

CFD MODELING OF DUST TRANSPORTATION AND DEPOSITION UNDER NEWTONIAN FORCES IN THE REDUCED SCALE
MODEL OF A TYPICAL ROOM AND PILLAR MINE

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ABSTRACT

Dust is ubiquitous in underground mining activities, carrying with it risk to personnel and machines. Sources of dust are widely studied, but transportation has been mainly based on experimental data and simplified models. A fundamental understanding of dust transportation in the mine airways is instrumental in the implementation of local dust control strategies. Computational fluid dynamics models were developed using Lagrangian particle tracking approach in a pseudo-two-dimensional flow volume. This paper presents the transportation and deposition profile of different sized dust particles moving under the effects of Newtonian forces along a 7' high airway.

ACKNOWLEDGMENT

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INTRODUCTION AND LITERATURE REVIEW

Dust generated in underground coal mines contribute to health and safety hazards. While respirable coal dust has been shown to the cause an onset of the irreversible and fatal coal workers pneumoconiosis, float dust is responsible for deadly explosions. Thousands of miners have lost their lives to black lung disease and to coal dust explosions triggered by 'methane puffs'.

Characterization of dust particles is crucial to the identification of their physical and hence transportation properties. Dumm and Hogg used a variety of classification and particle size analysis techniques on respirable dust. The results obtained from cascade impactors agreed well with those from centrifugal sedimentation, laser diffraction, and automatic particle counting (Dumm & Hogg, 1987). Studies by the US Bureau of Mines in have shown that the transportation of dust generated on the surface mine while drilling decreases rapidly with distance (Page & Maksimovic, 1987). Underground, dust is transported violently during explosions riding on the shock wavefronts (Sheng & Otuonye, 1989). Shankar and Ramani investigated the deposition velocities and showed that most of the fine coal dust was accumulated close to the source itself (Bhaskar & Ramani, 1990). This could have significant implications for dust control measures. Further, in 1996, they used wind-tunnel testing and in-mine experiments and established that respirable dust could also be transported into the main ventilation network via re-entrainment in an underground mine (Shankar & Ramani, 1996).

Mine operators usually adopt a variety of remedial measures to combat dust. Using ventilation air stream to lower the concentration of dust is the mainstay of the techniques to render the particles cluster to harmless levels. Other prominent measures include using a variety of water sprays, using physical barriers like curtains, and pressurized operator cabins. However, understanding the transportation of dust particles is crucial to choosing suitable remedial measures. This would

also enable making a judicious decision on the quantity and frequency of application of inert rock dust.

The National Institute for Occupational Safety and Health (NIOSH) carried out detailed studies of dust concentration at the face in deep cuts in six different coal mines. The investigation further reinforced the fact that the scrubber flow was important to dust alleviation at the face. It was also found that the fibrous filter clogging led to about 22-35% depletion in airflow in the flooded-bed dust-scrubber (J.D.Potts, Reed, & Colinet, 2011). Recently, NIOSH also characterized the float coal dust produced during the continuous miner, the longwall and, belt transport operations. Many sampling instruments were used to quantify the ratio of float to respirable dust in the airways. Continuous mining operations were found to have the highest concentration of airborne float coal dust (Shahan, Seaman, Beck, Colinet, & Mischler, 2017). Setting up experiments on large-scale mining operations could be difficult, expensive, and time-consuming. Scale modeling technique, therefore, is used to address the problem of a reduced manageable length scale.

Scale modeling technique has been instrumental in addressing complex problems of large length and time scale. Development and application of scaling laws are based on the identification of most important forces. Breslin and Stratizsar at the US Bureau of Mines worked on a reduced scale model of coal mine entries and mining machinery. They established that the distance of brattice or ventilation controls from the active face in addition to the secondary ventilation system assisted in reducing the dust concentration by over 90 % (Breslin & Stratizsar, 1976).

