducers with a frequency response of 1000 Hz and a sampling rate of 2000 samples/s/channel. The dynamic pressure gages were fabricated by the U.S. Bureau of Mines based on the design of McCaffrey and Heskestad [7]. The bi-directional velocity probe is an impact probe similar to the pitot-static probe. Unlike in the original probe, the pressure transducers were located within 15 cm of the sensing head. The size of the sensing head is 20 mm in diameter with a 40 mm length. The probe obstructs the flow and a pressure differential exists between its front and rear surfaces. The pressure difference is measured using a 0–70 kPa differential pressure transducer (1000 Hz) and the total pressure was measured by a 0–3210 kPa (1000 Hz) transducer.

The same coal dust and rock dust mixture used for flammability studies was also placed between the rails and raked level with the top of the rails, creating a 25-mm thick dust layer. Before and after the explosibility test, measurements of the dust depth within ± 0.1 mm were taken at 30-cm intervals beginning at 61–244 cm with the leading and trailing sample discarded due to potential leading and trailing edge effects (Fig. 2). All of the tests were conducted in the winter months when the humidity within the mine is at its lowest and all dusts used were dry. Thus moisture was not a factor to influence the lifting of the dusts during the Lake Lynn Experimental Mine study.

3. Theory

Two correlations methods are used to predict the depth of dust layer removal. These include a strawman method proposed by Ural and a method based upon mass flux as determined by the local gas density and velocity which was proposed by Edwards and Ford [8,9].

3.1. Correlation 1-Ural in 2011

As part of the Fire Protection Research Foundation (FPRF) project entitled “Dust Explosion Hazard Assessment Methodology,” Ural conducted an extensive international literature review on relevant research addressing airflow induced dust entrainment rates [8]. Effects of factors such as aerodynamic flow and boundary layer characteristics, dust particle sizes and shapes, and dispersibility were examined. Since the dust entrainment occurs deep in the boundary layer, friction velocity rather than the free stream velocity is the more appropriate parameter to correlate the entrainment rate. Data collected from full-scale dust explosions conducted at the NIOSH’s LLEM was included in the FPRF report. Data for these coal dust-rock dust mixtures were also used in part to support the development and validation of the proposed strawman correlation as follows:

The following correlation was proposed by Ural as a strawman towards estimating the entrainment mass flux [8]:

$$m'' = 0.002\rho(U^{0.5} - (U_t^2/U^{1.5})) \text{ for } U > U_t \quad (1)$$

where m'' is the entrained mass flux, $\text{kg/m}^2/\text{s}$; ρ the gas density, kg/m^3 ; U the free stream velocity, m/s ; and U_t the threshold velocity, m/s .

The threshold velocity, U_b is the minimum air velocity at which dust removal from the layer begins and it depends on factors such as particle size, particle shape, and particle density. The report provides algebraic correlations and charts to estimate this parameter. Ural suggested an alternative empirical algebraic relationship, based on the Kalman et al, work for predicting the minimum threshold velocity for poly-dispersed dust with a broad particle size distribution [8,10]. In applications where dust particles are expected to be removed as agglomerates, Ural suggested that substituting the particle density with its bulk density may be more appropriate [8]. For nearly spherical particles, the minimum threshold velocity, cm/s , is

$$U_t = 460\rho_b^{1/3} \quad (2)$$

where ρ_b is the bulk density, g/cm³.

To determine the depth of the dust layer removed from the mass of coal and rock dust homogeneous mixture scoured, the bulk density of the layered mixture is needed. The bulk density of the mixture is defined in terms of the bed porosity, rock and coal dust particle densities, and mass fraction of rock dust in the mixture:

$$\rho_B = (1 - \Phi) / [f/\rho_R + (1 - f)/\rho_C] \quad (3)$$

where ρ_B is the mixture bulk dust density, g/cm³; Φ the porosity (0.5); f the mass fraction of rock dust in the mixture; ρ_R the rock dust particle density, 2.75 g/cm³; and ρ_C the coal dust particle density, 1.35 g/cm³.

This proposed method primarily determines the maximum amount of dust that the initial air velocity can remove from the surface of a smoothed floor dust layer. At low flow velocities, the entrainment rate tends toward zero at the threshold velocity. The small cohesive particles may be lifted from the surface in the form of aggregates. The breakdown of these aggregates in a turbulent flow field is of importance in determining the extent of the dispersion. For rock dust to be effective it must be dispersible with the coal dust as described by Hartmann et al. [4]. Singer et al. also found that the uniformly mixed beds always dispersed without separation, whereas in the case of a coal dust layer deposited over a rock dust layer, only the coal dust is dispersed if the peak airflow velocity is in a range between the threshold velocities of the coal and rock dust [5].

