Effect of Rock-Dust Height on Suppression of Coal-Dust Entrainment by Shock Waves

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1 Introduction

Dust explosions have been a serious industrial hazard for centuries in underground coal mines. These explosions result from the ignition of the dispersed combustible dust that accumulates in the air. In an underground coal mine, coal dust generated during the mining operation can be dispersed into the air by propagating shock waves formed in an initial explosion. The dispersed coal particles, if ignited, may lead to a secondary explosion, which is much more destructive than a primary one [1, 2]. These explosions pose threats to both the mining operations and the miners' lives. As a result, inerting and suppressing coal-dust dispersion and ignition is important for explosion prevention.

One of the most common safety measures practiced in coal mines is rock dusting, where inert rock dust is regularly applied to the surface of a mine during the mining operation, and a dust layer containing stratified rock and coal particles will be formed. It is required by MSHA (Mine Safety and Health Administration) that the total incombustible content (TIC) is at least 80% when mixed with coal to prevent dust explosions [3]. Ideally, the rock dust would suppress the dispersion of the coal dust underneath, forming a coal-rock mixture in the dispersed region, acting as a "thermal inhibitor", and preventing flame propagation [4]. In actual situations, the segregation of the rock and coal particles due to different particle size and density by the propagating shock wave could destroy the well-mixed rock-coal mixture, and the ignition of the separated reactive coal particles can still lead to further explosions. Therefore, understanding how the rock- and coal-dust cloud forms due to the propagating shock wave, and understanding the possible segregation phenomenon between rock and coal particles provides important information that can be used to determine how to prevent or at least mitigate a dust explosion.

In this paper, we'll focus on the dust dispersion in actual coal mine scenarios, where the dust has the properties of rock and coal particles. Numerical simulations were performed to study the dispersion of a shock passing over two layers of dust, where the top layer contains rock particles and the bottom layer contains coal particles. Specifically, the effect of rock-layer thickness on the dust dispersion is considered.

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2 Methodology

The simulations were performed using a multifluid granular model [5, 6] based on KTGF (Kinetic Theory of Granular Flow). A full description of the physical model and numerical algorithm can be found in Houim and Oran [6] and in Lai *et al.* [5]. The model solves (N+1) sets of Euler equations, one for the gas phase and N for the N particle phase. It takes into account different particle types using a binning approach, in which each bin of particles contains one particle size and density. This model is valid for high-speed, compressible flows with particle bulk densities ranging from very dilute to densely packed regimes, and allows us to study the segregation phenomenon of polydispersed systems for high-speed flow.

The governing equations are solved using an operator-splitting approach to integrate the hyperbolic terms and the source terms. The hyperbolic terms are solved using a high-order Godunov-based scheme [7], where the primitive variables are implemented using a MUSCL method with a third order parabolic reconstruction. A total variation diminishing (TVD) scheme with minmod slope limiter is also adopted to reduce small oscillations near discontinuities. A modified HLLC method, which returns primitive variables directly, is used to solve for the gas-phase flux. The granular flux is computed using a modified AUSM+ -up method to increase dissipation in highly packed regions. The solution algorithm uses a third-order Runge-Kutta scheme [8] for time advancement. Adaptive mesh refinement is implemented through the Boxlib library [9].

We identify six governing forces responsible for the granular motion. Evaluating these forces helps to understand the dust-lifting mechanism. Table I summarizes the six forces that act on particle type l. The lift and drag forces result from the velocity difference between the particles and the gas. The Archimedes force is due to the gas-phase pressure pushing on the particles. The intergranular stress corresponds to the collisional and frictional effect of the particles. The particle-hindrance force is a drag-like force between the two particle types.

Table 1: Forces acting on particle type l

Archimedes Force	$-\alpha_{s,l}\nabla p_g$
Intergranular Stress	$-\nabla p_{s,l} - \nabla p_{fric,l}$
Drag	$K_{lg}(\boldsymbol{v_g} - \boldsymbol{v_{s,l}})$
Lift	$C_l\alpha_{s,l}\rho_g(\boldsymbol{v_g} - \boldsymbol{v_{s,l}}) \times (\nabla \times \boldsymbol{v_g})$
Particle-hindrance force	$K_{s,lm}(\boldsymbol{v_{s,l}} - \boldsymbol{v_{s,m}})$
Gravitational	$\alpha_{s,l}\rho_{s,l}\boldsymbol{g}$

3 Results and Discussion

In this paper, the effect of rock dusting in preventing and reducing the coal-dust dispersion and explosion is explored. Here, the rock and coal dusts are assumed to be monodispersed. The rock dust is assumed to be 15 μm and 2680 kg/m^3, and the coal dust is assumed to be 30 μm and 1330 kg/m^3. (These parameters were provided courtesy of Marcia Harris and Michael Sapko of NIOSH). Earlier invesitations [5] on the motion of a particle cloud containing a distribution of particle sizes (six particle bins) have been performed.