SCALING THE AIR FLOW RATES

Mining environments often deal with enormous flow rates. Scale modeling could be used to scale down some of the parameters to make the set-up conducive to laboratory testing of numerical models. With the major governing forces for a process or phenomenon are identified first, the ratio of those forces is used to generate dimensionless quantities called the π -numbers. Reynold's number, being the ratio of inertial and viscous forces is a well-known π -number and is a strong indicator of the nature of flows in a domain. A Reynold's number exceeding 5,000 often points to a fully developed turbulent flow regime through a cross-section. The flow inside the reduced scale model of the mine could be driven by the inertia of airflow and gravity action. The forces could be described by,

$$\text{Inertial force, } F_i = \rho l^2 v^2$$

$$\text{Gravitational force, } F_g = \rho l^3 g,$$

where ρ is the density of air at nominal temperature and pressure (1.2 kg/m³), g is the acceleration due to gravity (-9.81 m/s²), v is the characteristic velocity (m/s) in the domain and l (m) is the characteristic length. The ratio of inertial and gravitational forces is a dimensional quantity called the Froude's number.

$$\pi - \text{number} = \frac{\rho l^2 v^2}{\rho l^3 g} = \frac{v^2}{lg} \quad (i)$$

This simply indicates that for a reduced scale model with the dimensions shortened by a known scaling factor, the airflows would have to be lowered according to the equation (i). Although the airflow in the domain could be scaled using the Froude's number, a corresponding scaling of dust particles would result in a significant departure from the characteristics of those particles. Partial relaxation of geometrical scaling was therefore used for dust particles to ensure that the properties of the dust particles are not altered by the scaling process (Sekimoto, 2008). This could be compared to the scale modeling of the sedimentation process with water replaced by air and the properties of the dirt particles kept intact. Computational fluid dynamics (CFD) modeling technique was used to mimic the transportation of the dust particles in a 1/12th reduced scale model of the mine.

CFD MODELS PREPARATION

CFD is a powerful numerical tool to mimic airflows in the underground mine environment. CFD models were set up and run in SC/Tetra V14 which has excellent unstructured mesh generation capabilities. Independent modules for the pre-processor, the solver, log file analysis, and post-processor offers flexibility towards optimization of total simulation time.

Two different scenarios of flows were modeled:

- (i) A scaled down 1/12th model of a room and pillar coal mine where the dust particles were released close to each of the face.
- (ii) A pseudo-2D model to mimic a 7' high section where the dust particles were released at the top corner and allowed to travel under the influence of Newtonian forces.

Figure 1 shows the schematic layout of the ventilation circuit. The model coordinates extend from -6.31 to 4.13 in X-direction and from -13.11 to 12.94 in the Y-direction. The reduced scale model is visually similar to the full-scale room and pillar coal mine. A volume flow rate of 12,000 cfm (5.66 m³/s) is sent via the inlet marked by the letter A, to the mining faces C, D and E. An airflow of 3,000 cfm (1.42 m³/s) is split and sent via the segment B and serves as the neutral airway. Owing to the frequent movement of shuttle cars, an airflow of 500 cfm (0.24 m³/s) has been assumed to leak through the segment F into the neutral branch, leaving 8,500 cfm (4.01 m³/s) to ventilate the faces D and E. A flow of 9,000 cfm (4.24 m³/s) sweeps the face C. All these flows were scaled using Froude's number scaling with a scaling factor of 1/12.

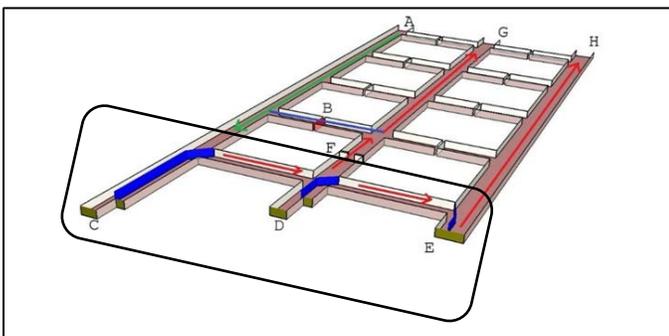


Figure 1. Layout of the ventilation circuit with the main control points marked by letters.