3.2. Correlation 2-Edwards and Ford in 1988

The U.S. Bureau of Mines (USBM) researchers Edwards and Ford developed a model of coal dust explosion suppression by rock dust entrainment [9]. To calculate the aerodynamically induced lifting of coal and rock dust from a composite deposition on a mine entry floor, the authors used a correlation proposed by Rosenblatt in which mass flux is uniquely determined by the local gas density and velocity:

$$m'' = (0.0021U^{0.25} - 4/U)\rho U \quad (4)$$

where m'' is the entrained mass flux, g/cm²/s; ρ the gas density, g/cm³; and U the free stream velocity, cm/s.

The ratio of the mass flux to the gas momentum flux depends solely upon the gas velocity. Eq. (4) implies a fixed threshold gas velocity of 420 cm/s for dust lifting to occur.

Edwards and Ford applied their numerical model to large-scale test data obtained from float coal dust explosions conducted in the Bruceton Experimental Mine to predict the mass fraction of airborne rock dust for both propagating and non-propagating float coal dust explosions [3,9].

In this effort, the threshold velocity is allowed to vary as predicted by Eq. (2) using the bulk density, ρ_B , of the test mixture and the fixed porosity, Φ , of 0.5. Rearranging Eq. (4) to include variable minimum entrainment velocity U_m yields:

$$m'' = (0.0021U^{0.25} - U_m/U)\rho U \quad (5)$$

where m'' is the entrained mass flux, $\text{g}/\text{cm}^2/\text{s}$; ρ the gas density, g/cm^3 ; U_m the minimum gas velocity to initiate dust removal, cm/s .

The minimum threshold velocity U_m to initiate dust removal:

$$U_m = 0.0021U_t^{1.25} \quad (6)$$

By substituting U_t from Eqs. (2) into (6), U_m can be rewritten in terms of mixture bulk density:

$$U_m = 4.47\rho_B^{0.417} \quad (7)$$

Eqs. (1) and (5) are used to calculate the total dust lifted from a bed of uniform mixture by integrating mass flux and air velocity over time.

4. Results

4.1. Measured depths of dust scoured

Table 1 lists the individual measured depths of dust scoured from within the trays for each full-scale test conducted. The leading and trailing samples (61-cm and 244-cm marks) were discarded due to potential edge effects. Also, for some of the 244-cm mark measurements, the dust did not reach far enough for a measurement or a crater was formed in the dust after the test so that an accurate measurement could not be obtained. The "Measured" values reported in Table 1 are an average of the measurements recorded at 91, 122, 152, 183 and 213 cm. The averages for the tests range from 1.0 to 2.6 mm with the highest measured individual value of 4.8 mm. The overall average for all of the tests was 1.7 mm of dust scoured with an average standard deviation of 1.1 mm. Negative values listed in Table 1 indicate measurements where material was deposited on top of the initial 25 mm thick layer.

4.2. Predicted depths of dust scoured

LLEM Test #511 featured a 25-mm deep dust layer of a homogeneous mixture containing 35% coal dust and 65% rock dust. This layer has a calculated bulk density, ρ_B , given by Eq. (3) of $1010 \text{ kg}/\text{m}^3$. The calculated bulk density is used in Eq. (2) to estimate the minimum threshold velocity needed to erode the dust mixture (4.6 m/s). Inserting the measured instantaneous gas velocity, calculated air density from the measured total pressure and threshold velocity into (Eqs. 1) and (5), the dust entrainment mass flux is calculated as a function of time. Cumulative mass removal per unit area (kg/m^2) is calculated as a function of time by integrating the entrainment mass flux over time. The dust bed bulk density was

used to convert the cumulative mass removal to dust removal depth and is compared in Fig. 3. In LLEM Test #511, the wind velocity associated with the pioneer pressure wave arrives at the floor dust trays approximately 0.45 s after the ignition of the methane-air mixture. The wind velocity peaks at approximately 176 m/s approximately 0.93 s after ignition and rapidly decays to 0 m/s at approximately 1.3 s. The calculated cumulative depth of dust removal increases to a maximum of approximately 2 mm at approximately 1.3 s when the local wind velocity returns to zero. Calculated depth of scour results for both models Eqs. (1) and (5) compare quite well.