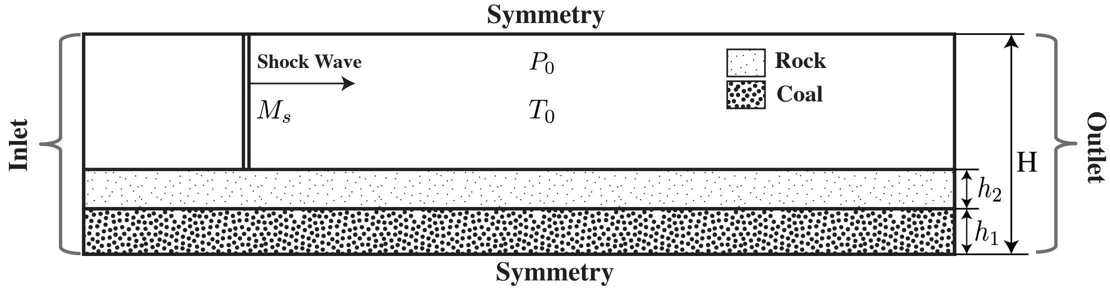

Figure 1: Schematic diagram of the initial conditions for the two-dimensional siumlations where a shock of strength M_s travels over two dust layers. A dust layer containing particle type I of thickness and h_1 lies underneath a dust layer containing particley type II of thickness h_2.

Increasing the number of particle bins increases the realism of the computations, but it also increases the computational expense. In this paper, only two particle bins (one represents coal particles, and the other on represents rock particles) are used in the 2D simulations shown below.

Figure 1 shows the initial and boundary conditions for the simulations. The two-dimensional channel is 10.2 cm high and 7 m in length. A Mach 1.4 shock placed at $x_{\text{shock}} = 5$ cm is propagating over a layer of rock dust placed on top of a layer of coal dust. The background temperature (T_0) and pressure (P_0) is 295 K and 67 kPa, respectively. The post-shock condition is determined by the Rankine-Hugoniot relations. The left and right side of the channel are non-reflecting, inflow-outflow boundary conditions and the top and bottom side of the domain are symmetry planes (These initial conditions are based on the experiments performed by Chowdhury *et al.* [10]). The gas is assumed to be air. Both types of particles have an initial volume fraction (α_s) of 0.47, and a coefficient of restitution, e, of 0.9.

3.1 Dispersion of 1 mm Rock Dust on 4 mm Coal Dust

The computed results of a shock passing over a layer of 1 mm rock dust placed on top of a layer of 4 mm coal dust is shown in Fig. 2. The top two images in Fig. 2 show the particle volume fractions for the coal and rock dust on a log scale. The bottom image in Fig. 2 indicates the location of coal and rock particles. Here, particles with a volume fraction less than 0.005% are not shown. The results show that the coal and rock particles are mixed with each other in most of the dispersed region, and there is no apparent separation between the two types of particles. In the area closer to the moving shock wave (400 $\sim$ 600 cm), however, the entrained dust is primarily rock dust (blue region). This is because dust lifting from the top layer begins immediately behind the propagating shock wave, and there is a delay in dust lifting from the bottom layer. In the rest of the region (0 $\sim$ 400 cm), the coal particles are lifted slightly higher than the rock particles, even though they were initially placed in the lower level. This result is consistent with earlier results that larger and lighter particles are lifted higher than smaller and heavier particles due to the differences in lift force and drag forces [5].

In this calculation, the 1.4 Mach number is selected to be consistent with the experiments performed by Chowdhury *et al.* [11], and our previous calculations [5]. The effect of Mach number on dispersion of stratified dust layers has also been investigated recently. The results suggest that the lifting behavior of the two dust layers remain qualitatively the same regardless of the Mach number.

