2019

Dust Transportation and Settling within the Mine Ventilation Network

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Digital Object Identifier: https://doi.org/10.13023/etd.2019.321

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Dust Transportation and Settling within the Mine Ventilation Network

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mining Engineering in the College of Engineering at the University of Kentucky

By
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ABSTRACT OF THESIS

Dust Transportation and Settling within the Mine Ventilation Network

Dust is ubiquitous in underground mine activities. Continuous inhalation of dust could lead to irreversible occupational diseases. Dust particles of size lower than 75.0 μm, also known as float coal dust, can trigger a coal dust explosion following a methane ignition. Ventilation air carries the float coal dust from the point of production to some distance before it's deposited on the surfaces of underground coal mine. Sources of dust are widely studied, but study of dust transportation has been mainly based on experimental data and simplified models. An understanding of dust transportation in the mine airways is instrumental in the implementation of local dust control strategies.

This thesis presents techniques for sampling float coal dust, computational fluid dynamics (CFD) analysis, and mathematical modeling to estimate average dust deposition in an underground coal mine. Dust samples were taken from roof, ribs, and floor at multiple areas along single air splits from longwall and room and pillar mines. Thermogravimetric analysis of these samples showed no conclusive trends in float coal dust deposition rate with location and origin of dust source within the mine network. CFD models were developed using the Lagrangian particle tracking approach to model dust transportation in reduced scale model of mine. Three dimensional CFD analysis showed random deposition pattern of particle on the mine model floor. A pseudo 2D model was generated to approximate the distance dust particles travel when released from a 7 ft. high coal seam. The models showed that lighter particles released in a high airflow field travel farthest. NIOSH developed MFIRE software was adopted to simulate dust transportation in a mine airway analogous to fume migration. The simulations from MFIRE can be calibrated using the dust sampling results to estimate dust transportation in the ventilation network.

KEYWORDS: Dust control, Computational Fluid Dynamics Modeling, MFIRE.

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Date: July 26, 2019

Dust Transportation and Settling within the Mine Ventilation Network

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To Mom, Dad, and Sister

ACKNOWLEDGMENTS

I express my sincere gratitude to Dr. Steven Schafrik, who served as my advisor throughout my graduate studies at the Department of Mining Engineering, University of Kentucky. He gave me immense opportunities to work, learn and grow, for which I will be forever grateful. I would also like to thank Dr. Ashish Kumar for his extensive support and encouragement throughout my research.

I acknowledge Dr. Agioutantis for his guidance with coursework and support throughout my graduate studies. I would like to thank Dr. Thomas Novak and Dr. Josh Werner for serving on my graduate committee. I acknowledge Megan Doyle, Kathy Kotora, Geaunita Caylor, Alycia Tidrick, Adriane Russell and Kathy Ice-Wedding for making my journey at the graduate school truly memorable. I thank Alind Chandra, Tushar Gupta, Oscar Velasquez, Kayla Mayfield, Brad Coleman, and all other graduate students for their support and assistance.

I acknowledge the National Institute for Occupational Safety and Health (NIOSH) for funding this research via the contract 200-2014-59922, "Coal Mine Dust Mitigation Through Novel Scrubber Development and Numerical Modeling." The views, opinions, and recommendations expressed herein are solely those of the author and do not imply any endorsement by the CDC/NIOSH.

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Chapter 1 Introduction and Problem Statement

1.1 Background and Motivation

Coal has an important role in meeting global energy demands and is critical to infrastructure development. Around 38% of the world's electricity and 71% of the world's steel is produced using coal [1]. Additionally, recent research has shown that coal and its byproducts are significant sources of rare earth elements [2]. Coal is mined by surface 'opencast' mining or underground mining. Surface mining is often used for coal deposit less than 200 feet underground, in which the top soil is removed by drilling, blasting or using large machines. However, underground mines are economical when the coal seam is several hundred feet below the surface. Underground mines can be hundreds of feet deep, involving a complex system of connected tunnels and vertical mine shafts.

Underground coal mining is a highly mechanized process, which creates dust when fracturing and transporting coal and rock. The dust generated at the working face is the highest contributions to the dust present in underground mine airway. Dust is also produced at the conveyors, material transfer points, and through movements of machines and workers. Coarse dust particles settle out of the air rapidly, but the fine fraction known as float coal dust particles less than 75 μm remains in the air as it is transported and dispersed by the mine ventilation network [3]. This dust is deposited on mine airways at a rate governed by several physical phenomena, which includes the influence of gravity, eddy and Brownian diffusion, coagulation and inter particle collisions, and advection [4]. These float coal deposits are hazardous during methane explosion as dust can be re-entrained and can cause coal dust explosion which is more violent than methane explosion [5].

The primary defense against coal dust explosion is rock dusting, which is directed at the roof, floor, and ribs of underground mine [6]. If an explosion should occur, the rock dust disperses, mixes with the coal dust and prevents flame propagation by acting as a thermal inhibitor or heat sink [7]. The regulations state that rock dust shall be distributed in such a manner that incombustible content combined must not be less than 80% in return airways and 65% in other areas in a mine [8]. Therefore, the necessity of designing and implementing suitable rock dusting practices are important. There are several methods used for dispersing rock dust into the mine. However, the deposition behavior of float coal dust is unknown and necessitates research. This results in casual practices of rock dusting that may cause a safety hazard.

This thesis presents dust sampling results gathered from a longwall and room and pillar mines. The purpose of this study was to investigate the deposition behavior of the airborne coal dust in the mine airway. These results were crucial inputs to computer modeling and simulation of dust transportation and settling within the mine ventilation network.

1.2 Research Objectives

The research objective was to model the dispersion of float coal dust in mine ventilation networks and develop an application to aid scheduling of rock dusting in coal mine airways. A dust transportation network model was developed in a reduced scale model for this research, and MFIRE software was adopted to estimate migration of dust. The research aims have been enumerated below:

(i) Dust sampling from longwall and room and pillar mines and its thermogravimetric analysis;

(ii) Modeling of dust particles in the mine ventilation network to obtain dust deposition profile;

(iii) MFIRE software analysis to estimate dust migration.

Chapter 2 Literature Review

This chapter outlines the previous prevailing research and developments in dust combating practices applicable to mining operations.

2.1 Combustible Dust Hazards in Coal Mine

In an underground coal mine, dust is generated during various mining operations such as impact, crushing, cutting, grinding or blasting [9]. This dust is finely divided solid particles ranging in size below 1 μm up to around 100 μm, which can become airborne depending on various conditions [3]. Combustible dust in an underground coal mine is considered to be the dust particles of size less than 75 μm passing through a U.S. Standard No. 200 sieve [10]. This dust, also known as "float coal dust," has led to multiple explosions in underground coal mines. If this generated dust is not captured at the face, it is dispersed into the mine environment through ventilating air. In the event of usually less harmless methane ignition or explosion, the propagating shock wave disperses the coal float coal dust in the mine airstream and makes the environment prone to dust explosion, which is often violent and deadly. The explosion on April 26th, 1942 in Benxihu colliery in China is the worst disaster in the coal mining history and led to 1,549 fatalities [11]. Farmington mine disaster, which occurred in 1968 at Mannington, West Virginia, United States, killed more than 78 miners [12]. Figure 2.1 shows the smoke and flame pouring from the shaft at Farmington mine. The Jim Walters No. 5 Mine in Brookwood Alabama and the Upper Big Branch Mine in West Virginia disasters together killed 42 miners [13] [14]. The Sago Mine explosion in West Virginia on January 2nd, 2006, trapped 13 miners, 12 of whom eventually lost their lives [5].

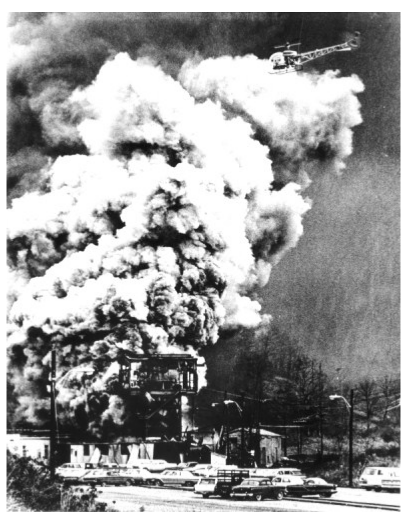


Figure 2.1: Farmington mine disaster
[12]

The Mine Safety and Health Administration (MSHA) carried out a detailed investigation given the accident to a coal dust explosion, triggered by a methane explosion at the longwall face [14]. Numerous research projects have been carried out to investigate mine explosions in the US and China [15] [16]. These studies have led to several efforts to mitigate the explosion by mining companies. The major conclusion is to dilute the dust concentration in the underground mine environment with incombustible rock dust (usually pulverized limestone), which can act as a heat sink and reduces heat transfer between coal dust particles [17] [18]. Despite the protective measures, chances of occurrence of explosions cannot be ruled out due to which continuous improvement on dust mitigation is encouraged.

2.2 Health Hazards of Dust in a Coal Mine

Dust generated in many unit operations in mining has significant impacts on miners. Prolonged exposure to dust particles having an aerodynamic diameter less than 10μm can cause coal workers to develop pneumoconiosis (CWP), silicosis, emphysema, and chronic bronchitis, collectively known as black lung [19]. Black lung is incurable and is caused a build-up of inhaled dust in the lungs that can not be removed [20]. The severity of the disease increases with the length of exposure. The National institute of Occupational Health and Safety (NIOSH), report"Work-Related Lung Disease Surveillance Report," states that black lung killed more than 10,000 miners between 1995 and 2004 [21]. Another report by The Mine Safety and Health Administration (MSHA),"Exposure to Respirable Coal Mine Dust, Including Continuous Personal Dust Monitors," shows that since 1968 black lung has contributed to the deaths of 76,000 coal miners [19]. Factors responsible for silicosis were discussed in Johannesburg in 1930, at a conference by Mavrogordato [22], after which Fay and Ashford developed models to classify the radiograph films for the medical personnel who would ascertain the extent of disease while examining miners [23].

The pneumoconiotic shadow in the diagnosis reports and loss in lung function in exposed miners were first indicated by pathological studies at a colliery in Midlithina, Great Britain [24]. Irreversible respiratory system damage in miners led to several pieces of improved and revised safety legislation in the US [25]. The CWP prevalence among examinees employed at US underground coal mines is shown in Figure 2.2 [21] and it indicates a declining trend in the occurrence of CWP during those years. Recently, in the Appalachian region in the eastern United States, there has been an increase in the occurrence of CWP [26]. Respirable quartz, silica, and other mineral matter found in Appalachian coals [27] has increased the severity of the diseases [28].