Table 2 lists some of the test conditions such as the percent of rock dust in the trays and the type of coal dust in the dust mixtures. The fraction of rock dust ranged from 65% to 80%. All of the coal dust used during the Lake Lynn Experimental Mine study consisted of Pittsburgh seam coal. In general, the Pittsburgh Pulverized Coal (PPC) contained approximately 80% minus 200 mesh material (<75 microns or μm). The coarse coal contained approximately 20% minus 200 mesh particles and the medium coal contained about 40% minus 200 mesh material. The calculated peak velocity, produced from the measured dynamic pressure, along with relevant calculated bulk densities and threshold velocities are shown in Table 2.

As shown in Table 2, the medium coal dust contained approximately 40% minus 200 mesh material. Further details of the coal dusts are listed in NIOSH RI 9679 [6].

Table 3 summarizes the measured depth of dust scoured and the values of the predicted depth of dust scour.

The average measured depth of dust removal for the LLEM tests #511 through #520 range from 1 to 2.6 mm (average = 1.8 mm) with standard deviations ranging from 0.3 to 2.4 mm (average = 1.2 mm). The predictions of both dust removal models agree quite well with each other.

4.3. Dust layers

Float coal dust is constantly produced as a consequence of active coal mining. However, abatement through rock dusting occurs intermittently. Over time, without raking and/or mixing of the coal and rock dust layers, layering can occur whereby explosible accumulations of coal dust may lay on top of rock dust. If the layer is uniform, Singer et al. found that the uniformly mixed beds dispersed without separation [5]. The same cannot be said for stratified layers of coal dust deposited on top of rock dust where the coal dust will disperse and lift first and then be followed by the underlying rock dust.

To help illustrate the explosibility danger from accumulations of coal dust lying on top of rock dust, Eq. (1) is used to predict the rate and depth of both coal and rock dust removal when exposed to a wind velocity such as that measured in LLEM Test #511. The layered predictions are shown in Fig. 4 and can be compared to the uniform mixture shown in Fig. 3. The top coal dust layer, with a minimum entrainment velocity, $U_{m\beta}$ of 4.0 cm/s starts to lift and disperse before the rock dust with a minimum entrainment velocity of 5.1 cm/s. The rate of depth removal of coal dust is about twice that of rock dust as indicated by the slopes of

dust removal. Furthermore, only the coal dust is dispersed if the airflow velocity is in a range between the minimum entrainment velocities of the coal and rock dust of 4.0 and 5.1 m/s, respectively. This comparison does not take into account the free moisture and an associated cohesion of the dusts. For example, non-treated rock dust readily absorbs ground moisture forming a paste and a cake when dried whereas coal dust lying on top is very difficult to wet and remains dispersible thereby making for a more hazardous condition for propagation a dust explosion. They were also used to compare the surface removal of pure float coal dust lying on top of a thick layer of pure rock dust shown in Fig. 4.

5. Discussion

From these experimental tests, the results indicate that the top 1.8 ± 1.2 mm of dust was lifted from a 25-mm thick floor dust layer. This would be the dust available for participation in the combustion process. This result has implication on methods for identifying potential accumulations of explosible dust accumulations. When stratified floor layers of coal and rock dusts are not raked and mixed to a uniform consistency, collecting samples greater than this depth may fail to identify explosible accumulations of dust that is likely to participate in the combustion process. Considering the large standard deviation in the depth of dust removal measurements, the in-situ assessment of a potential dust explosion hazard should focus on identifying the explosibility of the top 0.6–3 mm when floor dust deposits are greater than 3 mm deep.

One-on-one comparisons between measured averages for a single test and their predicted calculated values are not very good. However, surprisingly or perhaps fortuitously, the average dust removal measured is $1.8 \text{ m} \pm 1.2 \text{ mm}$ for the eight large-scale experiments and almost identical to the predicted calculations' average of $1.8 \pm 0.3 \text{ mm}$.

Given that dust deposited in underground mining operations results in near-pure layers of coal dust and rock dust, a “float coal dust” explosion can be produced when a layer of coal dust is deposited on top of rock dust. It is seen in Fig. 4 how much easier coal dust is lifted compared to rock dust in layered deposits. Therefore, measures must be employed to either prevent layering or to mitigate the layering. Measures that have been used to help mitigate the formation of a float coal dust layer are raking/mixing together the floors' surface coal dust with the underlying rock dust, re-application of rock dust on the rib and roof surfaces, and continuous dispersion of rock dust into the return ventilating air during mining operations. Additional efforts to prevent the production or release of float coal dust will in turn necessitate less of these mitigation efforts. Such efforts have been devoted to study methane and dust dispersion in underground coal mines. For example, methane emission and dust concentration were numerically investigated using a computational fluid dynamics (CFD) approach [11,12]. Results indicated that the presence of a continuous miner adversely affects the air flow and leads to increased methane and dust concentrations. On the other hand, such effects can be minimized or even neutralized by operating the scrubber fan in suction mode. CFD simulations using a combination of scrubber fan in suction mode with brattice curtains indicated the best approaches for the removal of dust and methane from the mining face.