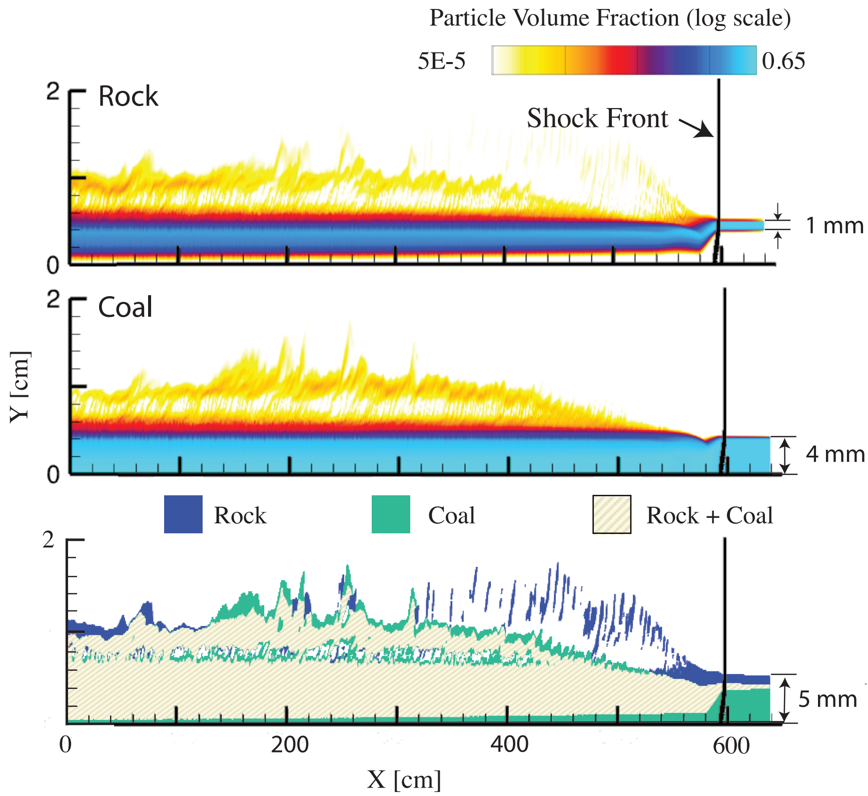

Figure 2: Simulation results of a Mach 1.4 shock passing over 1-mm rock layer on top of 4-mm coal layer. The top two image show the particle volume fraction contour of the rock and coal particles. The bottom image indicates the location of each type of particle.

3.2 The Effect of Rock-Layer Height on Dust Dispersion

Here, the effect of the rock-layer (upper layer) thickness on dispersion of a 4-mm coal layer (lower layer) is examined. Rock-layer heights of $h_2 = 1$, 2, and 3 mm are considered. The computed rock-dust concentrations for all the three cases are shown in Fig. 3 where the edge of the coal particles is indicated. Here, blue indicates a coal-dominate region, while red indicates a rock-dominate region. The results show that the coal dust from the lower layer rises more slowly with increasing rock-layer thickness in the upper layer. In addition, the rock dust in the upper layer also becomes less dispersed with increasing rock-layer thickness. In the first case ($h_2 = 1$ mm), rock particles have a concentration close to or less than 50% in most of the dispersed region and coal particles are lifted to a similar level as the rock particles. In the second case ($h_2 = 2$ mm), the rock particles are more dispersed than the coal particles, and rock particles dominate in the dispersed region with a concentration ranging from 60% to 100%. In the last case ($h_2 = 3$ mm), the dispersed dust consists of primarily rock particles and the coal dust is hardly lifted. In this case, the 80% total incombustible content (TIC) requirement is achieved in most of the dispersed region.

To keep the coal dust from rising and igniting, we need two conditions to be fulfilled: rock particles from the upper layer should suppress the coal particles from the bottom layer, and the rock concentration in the dispersed region should be greater than 80%. As a result, although the inert particles applied in the first case