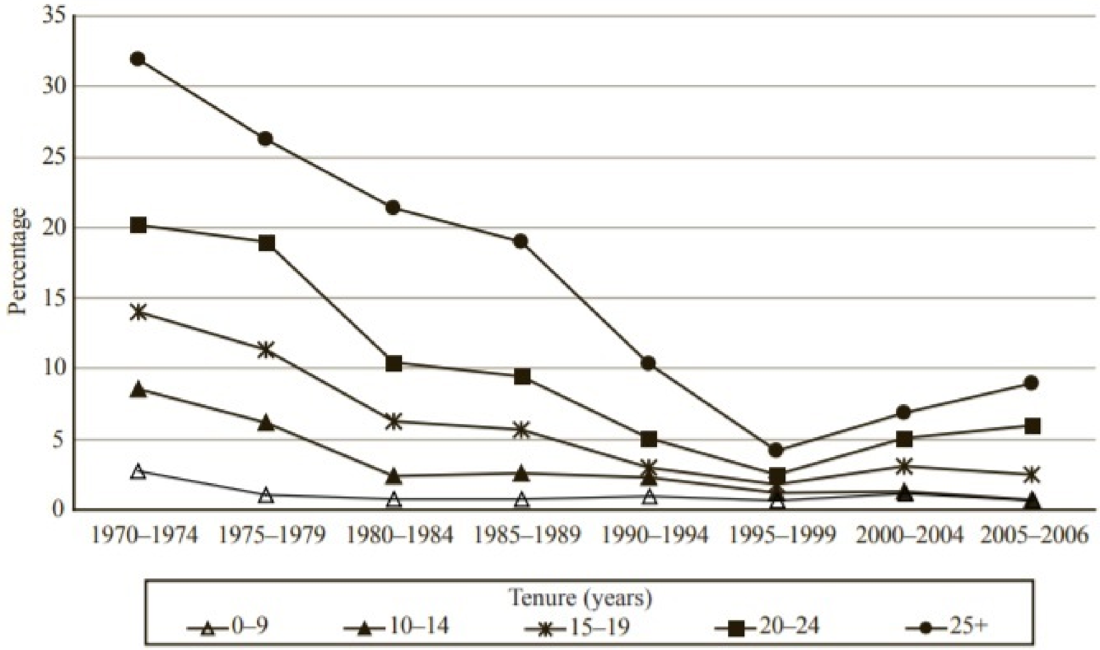


Figure 2.2: Percentage of examined miners with coal workers pneumoconiosis by tenure in mining
[21]

Like the coal industry, workers in metal mining and other industries suffer from occupational diseases [29]. Clinical aspects of CWP and silicosis studied by Balaan et al. mark the group of fibrotic lung diseases caused by exposure to silica [30]. Prolonged exposure to asbestos particles can lead to "asbestosis," an irreversible lung disease [31]. During the 1930s hundreds of workers died working in the Hawks Nest tunnel in West Virginia due to silicosis and other exposure related lung diseases. These findings show that exposure related diseases are prevalent in all mining; therefore, this requires greater research towards mitigation.

2.3 Dust Control Legislation in the US

To reduce and research the accidents in mines U.S Bureau of Mines was established by Congress in 1910. The Bureau of Mines had limited authority via the Federal Coal Mine Health and Safety Act of 1952. The first major step taken towards dust control in underground mines was the enactment of the Federal Coal Mine Health and Safety Act of 1969 (U.S. Public law 91-173), commonly known as the "Coal Act," brought after Farmington mine disaster [12]. This act required at least two annual inspections of every surface operation and atleast four of the underground coal mines in the United States. It was also designed to establish health and safety standards for the coal mining industry. The Coal Act provided for miners' protection towards dust exposure limits. The Act had a rule to maintain a concentration below 2.0 mg/m^3

and 1.0 mg/m^3 at the working face, and in the intake air, over an eight hour shift in an underground longwall coal mine. In addition, the act provided monthly cash benefit for coal miners who were "totally disabled" because of pneumoconiosis.

The Coal Act was further amended as the Federal Mine Safety and Health Act of 1977 (Public law 95-164), and it led to the establishment of MSHA as an independent body to check on the health and safety aspect of mining [32]. This act was also known as the Mine Act, brought after the Hurricane Creek mine, disaster which mandated miner training and required mine rescue teams for all underground mines. In 2006, "The Mine Improvement and New Emergency Response (MINER) Act" [33] was passed to require specific emergency plans for every mine. Furthermore, the New Dust Rule, also known as the Final Rule enacted in August 1st, 2014, had key provision that redefined the term "normal production shift" as a production shift which has at least 80% of average production. It requires the underground coal mine operators to take respirable dust samples when production in a shift is at least 80% of the average production for 30 recent production shifts. Moreover, this Act also lowered the dust exposure limit and changed the dust limit from 2.0 mg/m^3 to 1.5 mg/m^3 and 1.0 mg/m^3 to 1.5 mg/m^3 at working face and in the intake. Most of these acts and laws were passed immediately after coal dust explosions.

2.4 Overview of Dust Mitigation Strategies

NIOSH investigations showed that about 7.25 kg (16 lbs.) of ordinary run-of-face broken bituminous coal had enough respirable-size adhering dust to contaminate 28,316 m^3 (1,000,000 ft^3) of air up to a level of 2 mg/m^3 if the adhering dust had become airborne [34]. To control respirable and float coal dust in an underground mine environment, the dust control methods and operating practices have been evolving. The following are common technologies used in underground mines.

2.4.1 Dilution via Ventilation

Dilution of dust concentration with ventilation air is the mainstay of dust control strategies in underground mining. The underlying principle is to provide sufficient air to dilute and carry the airborne dust away from the face where the miners are located. The mine ventilation system has been improved with time and research to meet production demand [35]. To regulate the airflow in different parts of mine a series of controls are used (written in mg/m^3). A survey by NIOSH from the years 2004 to 2008 showed that the average face air quantity was around 31.6 m^3/s (67000 cfm) [36]. In one of the other study, three different reduced-scale models of coal mining entries and the mining machines were used. Methane was used to mimic dust transportation in the models [37]. An important factor for dust reduction was the distance of the end of the brattice from the coal face.
Inadequate ventilation leads to explosions in mine [38], but raising airflow beyond a certain point can also have a negative impact on dust concentration as it can cause entrainment of respirable dust. Computational Fluid Dynamics (CFD) modeling is

a good tool to investigate flow patterns where running experiments to collect data could be difficult due to the hostile workplace environment [39].

2.4.2 Water-Sprays Application for Dust Control

Water sprays are one of the most widely used dust reduction methods in mines. Water sprays primarily wet the broken material and capture the airborne dust particles within the droplets. Water spray systems entirely depend on the nozzle and operational parameters for the application. The best dust control result by sprays is achieved when the surface of the cut coal is uniformly wetted by aiming the nozzles at broken material during the breaking process. NIOSH research shows that full cone sprays have average coal dust capture efficiency of about 26.4%. Gravimetric samples have indicated an airborne dust-removal efficiency of about 19.6% [6].
The splitter arm shown in Figure 2.3 has multiple venturi sprays facing towards the coal face. This spray helps in capturing the airborne dust generated at the face.

Figure 2.3: Venturi sprays directed towards coal face (Source: Dust Control Practices for Underground Coal Mining, CDC, NIOSH.)

Sprays are also installed on longwall shearer at main control and drive modules, which capture the dust migrating into the walkways. Continuous miners have strategically installed water sprays to combat dust generally near the cutting drum. In addition, to improve coal wetting and assist with dust capture wetting, agents are often added to the spray water. The wetting agent lowers the surface tension of water droplets and allows better spread over the dust particles [40]. The effectiveness of sprays has been tested by numerous pieces of research. Studies done by Taylor and Zimmer showed that methane concentration at the face was reduced significantly with the use of sprays and exhaust ventilation systems [41]. Later, Goodman showed that water sprays also improve the performance of the flooded-bed dust scrubbers [42].
Airflow induced by different spray nozzles and their effect on dust capture were

studied by Pollock and Organiscak [43]. These nozzles were either a hollow cone, a full cone, a flat fan, or an air atomized type as shown in Figure 2.4.

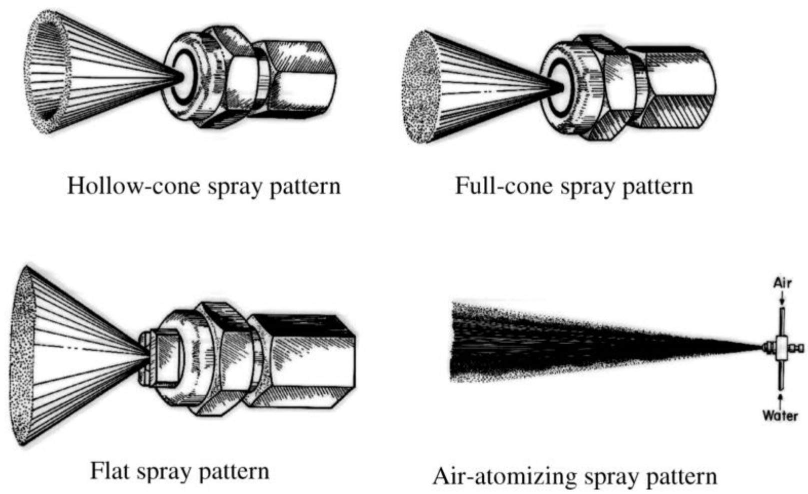


Figure 2.4: Nozzle designs used by Pollock and Organiscak [43]

Wider spray angle nozzles encouraged more flow but resulted in lower dust capture. Water droplets of a size similar to that of respirable dust offer more airborne dust capture, but it requires small orifices and the nozzle is unsuitable for severe underground mining environment as the nozzle was more prone to clogging [44]. The airborne capture performance of the four nozzles types at different water pressures is shown in Figure 2.5. Water sprays have a lot of advantages, but there are circumstances where sprays can increase dust exposure to the workers. High-pressure spray can also entrain a large volume of air and can lead to the dispersion of dust instead of capture [44]. The US Bureau of Mines has shown the effectiveness of water sprays in assisting scrubber ventilation [45]. Recently, water sprays have become effective in scavenging diesel particulate matter (DPM) [46] [47].