The dense octree was generated first with a preferential higher allocation of the cells close to the impermeable walls and in the zones of recirculation. Five prism layers were imparted to model the boundary layer phenomenon. The mesh was adapted systematically in three runs to have a much higher element packing density in the areas of interest as shown enclosed by the box. The analysis conditions included a known flow rate at the inlet while the outlet was assigned a static pressure of 0 Pa. All other surfaces had imparted impermeable wall conditions. The accuracy of time derivative terms was set at second order. Figure 2 shows the contours of normalized wall distances on the impermeable surface of the model. An average scalar

integral of the y+ value was obtained to be lower than 1.0 and indicates that the airflow close to the wall has been resolved well. This also encouraged the application of the SST-kw turbulence model to model the particle transportation later. Figure 3 shows the contours of velocity magnitude on a plane parallel to the mine floor. The airflow is observed to accelerate close to the face aided by the ventilation curtains. Slightly higher velocity magnitudes on the belt airway and due to the leakages near the active face are clearly visible. Once, a steady state flow profile was established, particle tracking was initiated.

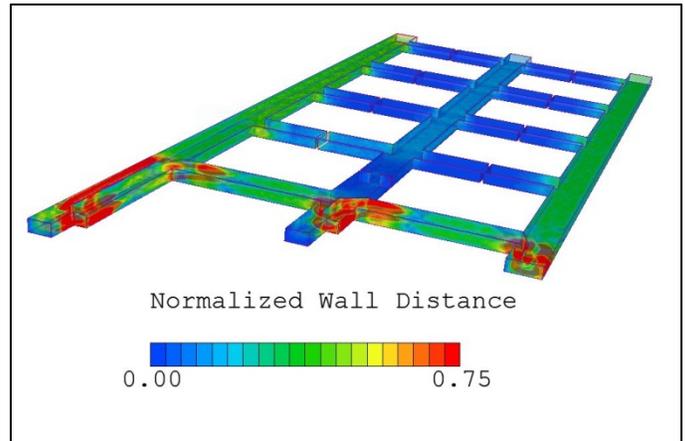


Figure 2. Contours of normalized wall distances on the impermeable surfaces.

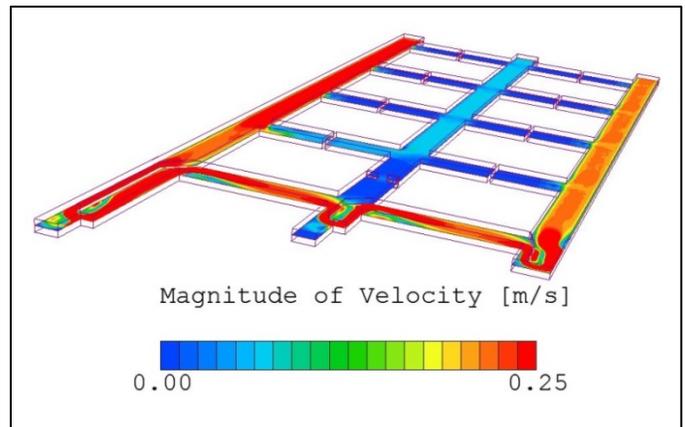


Figure 3. Contours of velocity magnitude on a plane parallel to the coal floor and midway through the walls.

The restart file with the information of the converged steady-state flow scenario was used to inject particles into the converged flow field. The particles were released randomly from the active face of the deepest cut furthest to the right for a period of 30.0 s. These particles were assumed to be coal dust specks and were assigned diameters in the range 1-30 μm. The diameters were adjusted using Cunningham's slip correction factor to account for comparable dimensions of the particle sizes and mean free path of the air molecules at nominal temperature and pressure (Cunningham, 1910). The particles were tracked for next 210.0 s, until 240.0 s. This time was determined during the preliminary transportation and deposition profile of the particles and balanced the available computing resources. Figure 4 shows the position of the particles at the time, t= 210.0 s.

The figure clearly shows that while the particles of size 1.0 and 5.0 micron continue to travel riding on the ventilation airstream, the particles of size 10.0 micron started settling down in the return airway. Particles of size 15.0 micron do not travel as far. Particles of size 20.0 and 30.0 microns are not able to escape the deep cuts and settle down close to their source of generation. Figure 5 and Figure 6 show the lateral displacement of particles by their size. The particle distribution within a certain size range is predominantly random. This clearly

shows that despite a wide range of particles generated at the coal face by size, no conclusive trend of particle size on the floor could be obtained. This could be attributed to a turbulent flow profile with a chaotic change in flow velocity in a flow volume enclosed by irregular walls. This has also been observed in recently sampling exercises carried out by the University of Kentucky mining engineering department.