6. Conclusions

In these near-limit propagating explosions, the average depth of dust scoured in the leading edge of the explosion development is 1.8 ± 1.2 mm. Two dust erosion models were used to predict the depth of dust removal using the average air velocity from a 25 mm thick floor dust layer at approximately 80 m downwind from the initiation of a methane-air explosion.

This effort provides some data on depth of dust removal during the early stages of explosion development relevant to identifying potential dust explosion hazards. Previously, the method of assessing a hazardous condition relevant to propagating explosions was to collect a “band” sample from the roof, ribs, and floor. The former sampling depth for the floor portion of a band sample was 25 mm.

If the actual amount of dust scoured is much less than the 25 mm, a hazardous float coal dust condition could go undetected. In other words, if the top scoured surface of the dust is less than 80% incombustible content, a hazardous condition is present. However, if that top scoured amount is mixed with a full 25 mm of >80% incombustible content during the sampling procedure, the hazard may not be identified.

7. Disclaimer

Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health. The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of NIOSH.

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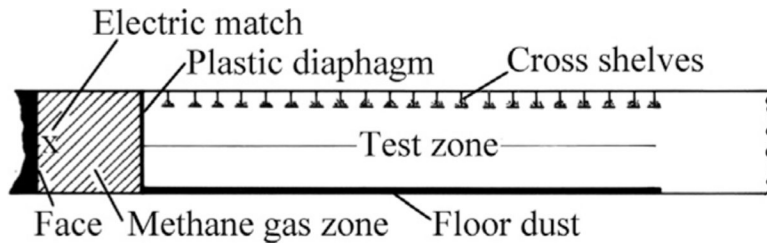


Fig. 1.
Explosion test setup and dust distribution.

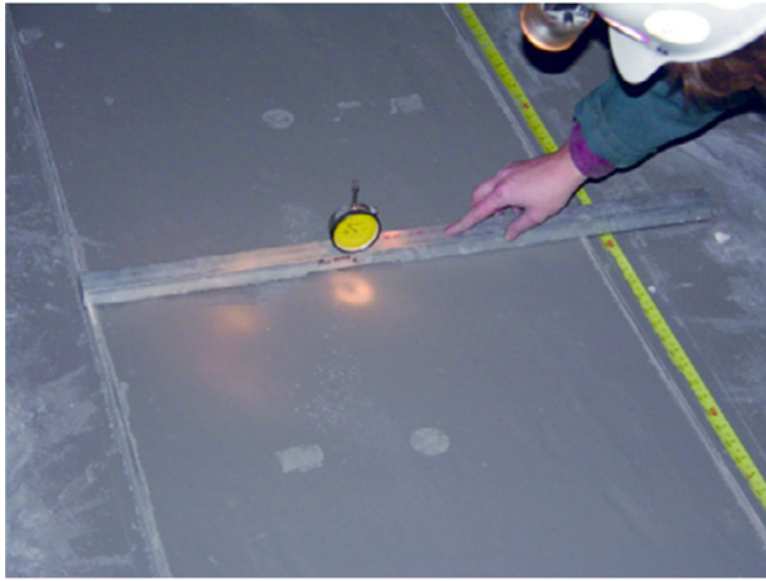


Fig. 2.
Taking a dust scour measurement.

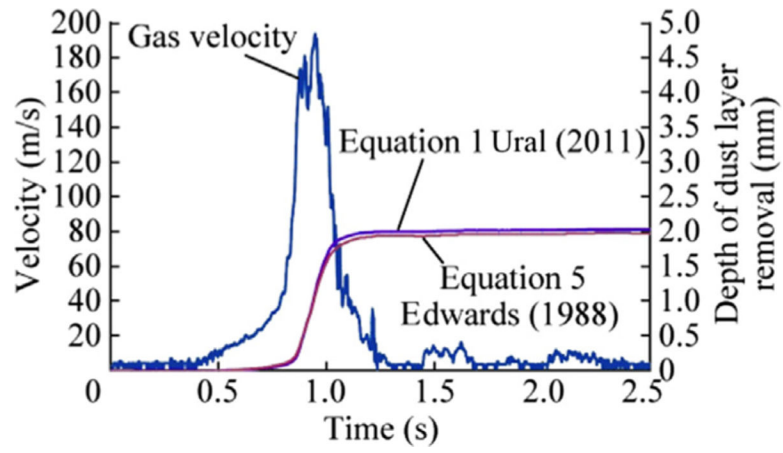


Fig. 3. Comparison of predicted scouring depths using Eqs. (1) and (5) with average measurements from LLEM test #511.