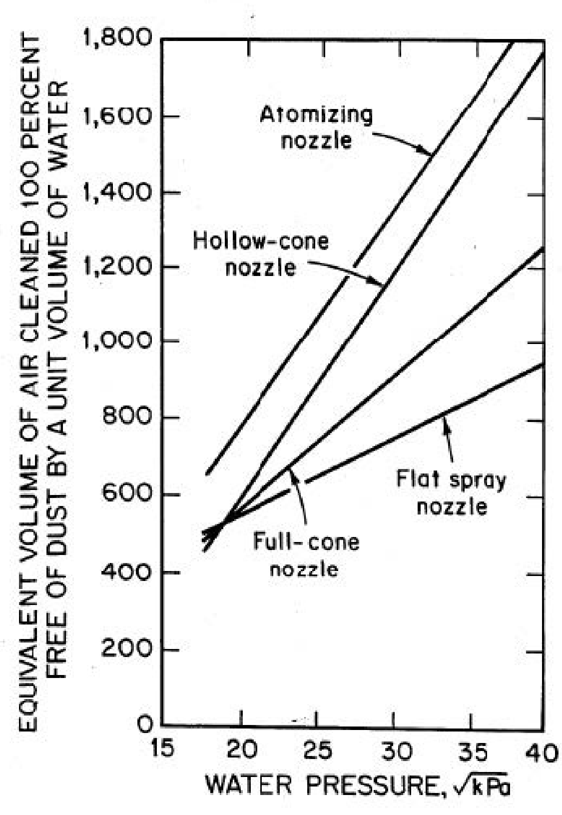


Figure 2.5: Performance of nozzles at different pressure (Source: Kissell, 2003.)

2.4.3 Cutting Head Drum Sprays

The principle behind using cutting head drum sprays is to capture dust at its source. This is now standard practice at any underground mining machines. Sprays are installed on top of drum vanes near the cutting bit. This minimizes the risk of coal ignition and wear out of bits [48]. Figure 2.6 shows the shearer using water sprays aimed at the tip of the cutting bit. This practice is employed by various underground machines, such as shearers, continuous miners, and road headers. Drillers also use high-pressure water for operations which keeps the bits cool and extends their life. [49]. Sprays are also powerful air movers and redirect the dust laden air away from the miner using the machine. The Safety in Mines Research Advisory Committee (SIMRAC) states that wet-head cutting drums on shearers, road-headers, and continuous miners lower the occurrence of frictional ignition [50]. The weak "methane-puffs" experienced when a cutting bit works against the solid coal face are extinguished quickly by the water sprays mounted on the machine itself.

Figure 2.6: Water sprays on longwall shearer (Source: CDC, History of the Mining Program)

2.4.4 Dust Scrubbers

Dust scrubbers are actively used on mining machinery, such as continuous miners. Figure 2.7 shows a schematic layout of a dust scrubber collector. Certner et al. studied a wet dust scrubber with pneumatic nozzle and investigated the collection efficiency with regard to the mechanisms of inertial impaction, turbulent diffusion, and coalescence induced by turbulence [51].

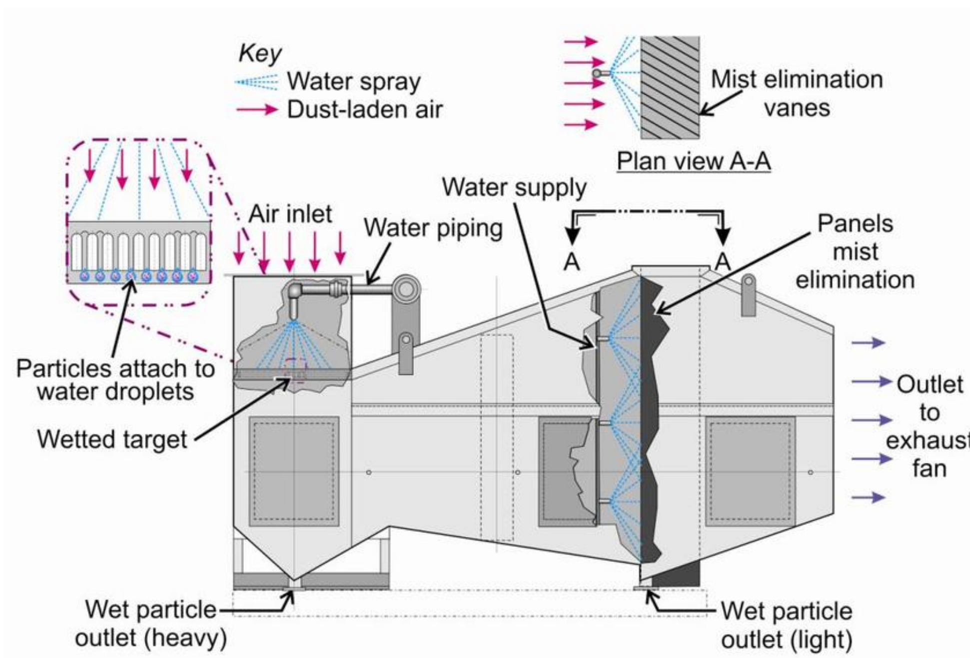


Figure 2.7: Dust scrubber layout [52]

This investigation indicated that the inertial impaction is the primary capture mechanism. Impingement screens and the surface of the vortex chamber serve as the impaction surface as the flooded surface of the scrubbers. Venturi scrubbers are also widely used in scrubbing systems [53].

2.4.5 Dust Collectors

Dust collectors in underground mine are mainly used on roof bolters as shown in Figure 2.8. A vacuum pump on the machine draws the dust through the bit and drill steel into an enclosed dustbox. The box has several compartments and functions as a rough size classifier, allowing the coarser dust sizes to settle out of the airstream in the large compartment (about 95% of all the dust entering the box). The dust that then passes through the large compartment is routed through cyclones and then into the filter chamber for deposition via a paper canister filter. The filtered air flows through the vacuum pump, a noise-reducing muffler, and then it is exhausted into the mine environment [54].

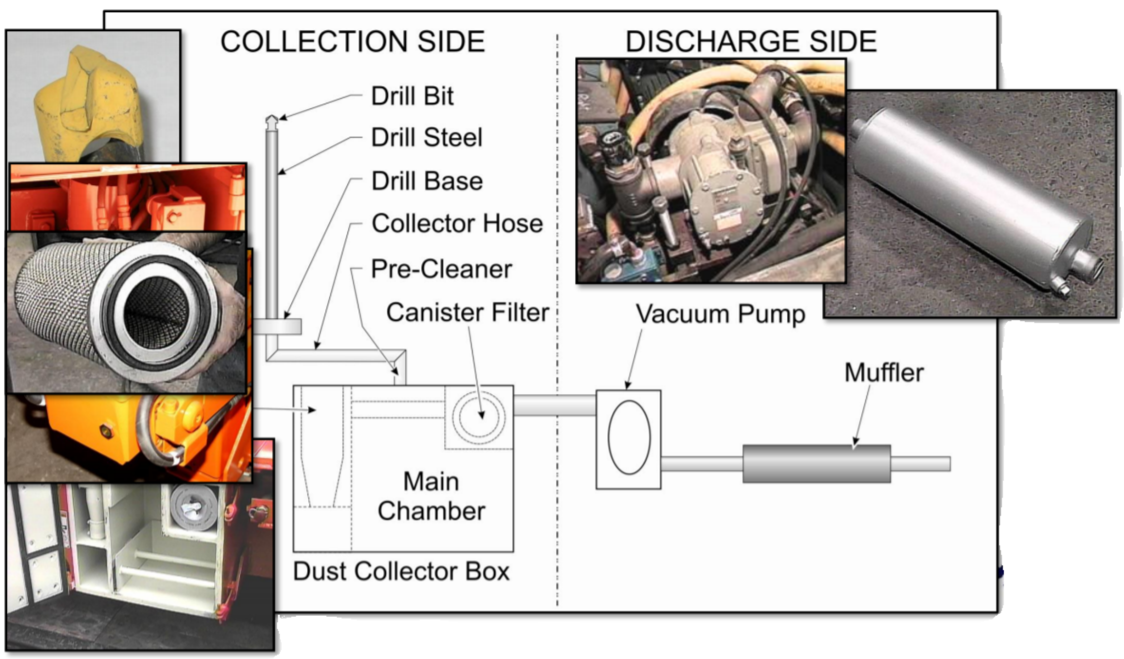


Figure 2.8: Roof bolter dust collector (Source: MSHA, Controlling Dust on Continuous Mining Operations)

A cyclone dust collector, as shown in Figure 2.9 a low maintenance dust collector, is also used widely. However, it has low efficiency in removing smaller dust particles and therefore can be used as a pre-cleaner filter to remove larger particle from dust laden air streams. There are various other kinds of dust collectors, such as baghouse collectors, mechanical shaker collectors, and reverse collectors.

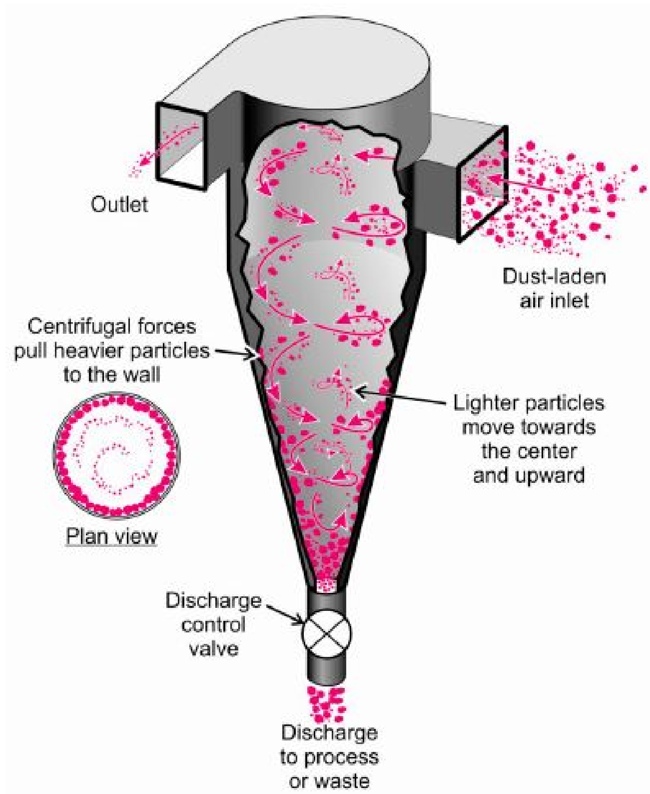


Figure 2.9: Cyclone dust collector system [55]

2.5 Flooded Bed-Dust Scrubbers and its Development

Today flooded-bed dust scrubbers are mounted on most continuous miners. Figure 2.10 shows a cross-section view and components of a flooded bed dust scrubber. Numerous studies have led to the improvement of designs to the systems that are used today. The Donaldson Company conducted research for the US Bureau of Mines in 1979 and recommended a fibrous bed type filter flooded with water [56]. Figure 2.12 shows the accepted design of the filter.