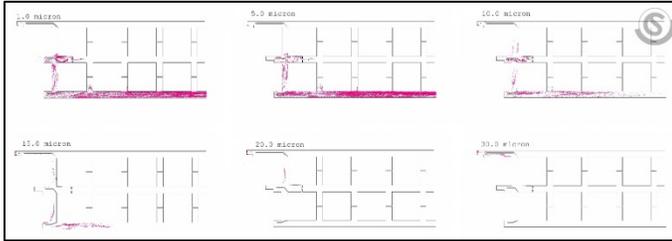


Figure 4. Position of dust particles at the time, $t=180.0$ s, when first specks of dust were released at the time, $t=30.0$ s.

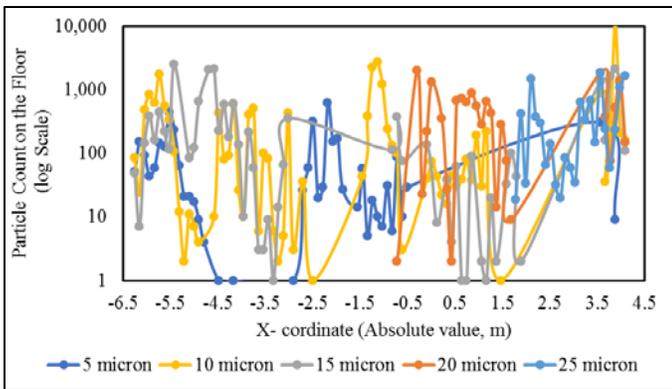


Figure 5. Lateral displacement of the dust particles by count on the mine floor.

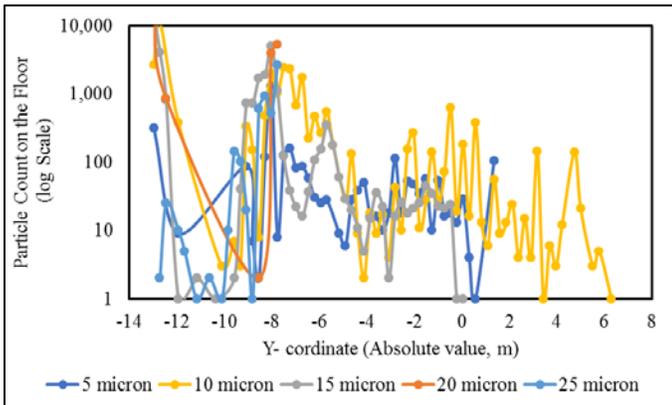


Figure 6. Lateral displacement of the dust particles towards the exhaust airway out of the mine

A simple pseudo-2D model was created to scale the results to a full-scale model and to predict the distance dust-particles of different densities would travel. This was done to mimic the distance the dust particles could travel under different ventilation airstream flows. Therefore, the motion of particles in the third dimension was deemed inconsequential. The model measures 2.13 m (7 ft.) in height and is 30.48 m (300 ft.) long. The thickness of the flow volume has been assigned to be 0.0254 m (1.0 in.) While generating the pseudo-2D meshes, two layers of grid elements were assigned in the third dimension. This resulted in a massive reduction in the number of mesh elements, a part of which could not be used for a higher packing density. Figure 7 shows the surface mesh in the flow volume.

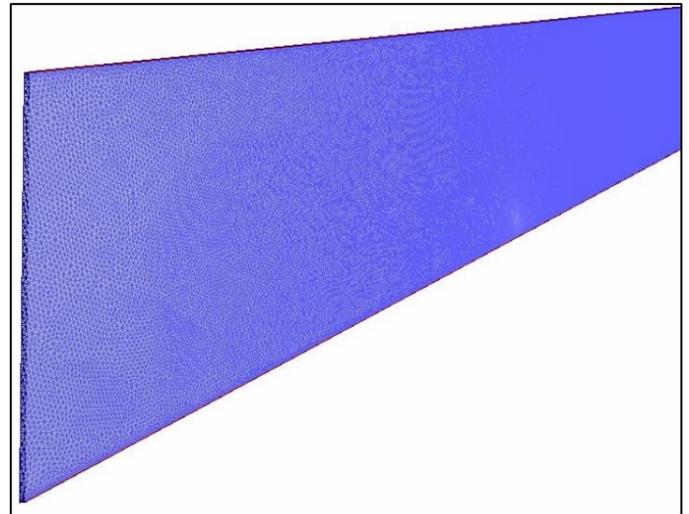


Figure 7. Surface mesh on the isometric projection of the pseudo-2D flow volume, spanning 7' X 300'.