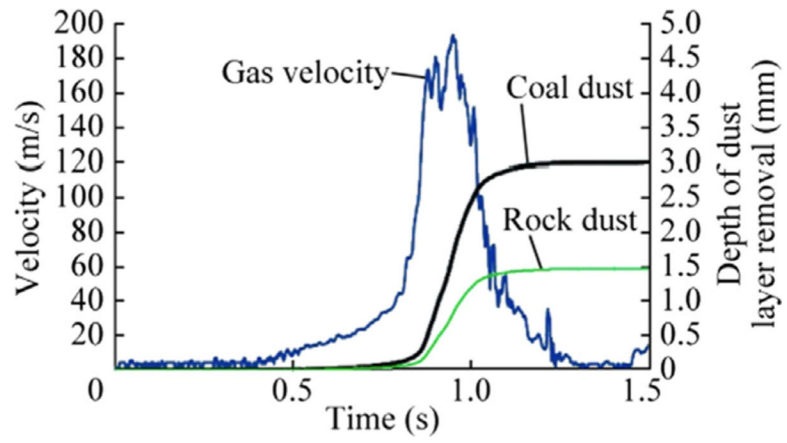


Fig. 4. Prediction of dust scour if layering occurs.

Table 1

Differences of measured values of dust depth before and after the LLEM explosion tests.

Test location (cm)	511 (mm)	512 (mm)	513 (mm)	514 (mm)	516 (mm)	517 (mm)	518 (mm)	520 (mm)
61	1.07	2.16	-0.56	1.24	0.97	0.77	0.71	2.49
91	2.02	2.00	-0.86	1.62	0.76	2.00	1.64	-0.93
122	1.79	1.77	1.89	1.42	0.85	3.48	2.46	2.48
152	2.45	4.02	3.20	2.30	0.93	-0.10	2.67	4.80
183	1.61	4.02	0.25	2.89	1.63	4.13	1.54	-0.40
213	2.02	1.40	0.57	2.46	1.62	-1.60	1.99	1.21
244	1.28	-0.31	*	1.99	0.00	-1.41	2.13	1.82
Average of locations 91–213	2.0	2.6	1.0	2.1	1.2	1.6	2.1	1.4
Standard deviation of locations 91–213	0.3	1.3	1.6	0.6	0.4	2.4	0.5	2.3

Note:

* means the crater formed by debris, could not measure value.

Traits of coal and rock dust mixtures used in LLEM full-scale dust explosions and calculated properties used in comparing dust removal models.

Table 2

LLEM Test No.	% RD in floor dust mixture (%)	CD type in mixture	Maximum gas velocity (m/s)	Bulk density (g/cc)	Threshold velocity (Eq. (2)) (m/s)	Threshold velocity (Eq. (6)) (m/s)
511	65	PPC	176.0	1.01	4.60	4.42
512	75	PPC	120.0	1.09	4.73	4.56
513	80	PPC	110.0	1.14	4.79	4.64
514	64	Coarse	156.0	1.00	4.59	4.40
516	69	Coarse	147.0	1.04	4.65	4.47
517	71.7	Medium	129.0	1.06	4.68	4.51
518	74.4	Medium	129.0	1.09	4.72	4.55
520	68.5	Medium	141.0	1.04	4.64	4.47

Measured and predicted scoured dust depths for LLEM tests compared to those predicted using Eqs. (1) and (5).

Table 3

LLEM Test No.	Measured dust removal (mm)	Measured Std. Dev. (mm)	Predicted depth of removal (Eq. (1)) (mm)	Predicted depth of removal (Eq. (5)) (mm)
511	2	0.3	2.1	2.1
512	2.6	1.3	1.5	1.5
513	1	1.6	1.4	1.6
514	2.1	0.6	2.1	2.2
516	1.2	0.4	1.9	2.0
517	1.6	2.4	1.6	1.7
518	2.1	0.5	1.4	1.6
520	1.4	2.3	2.1	2.3