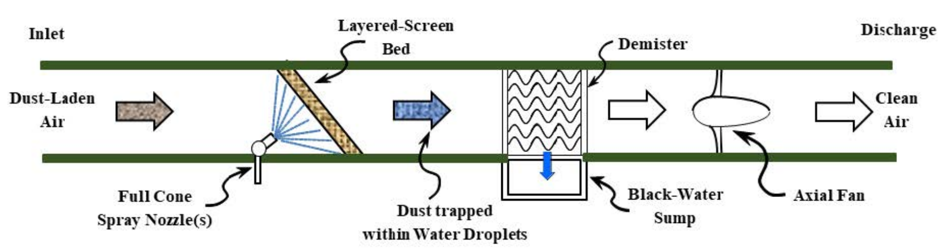


Figure 2.10: Cross-section view of a flooded-dust bed scrubber [57]

Du Plessis et al. studied machine-mounted scrubbers and showed that a 48 layer screen for dust capture is more efficient than others [58]. Higher airflow through the scrubber and higher water flow were also shown to increase dust capture efficiency. A NIOSH report states that water sprays can also be used to increase the capture efficiency of dust scrubbers [59]. A full scale model of a continuous miner was used for the laboratory experiment to show that additional water sprays placed on the side of the continuous miner have an improved impact on dust suppression. It was also found that the machine mounted scrubbers assist in the intake airflow reaching the face, increasing the dilution of methane to harmless levels [42].

The flooded bed-dust scrubber was first applied to a continuous miner by Dr. John Campbell in 1983 [60]. Figure 2.11 shows the flooded-bed dust scrubber mounted on a continuous miner. It has six major components:

(i) an inlet which is strategically placed adjacent to the cutting drum to capture the maximum possible amount of dust from the face;

(ii) a full cone water spray which typically sprays 0.41 l/s (6.5 gpm) water at 310 kPa (45 psi) on the flooded-bed screen;

(iii) a wire-mesh screen downwind of the spray;

(iv) a demister downwind of the screen;

(v) a water sump under the demister; and

(vi) a vane axial exhaust fan at the outlet.

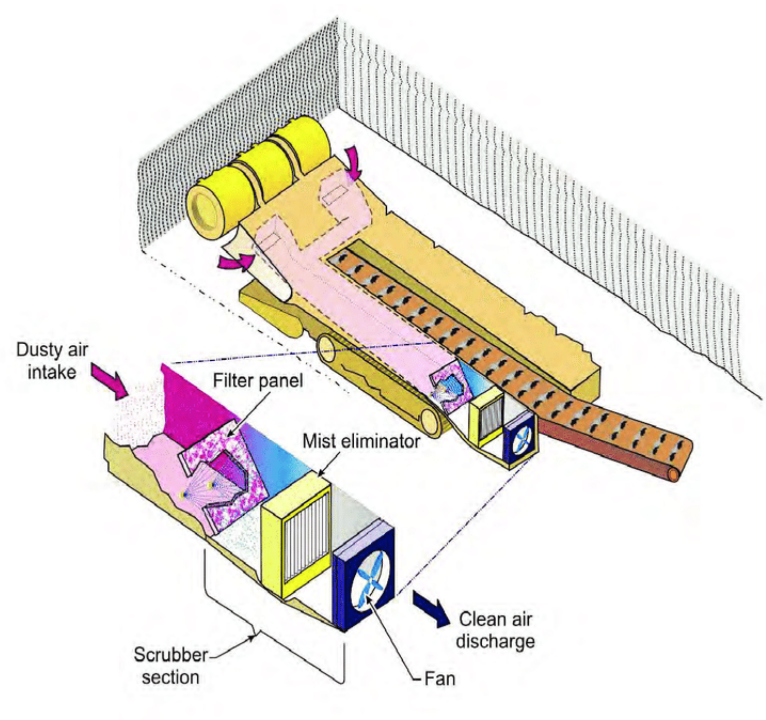


Figure 2.11: Flooded-bed dust scrubber installed on continuous miner [4]

Dust-laden air enters the scrubber via inlets located close to the drum and is driven by a powerful axial fan [60]. This air passes through the water-flooded wire mesh screen where the dust particles get trapped on the screen surface and assisted by the water droplets. This screen is kept flooded continuously to increase dust capture efficiency. A demister to trap water is located downstream of the wire mesh screen. The demister consists of parallel sinuous layers of PVC. Water droplets, being heavier, cannot follow the streamlines of air and are hence removed from the system into a sump located underneath the demister. The moist air, free of dust particles, is then discharged into the mine atmosphere aided by the fan. The performance of the flooded-bed dust scrubber is determined by two terms: capturing efficiency and cleaning efficiency. Capturing efficiency capturing efficiency is the percentage of the generated airflow captured by the scrubber inlet; the cleaning efficiency is the percentage of dust removed from the captured dust-laden air [61]. The Commonwealth Scientific and Industrial Research Organization (CSIRO), in association with the Australian Coal Association Research Program (ACARP), investigated airflow patterns on longwall panels working a thick seam [62]. A shearer mounted with flooded-bed dust scrubbers was designed and recommended for longwall environment [63]. Later, a modified flooded-bed dust scrubber was designed at the University of Kentucky, which could be installed on a site specific longwall shearer [64] [65] [66] [67].

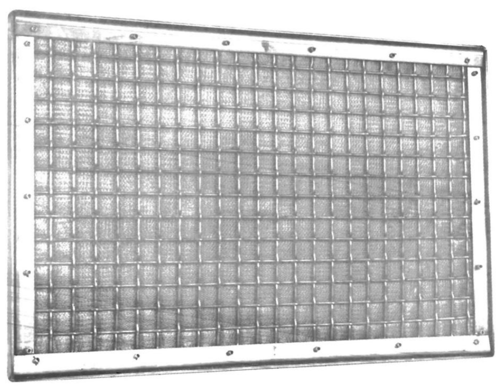


Figure 2.12: Fibrous filter design to be used in flooded-bed dust scrubber [56]

2.6 Characterization, Modeling, Transport, and Deposition of Dust Particles

Characterization and understanding transportation of dust particles is essential to the identification of their physical and their transportation properties. Dumm and Hogg, followed by Bhaskar, Ramani and Jankowski, used various classification and particle size analysis techniques on respirable dust [68] [69]. The result suggests that airborne respirable dust follows some size distribution relationships. These studies also showed that size distributions vary considerably from one source of dust to another [70]. Bradshaw, Godbert, and Leach conducted laboratory and field investigations that showed that the dust deposition rate decreases exponentially with distance from the source [71]. Courtney and Colinet also found, with their extensive studies in U.S mines, that the rate of dust deposition in roadways depends upon the concentration of airborne dust and decreases exponentially with distance from the dust source [72].

Dust deposition in mine airways studies performed by Bhaskar also suggested that dust concentration declines sharply within the first 100.0 m of the source and the deposition rate depends on dust particle size, concentration and air velocity [73]. Studies by the US Bureau of Mines have shown that the transportation of dust generated on the surface mine while drilling decreases rapidly with distance [74]. In 1990 Bhaskar and Ramani showed that most of the fine dust was accumulated close to the source itself [75]. This can have implication in dust control measures. Later, in 1996, wind tunnel testing and in-mine experiments established that respirable dust could also be transported into the main ventilation network via re-entrainment in an underground mine [76]. Dust explosibility is strongly dependent on the fineness of the coal dust particles. Nagy defines float coal dust particles that is finer than 200 mesh and the primary cause of coal dust explosion [77].

Courtney, Kost and Colinet suggested and exponential decay model for calculating dust concentration as a function of time [78]. Chiang, Peng and Luo proposed a mathematical model to predict the size distribution and concentration of dust along the longwall face, which assumes an exponential drop in dust concentration with distance [79]. Partyka developed a one-dimensional flows dust distribution model using convection-diffusion mechanics. Bhaskar and Ramani also developed a convective-diffusion mathematical model for transport and deposition of dust in mine airways which are considered source strength, dust cloud characteristics and basic mechanisms affecting particle behavior in mines [68]. Most of these models are one-dimensional and cannot be used as a reliable source to understand the three dimensional behavior of airflow fields and dust particles around the machines or to determine the effectiveness of the dust control techniques. Recently, NIOSH also characterized float coal dust produced during continuous mining operations, which had a higher concentration of airborne float coal dust. Various sampling instruments were used to quantify the ratio of float to respirable dust in mine airways [80].

2.7 Dust Standards and Sampling

Dust standards are vital for the regulation of environmental conditions in the mine. Standardization of dust concentration, exposure limits, sampling methods, locations, and frequency are essential. Oldham analyzed the variation of dust concentrations at a coal-face using a thermal precipitator [81]. The distribution of particles were predictable despite a wide variety of dust concentration. Effectiveness of exposure of 2.0 mg/m^3 was investigated by Althouse et al. Thousands of X-rays were examined, which indicated that about 0.79% of the miners with exposure of 1 to 9 years suffered from CWP [82]. Edward and Edwin, in 1963, a used brush and pan method to sample dust, and they used thermogravimetric analysis (TGA) of dust samples to study the deposition behavior of float coal dust in mine airway [83]. TGA analysis is a method of thermal analysis in which changes in physical and chemical properties of materials are measured as a function of increasing temperature (with constant heating rate), or as a function of time (with constant temperature and/or constant mass loss) [84]. Later, the float dust deposition meter and optical dust deposition meter was developed by Robert and Sapko [85] [86].