Steady-state models were generated with different average airflow speeds first. The restart files of the steady-state models were used to initiate particle tracking simulations. Particles of size 75 micron and specific gravities 0.8, 1.0, and 1.2 were released at the top left corner of the model to mimic the highest time of flight and hence, the lateral displacement. All Newtonian forces were calculated every time step. The particles were tracked until they hit the mine floor. Figure 8 shows the location of particles of different densities and at different instances in time. Figure 9 shows the surface plot of lateral displacements for all the particles.

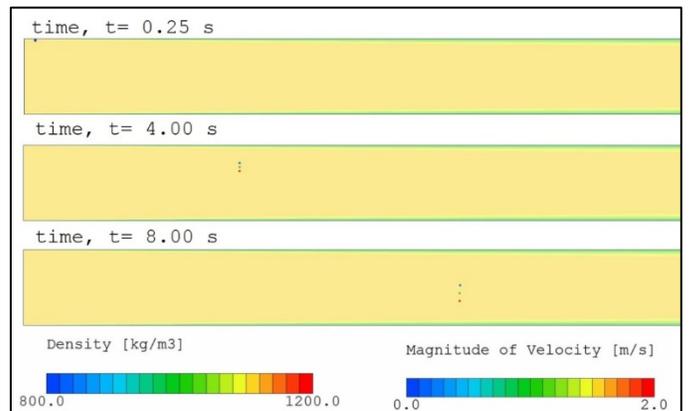


Figure 8. Position of the particles colored by their density.

RESULTS AND CONCLUSIONS

Particle transportation was modeled in a reduced scale model of a room and pillar coal mine. Since the flow is predominantly turbulent, the most important governing forces are the inertia of airflow and gravity. Viscous effects of air could be neglected owing to a high Reynold's number flow. The ratio of inertial and viscous forces yields Froude's number which was also used to scale the airflow quantities. Particles less than 1.0 micron in size were observed to follow the streamlines of airflow, while heavy particles settled down immediately. No conclusive evidence of deposition trends was observed within a known particle range when measured from the source of generation. Although the mine model used in this paper has known dimensions, similar random distribution of the float dust have been observed in coal mines. Computer models were generated to predict the distances particles would travel when released in the mine airstream. Time of flight of heavier particles was found to be lower since gravitational forces overcome drag forces immediately, and hence the lower lateral displacement in ideal straight-line flow conditions.

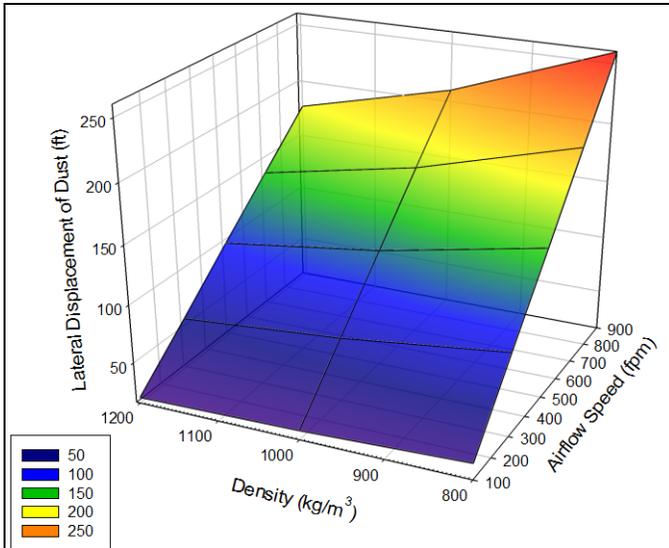


Figure 9. A 3D surface plot of horizontal distance the particles are displaced laterally when released in known airflow speeds.

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