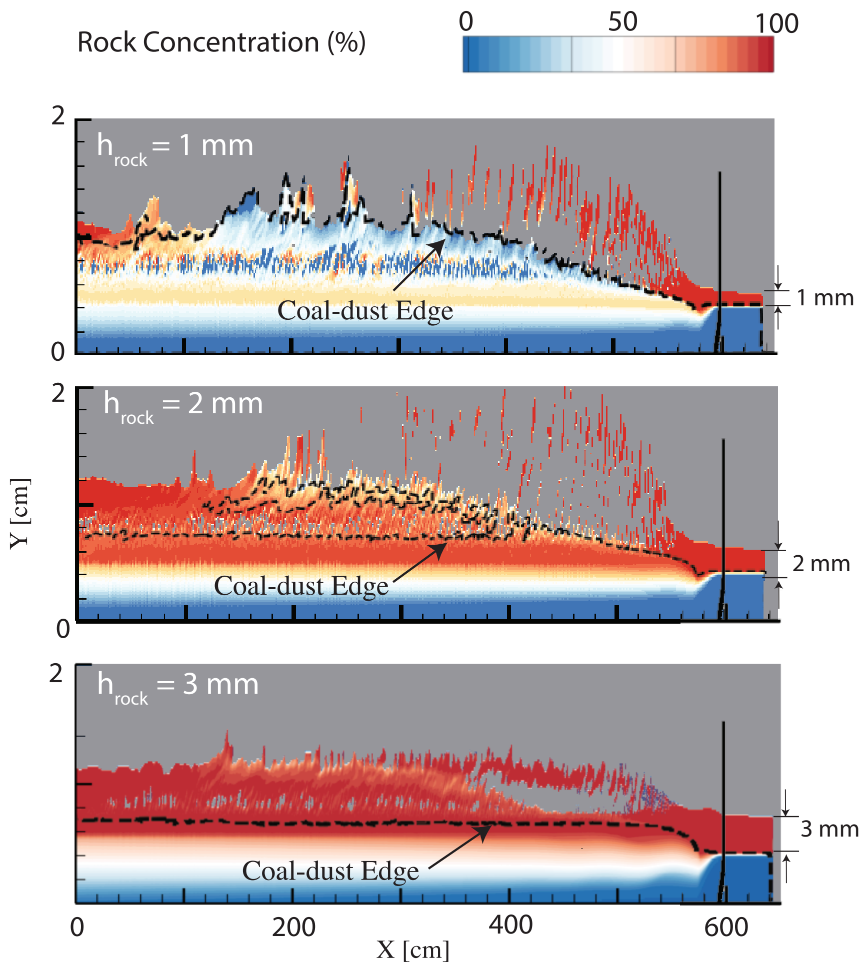

Figure 3: Computed rock concentrations for rock-layer thicknesses of $h_2 = 1$, 2, and 3 mm. The location of the dispersed coal dust edge and the propagating shock wave are indicated. The coal-dust layer remains at 4 mm for all cases.

(1-mm rock layer) are well mixed with the reactive coal particles in the dispersed region, the concentration of the rock dust is not high enough to ensure ignition mitigation. Figure. 3 shows that a relatively thick (3 mm) rock-dust layer is required to suppress lifting of the underlying coal-dust layer and meet the 80% TIC requirement. The coal particles begin to rise after the reflecting compaction wave interacts with the surface of the dust layer through positive intergranular stress and lift forces. This lifting behavior is then opposed by the negative particle hindrance effect. When an increasing amount of rock dust is applied, the positive intergranular stress (pressure-like effect on the granular particles) within the coal dust layer decreases, since the coal dust now has a lower granular energy due to interparticle collisions and friction. In addition, with more rock dust applied to the top layer, the dispersed coal particles experience a larger negative particle hindrance force, which suppresses the lifting. This explains why coal particles are more suppressed with a thicker rock-dust layer on top. The particle hindrance force also causes the coal-dust layer to rise more rapidly with decreasing rock-dust thickness. For the first case in Fig. 3, the coal particles underneath exert a large positive particle hindrance force on the rock particles above them during the dispersion process. For the case where h_2 = 3 mm, the positive particle-hindrance effect is less important, since the coal particles are now dispersed to a much lower height than the rock particles.

3 Future Work

The dispersion of stratified dust layers are complex processes that depend on many factors. Here, we focused the effect of particle size and the top-layer thickness. Other parameters, such as the shock wave Mach number, the bottom-layer thickness, coefficient of restitution, and initial packing could also be very important. More importantly, developing a general correlation that could be used to predict the dust dispersal height as a function of these parameters (particle size, dust-layer thickness, Mach number, etc.) would be extremely useful to optimize the selection of rock-dust properties applied in a coal mine to prevent explosions.

4 Conclusions

Simulations to explore the effect of the height of the applied rock-layer on dispersion of coal particles were performed using a multifluid granular model based on the kinetic theory of granular flow. The model takes into accounts multiple particle types with a binning approach, where each bin of particles has its own characteristic uniform particle size and density. In this work, coal particles are 30 μm and 1300 kg/m^3, and the rock particles are 15 μm and 2680 kg/m^3. A thin rock layer was placed on top of a thicker coal-dust layer. The rock-layer thickness of 1, 2, and 3 mm were considered. The results show that placing a 1-mm thick rock layer fails to suppress the coal particles from being lifted. The coal particles were still lifted slightly higher than the rock particles even though the coal particles were initially placed at a lower position. With increased rock-layer thickness, the coal dust rises more slowly, and a 3-mm layer of rock dust is needed to meet the 80% total incombustible content requirement.

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