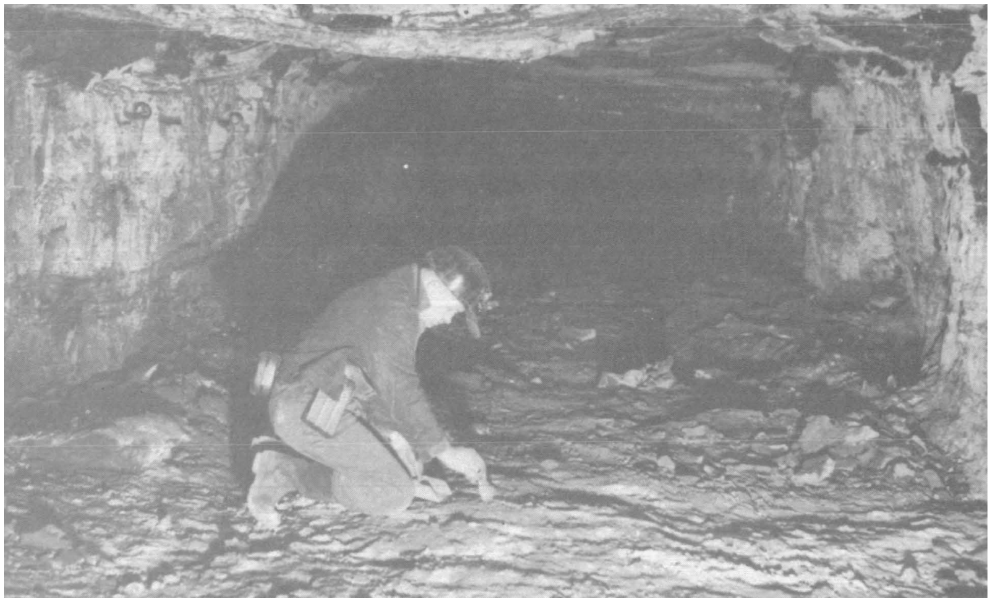


Figure 2.13: Brush and pan method sampling [83]

Gravimetric sampling was first introduced in 1960 [87]. Harris and Maguire designed a gravimetric sampler, as shown in Figure 2.14 which can be built into miners' cap-lamp and batter assembly, in 1968 [88]. The design samples at 1.85 l/min and uses, uses a cyclone elutriator to separate coarse dust and collects the fine airborne dust on a membrane filter for subsequent weighing and analysis. Researchers at NIOSH in 1984 recommended that every coal dust sampler should have a minimum accuracy certification [89]. Additionally, these dust sampling strategies were examined by Bodsworth et al. on coal faces during the 1990s [90]. Their results indicated that the distribution of dust-concentration on modern faces has changed significantly after the introduction of the gravimetric sampling method. Bugarski and Gautam emphasized count based measurement in addition to gravimetric measurements [91]. Gravimetric samplers measure the dust concentration in air in the unit of (mg/m^3). Today personal dust monitors as shown in Figure 2.15, are worn by miners to sample and report dust particle concentrations in real time. This allows the miners to take immediate corrective measures to reduce dust exposures [4]. Gillies and Wu, in 2006, investigated a real-time personal dust meter developed by Thermo Electro Corporation and found that it can be used to evaluate multiple dust sources in a mine [92].

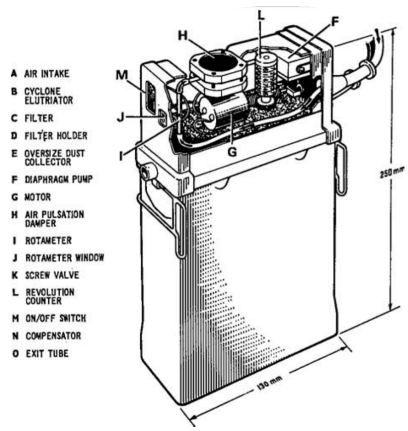


Figure 2.14: Portable gravimetric sampler [88]

Figure 2.15: Personal dust monitor [4]

Optical particle tracking method dust samplers are now widely used for dust related research. TSI OPS 3330, as shown in Figure 2.16, is one such instrument. This instrument counts and sizes particles within the size range of 0.3-10 μm. The gravimetric concentration can be displayed by programming the density and complex refractive index in the instrument. The mechanism of the instrument is presented in Figure 2.17.

Figure 2.16: TSI OPS 3330 optical particle counter

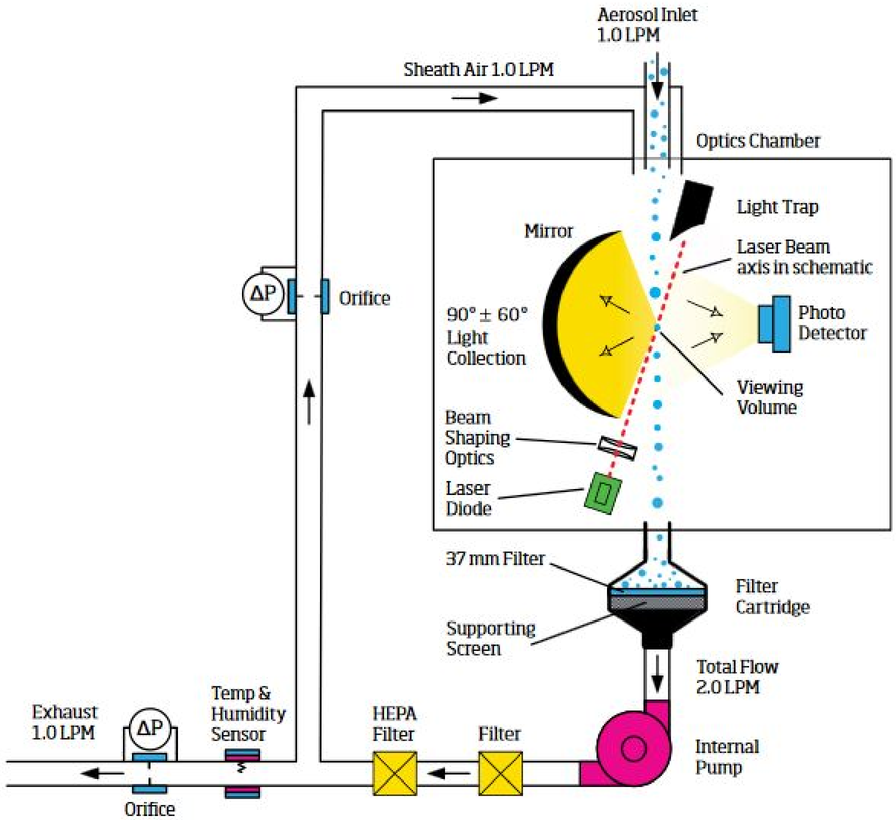


Figure 2.17: Mechanism of TSI OPS 3330 optical particle counter

This chapter compiles some of the previous and current dust mitigation strategies and their development in the mine. Dust legislation adopted to minimize dust related accidents in underground and surface mine also have been discussed. Current methods of dust sampling and dust characterization were also studied. The following chapter describes the dust sampling technique and analysis results used in this research.

Chapter 3 Float Coal Dust Sampling and its Analysis

To prevent a float coal dust explosion, maintaining sufficient rock dust coverage is vital. Sampling was done based on previous research done by the US Bureau of Mines [78]. Dust sampled from longwall and room and pillar mines were analyzed using thermogravimetric analysis [93]. Samples were taken from roof, ribs, and floor at multiple breaks along single air splits and were analyzed using thermogravimetric analysis to quantify float coal dust deposition. This chapter presents sampling and analysis techniques used with the results obtained.

3.1 Sampling Methodology

Sampling is essential for float coal dust analysis. The float coal dust sampling was based on US Bureau of Mines research [78]. Air velocity lower than 300 fpm in the region were chosen for sampling according to set rules. Therefore, it was ensured that the samples were obtained from region where velocity was less than the prescribed criteria using TSI Velocicalc Air Velocity Meter, as shown in Figure 3.1. This was vital as to avoid sampling re-entrained dust due to high air velocity in underground mine airways.
Standard equipment and material were used for sampling as listed below:

(i) 3x3 inch scoop;

(ii) Collection pan;

(iii) Brush;

(iv) No.100 sieve; and

(v) No. 200 sieve.

The following steps were followed while sampling from longwall and room and pillar mines;

(i) A skim dust sample was collected using the brush from superficial layer floor, not more than 1/8-inch-deep, in the scoop for standardized sampling;

(ii) Samples were collected from both the ribs with the help of brush and scoop keeping the area of sampling consistent shown in Figure 3.2;

(iii) The loose dust from the roof was collected using a brush and into the scoop; and

(iv) The same brush pan method was used to collect 1-inch deep sample from the floor.

Samples collected were screened through the No. 100 sieve at the sampling location, and the oversize portion was discarded. Furthermore, dust samples were screened through the No. 200 sieve, and the combustible contents were determined using thermogravimetric analysis (TGA).

Figure 3.1: TSI Velocicalc Air Velocity Meter

Figure 3.2: Sampling at West Virginia mines from ribs

3.2 Sampling from West Virginia Room and Pillar Mine

Eleven locations were chosen strategically to obtain pattern of float coal dust deposition. Sampling was done at two locations: one near the last open crosscut; and one away, as shown in Figure 3.4. The samples were taken from the floor predominantly. Samples from the ribs and the roof were scooped in considerable quantities. A total of 44 samples were bagged, as shown in Figure 3.3. TGA analysis was carried out on all the floor samples and samples taken from roof and ribs were found not enough in quantity for analysis. Results obtained from TGA analysis of floor samples is shown in Table 3.1 .

Figure 3.3: Sample bags collected from mines

Figure 3.4: Mine map and sampling location

Table 3.1: Carbon content in the sampled dust from floor

Sample Location	Initial mass (g)	Carbon Content (%)	Carbon mass(g)
1	1.217	4.026	0.049
2	1.268	4.810	0.061
3	1.206	4.892	0.059
4	1.285	3.813	0.049
5	1.510	3.774	0.057
6	1.204	4.651	0.056
7	1.217	4.930	0.060
8	1.447	2.695	0.039
9	1.269	4.570	0.058
10	1.281	4.059	0.052
11	1.337	4.936	0.066

3.3 Thermogravimetric Analysis

Thermogravimetric analysis was performed on samples using the standard ASTM D5142 moisture ash method. Sample was prepared by wet sieving through 200 mesh (75μm), shown in Figure 3.5.

Figure 3.5: Wet sieving of particles from 200 mesh

Anionic and cationic flocculent was added to wet sieved sample, which aided in separation of the particles, shown in Figure 3.6.

Figure 3.6: Separation of particles from the water

The separated particles were oven dried at 105°F (40.5°C) to get rid of moisture. The dried sample was then scrapped out of the filter and uniformly mixed to prepare a sample for TGA analysis, as shown in Figure 3.7.

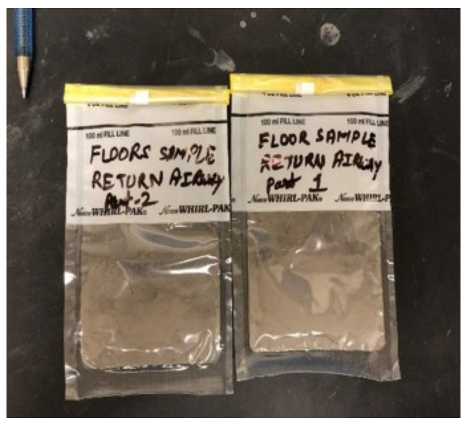


Figure 3.7: Prepared sample for TGA

Calibration of the analysis was performed by creating synthetic samples containing raw coal, rock dust, and an equal proportion of rock and coal dust as shown in Figure 3.8 figure 3.8.

Figure 3.8: Mixture of 50% raw coal, 50% rock dust

The analysis of synthetic samples indicated that the presence of rock dust alters the overall carbon content of the sample reported by TGA because limestone thermally decomposes to release CO_2 beyond 480°C, as shown in Figure 3.9. To determine true carbon content in the sample, weight loss of sample occurring around (360°C to 480°C) only was considered significant. This was vital, as moisture loss occurs before 360°C.

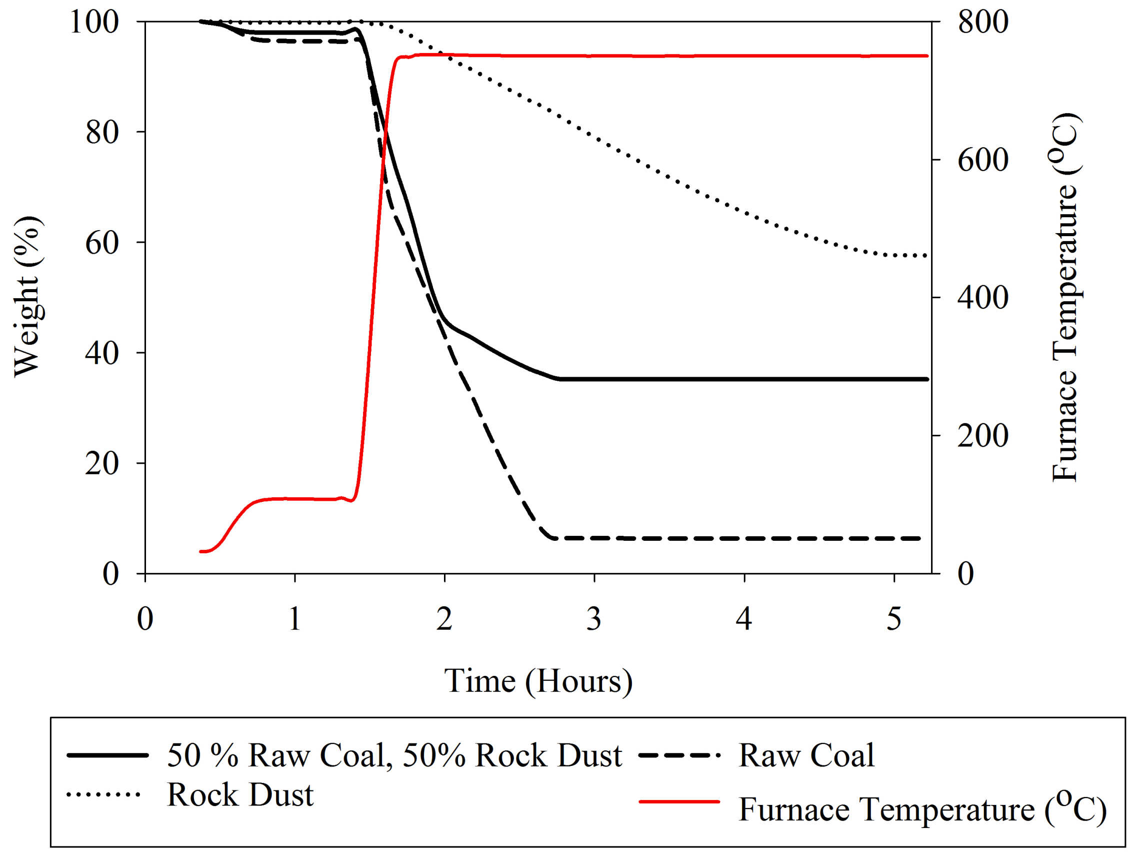


Figure 3.9: Representative thermo-gram of raw coal, rock dust, and an equal proportion of raw coal and rock dust

3.4 Sampling in the Longwall mine

Twelve locations were sampled in the longwall mine in two different sections. The mine map and sampling locations are shown in Figure 3.10 and Figure 3.11. A total of 45 samples were collected from floor, right rib, left rib, and roof. TGA analysis was carried out on the samples after sieving the samples through 200 mesh (75 μm) to deduce the amount of float dust deposited at the sampled location. The analysis results are shown in Table 3.2 [4 west section] and Table 3.3 [6 west section].

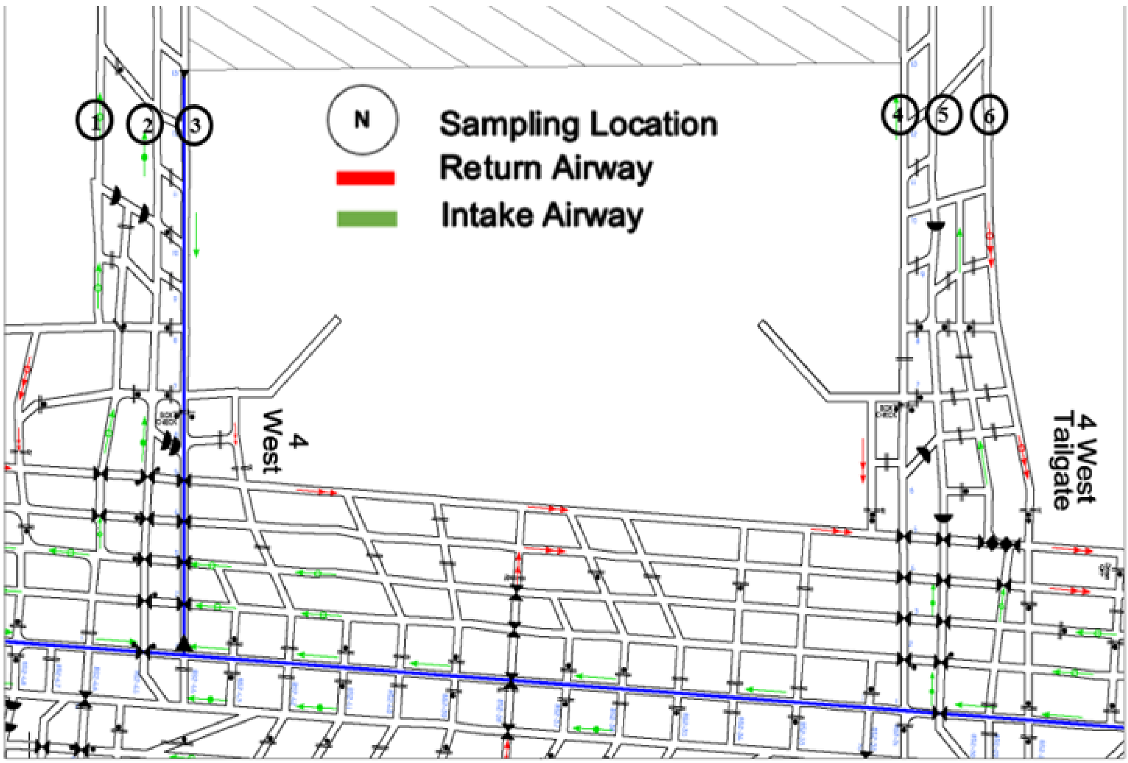


Figure 3.10: Mine map and sampling location [4 west section]

Table 3.2: Carbon content in the longwall mine at [4 west section]

Sample Location	Sampling Points	Initial mass (g)	Carbon content (%)	Carbon mass (g)
1	Intake floor	1.448	3.79	0.055
	Intake roof	1.514	3.36	0.051
	Intake R-rib	1.956	1.02	0.020
2	floor	1.983	3.07	0.061
	roof	1.119	5.54	0.062
	R-rib	1.225	1.79	0.022
	L-rib	0.796	2.13	0.017
3	Belt floor	1.929	1.96	0.038
	Belt roof	1.813	0.82	0.015
	Belt R-rib	1.366	1.31	0.018
	Belt L-rib	1.482	2.83	0.042
4	floor	1.316	3.11	0.041
	roof	1.069	2.52	0.027
	R-rib	1.143	3.67	0.042
	L-rib	1.501	2.79	0.042
5	floor	1.926	1.09	0.021
	roof	0.8511	2.93	0.025
	R-rib	1.253	2.07	0.026
	L-rib	1.105	5.34	0.059
6	floor	1.289	6.20	0.080
	roof	1.388	8.70	0.121
	R-rib	1.414	5.58	0.079
	L-rib	0.952	4.20	0.040

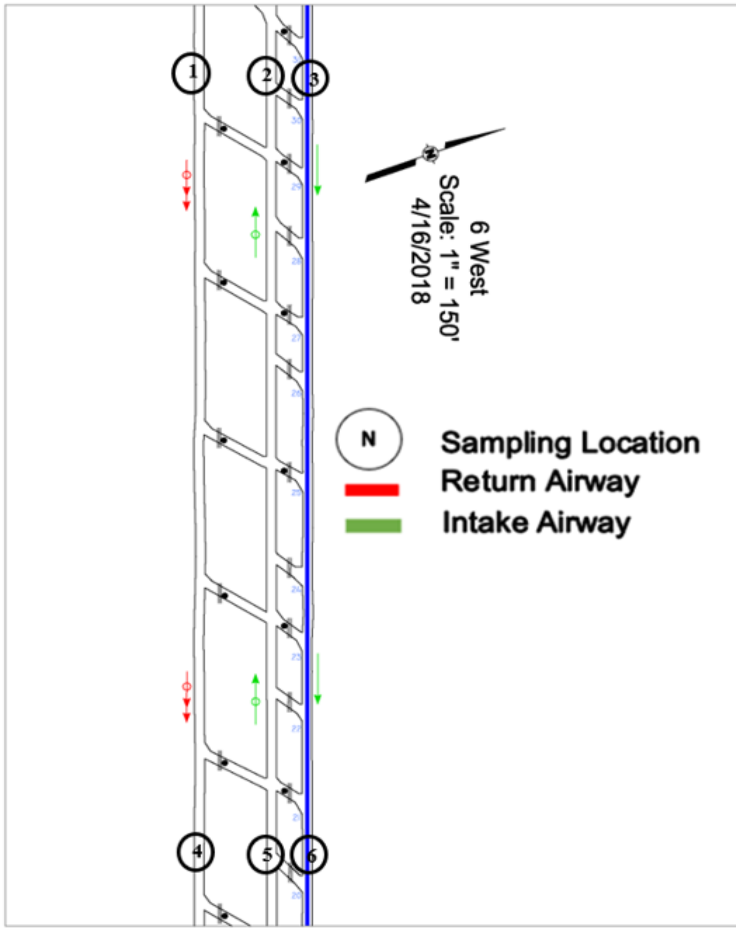


Figure 3.11: Mine map and sampling location [6 west section]

Table 3.3: Carbon content in the longwall mine at [6 west section]

Sample Location	Sampling Points	Initial mass (g)	Carbon content (%)	Carbon mass (g)
1	floor	1.425	6.52	0.093
	roof	1.049	6.38	0.067
	R-rib	0.876	4.90	0.043
	L-rib	0.944	6.13	0.058
2	floor track	2.967	0.23	0.007
	roof track	0.536	14.73	0.079
	R-rib track	0.665	1.80	0.012
	L-rib track	0.538	0.92	0.005
3	floor belt	0.917	5.77	0.053
	roof belt	0.931	6.22	0.058
	R-rib belt	2.269	6.08	0.138
	L-rib belt	1.452	7.64	0.111
4	floor return	1.609	3.72	0.060
	roof return	1.074	5.21	0.056
	R-rib return	1.080	6.38	0.069
	L-rib return	0.459	9.79	0.045
5	track R-rib	1.570	3.50	0.055
	track L-rib	1.506	3.25	0.049
6	floor belt	1.402	1.56	0.061
	roof belt	0.268	1.11	0.062
	R-rib belt	0.713	1.40	0.022
	L-rib belt	2.391	0.33	0.017

3.5 Sampling from Room and Pillar Mine as the Mining Progresses

It was vital that samples should be taken after the mining face has moved forward. Ten sampling locations sampled. Some samples were difficult to acquire due to high roof height. The procedure for TGA analysis was the same in previous mines. The mine map is shown in Figure 3.12, and the results have been summarized from Table 3.4.

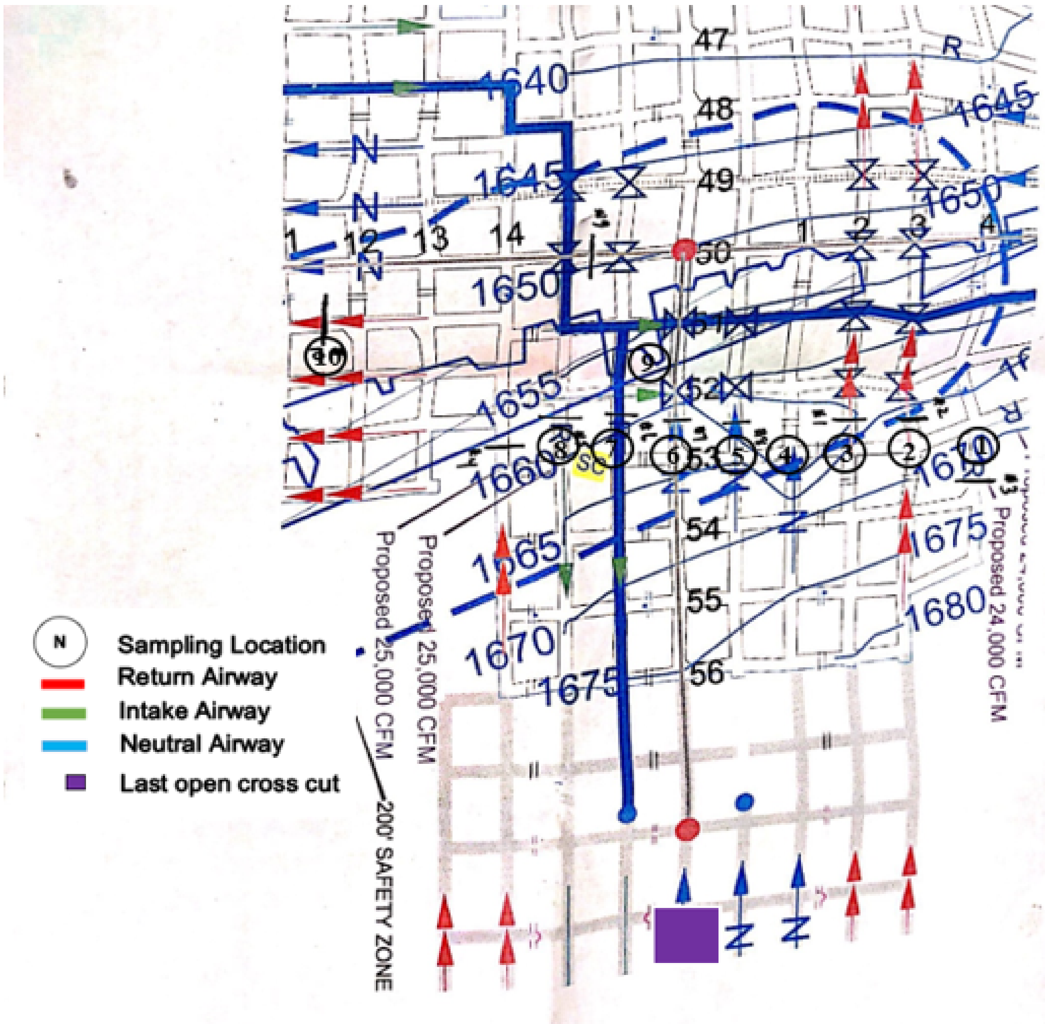


Figure 3.12: Mine and sampling locations

Table 3.4: Carbon content in the room and pillar mine

Sample Location	Sampling Points	Initial mass (g)	Carbon content (%)	Carbon mass (g)
1	floor	0.267	5.59	0.015
	roof	2.154	6.22	0.134
	R-rib	1.255	4.85	0.061
	L-rib	0.325	7.67	0.025
2	floor	1.530	2.61	0.040
	R-rib	1.655	1.26	0.021
	L-rib	0.925	2.37	0.022
3	floor	1.205	10.03	0.121
	roof	1.545	8.90	0.138
	R-rib	1.654	7.60	0.126
	L-rib	0.344	7.83	0.027
4	floor	0.473	6.75	0.032
	R-rib	0.958	5.11	0.049
	L-rib	1.125	6.31	0.071
5	floor	1.726	1.27	0.022
	R-rib	1.957	2.45	0.048
	L-rib	1.541	1.03	0.016
6	floor	1.249	0.64	0.008
	R-rib	1.174	0.93	0.011
	L-rib	1.209	0.33	0.004
7	floor	3.264	3.06	0.100
	R-rib	1.515	2.57	0.039
	L-rib	1.204	1.74	0.021
8	floor	0.473	6.75	0.032
	R-rib	0.928	4.95	0.046
	L-rib	1.345	5.20	0.070
9	floor	0.3587	1.67	0.006
	R-rib	1.965	2.89	0.057
	L-rib	0.785	3.81	0.030
10	floor	1.333	5.10	0.068
	R-rib	1.459	4.30	0.063
	L-rib	1.296	4.93	0.064

The mine airways of room and pillar, as well as the longwall panels, were systematically sampled. The samples were analyzed using TGA to investigate any patterns of deposition with respect to the constituents of the sample. The deposition profile of dust particles obtained from the room and pillar mine had uniform variation, and there was no apparent dependence of deposition rate concerning location and origin of dust source within the mine network. Results from the longwall mine survey shows a deposition rate higher in return airways, but the difference in carbon content is not significant enough to draw a firm conclusion.

Chapter 4 Modeling of Dust Migration and Settling within the Mine Network

Underground mining activities aid dust generation, and they are hazardous to personnel and machines. Dust sources underground are widely investigated in order to combat their generation at the source. Dust transportation in the mine airways, however, is essential to analyze and implement dust control strategies. Computational fluid dynamics models have been presented in this chapter. Some of the models were developed using the Lagrangian particle tracking approach to examine dust transportation and deposition of different sized particles moving under the effects of Newtonian forces for specific cases in an underground mine. The models were simulated in reduced scale as the ratio of dust particles size and flow domain is very small, which increases the use of mesh elements. The reduced scale model lowers the volume and hence the grid number. Even by reducing the flow domain dimensions, the dust particle concentration does not affect the nominal motion of airflow; also the physics of particle transportation in the flow domain is well understood.

4.1 Scaling Laws used for Computer Models

The underground mine environment often has a very large quantity of airflow rates. Therefore, scale modeling was used to scale down parameters to facilitate set-up for laboratory testing of numerical models. The major governing forces were identified first, and the ratio of those forces was used to generate dimensionless quantities called the π-numbers. Reynold's number, the ratio of inertial forces and viscous forces, strongly indicates the nature of flows in a domain, and it was used as a π-number to scale down the airflows. A turbulent flow regime through a cross-section often has Reynold's number exceeding 5,000. The flow inside the reduced scale model of the mine is driven by the inertia of airflow and gravity. The forces can be described as

$$Inertial force, F_{\mathrm{i}} = \rho l^2 v^2 \tag{4.1}$$

$$Gravitational force, F_{\mathrm{g}} = \rho l^3 g \tag{4.2}$$

Where ρ is the density of air at nominal temperature and pressure (1.2 kg/m^3); g is the acceleration due to gravity (-9.81 m^2); 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 Froude's number.

$$\pi - number = \frac{\rho l^2 v^2}{\rho l^3 g} = \frac{v^2}{lg} \tag{4.3}$$

According to Equation 4.3, for a reduced scale model with dimensions shortened by a known scaling factor, the airflows would have to be lowered 1.The dust particles were not scaled corresponding to the airflows, as it would result in significant departure from the characteristics of those particles. Partial relaxation of geometrical scaling was therefore used for dust particles to ensure that the properties are not altered by the scaling process [94]. Scaled modeling of the sedimentation process, with water replaced by air and the properties of the dirt particles kept intact, can be compared. To mimic the dust transportation of dust particles in a $1/12^{\text{th}}$ reduced scale model of the mine Computational Fluid Dynamics (CFD) modeling was used.

4.2 CFD Models Preparation

CFD is a powerful numerical tool to mimic airflows, and it can be used to model flows in an underground mine environment. The models were setup and run on SC/Tetra V14, which has excellent unstructured mesh generation capabilities. Optimization of total simulation time was done by using independent modules of pre-processor, the solver, log file analysis, and post-processor which are available in SC/Tetra V14.

Two different scenarios of flows were modeled:

(i) A scaled down $1/12^{\text{th}}$ model of a room and pillar coal mine where the dust particles were released close to each of the face; and

(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.

4.2.1 Modeling of Room and Pillar mine

The schematic layout of the ventilation circuit is shown in Figure 4.1. The coordinates of the model 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 was designed to be visually similar to the full scale room and pillar mine. A volume flow rate of 12,000 cfm (5.66 m^3/s) was sent via the inlet, marked by the letter A, to mining faces C, D and E. An airflow of 3,000 cfm (1.42 m^3/s) was split and sent via segment B and serves as the neutral airway. Owing to the frequent movement of shuttle cars, an airflow of 500 cfm (0.24 m^3/s) was assumed to leak through segment F, into the neutral branch, leaving 8,500 cfm (4.01 m^3/s) to ventilate faces D and E. A flow of 9,000 cfm (4.24 m^3/s) swept face C. All these flows were scaled using Froude's number scaling by a factor of 1/12.

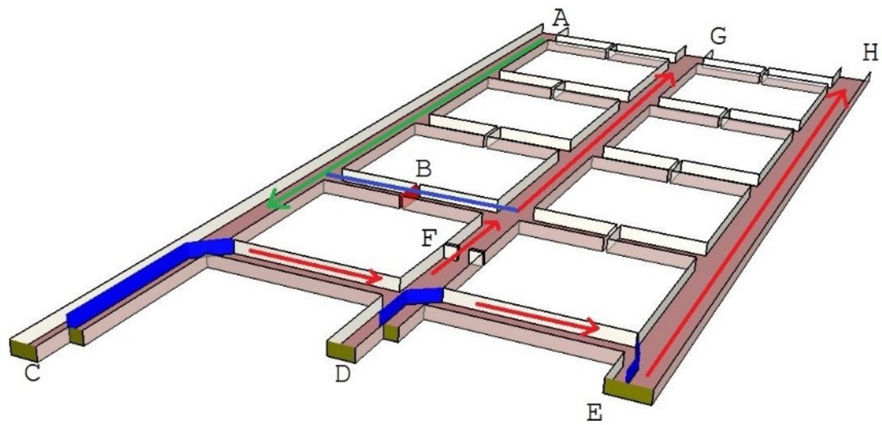


Figure 4.1: Layout of the ventilation circuit with the main control points marked by letters

Preferential higher allocation of the cells close to the impermeable walls and in the zones of re-circulation, was done and a dense octree was generated. Boundary layer phenomena modeling was done by disseminating five prism layers. To meet higher element packing density required adaptive meshing, and it was provided by the software. Static pressure of 0 Pa was allocated at the outlet while the inlet was assigned a designated flow rate. All the other surfaces were assigned impermeable wall conditions. Correctness of time derivative was set to second order. Contours of normalized wall distances on the impermeable surface of the model is shown in Figure 4.2. To confirm that computer models show well resolved airflow close to the wall average scalar integral of the y+ value was calculated and was found to be lower than 1.0. This was important as to accurately model particle transportation in SST-kw turbulence model. Ventilation curtains aids the airflow to accelerate near the face as seen in the computer models. Contours of velocity magnitude on a plane parallel to the mine floor is shown in Figure 4.3. Slightly higher velocity magnitudes on the belt airway and due to the leakages near the active face are clearly visible. Particle tracking was initiated after a steady flow profile was established.

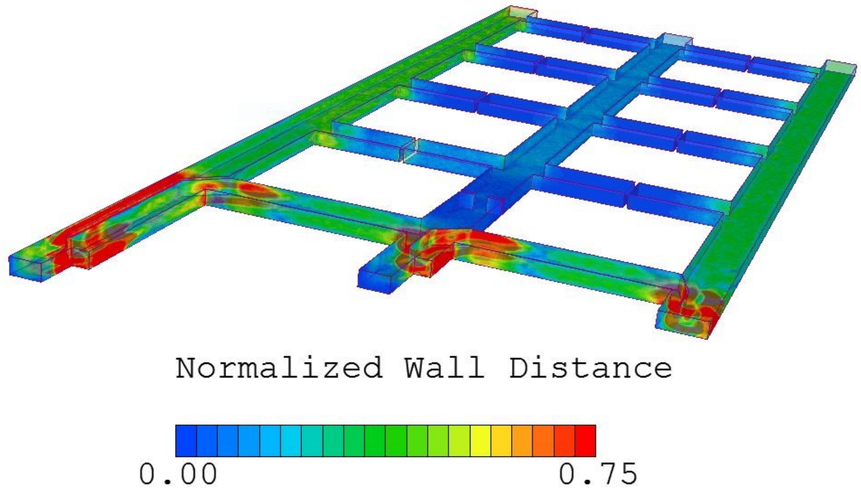


Figure 4.2: Contours of normalized wall distances on the impermeable surfaces

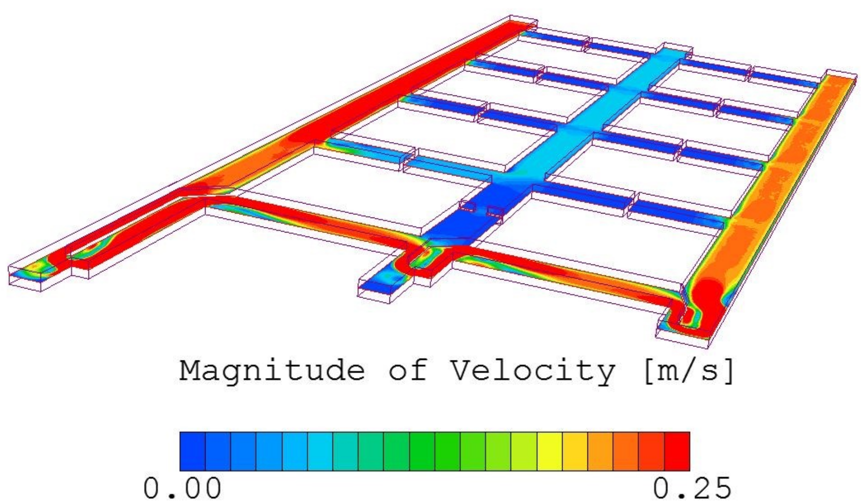


Figure 4.3: Contours of velocity magnitude on a plane parallel to the coal floor and midway through the walls

The Particles were injected into a converged flow field, and they were released randomly from the active face of the deepest cut furthest to the right for a period of 30.0 s. Diameters in the range 1-30μm were assigned to the dust particles and were assumed to be of coal dust specification. The cunningham slip correction factor was used to adjust the particle sizes and mean free path of air molecules at nominal temperature and pressure [95]. Particles were tracked in steady state models for 210 s, until 240 s. Preliminary transportation and deposition profiles of particles was used to determine this time and also to balance available computing resources. Figure 4.4 shows the results of particle tracking, t=210.0s. The Figure shows clearly that particle of size 20.0 and 30.0 microns are not able to travel far and settle down close to their source of generation, and particle sizes of 15.0 microns do not travel so far. Particles of size 10.0 microns start settling in the return airway but, particle of size 1.0 and 5.0 micron continue to travel along on the ventilation air stream.

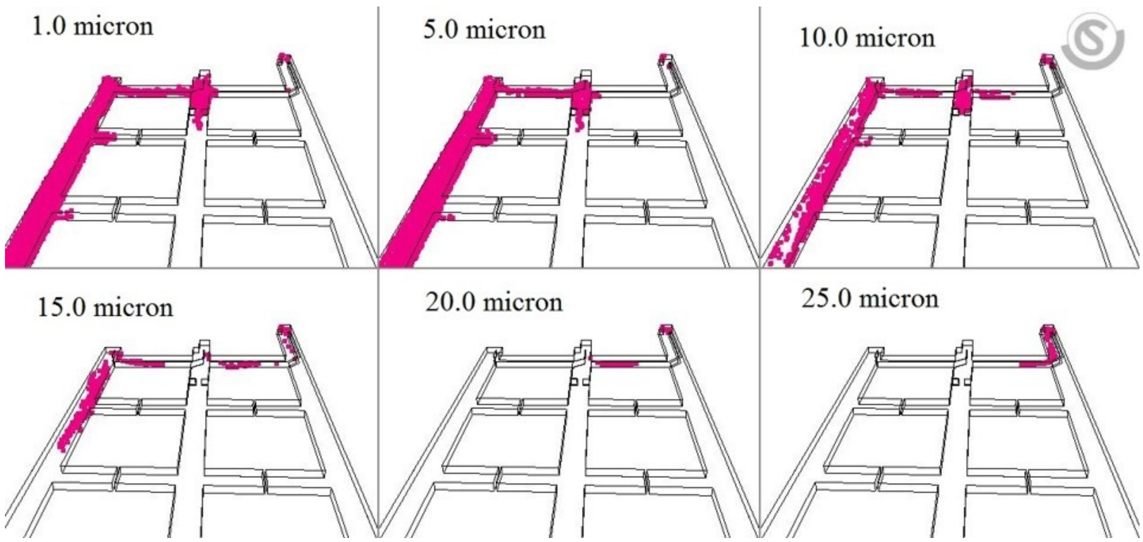


Figure 4.4: Position of dust particles at the time, t=180.0 s, when first specks of dust were released at the time, t=30.0 s

The lateral displacement of particles by their size is shown in Figure 4.5 and Figure 4.6.

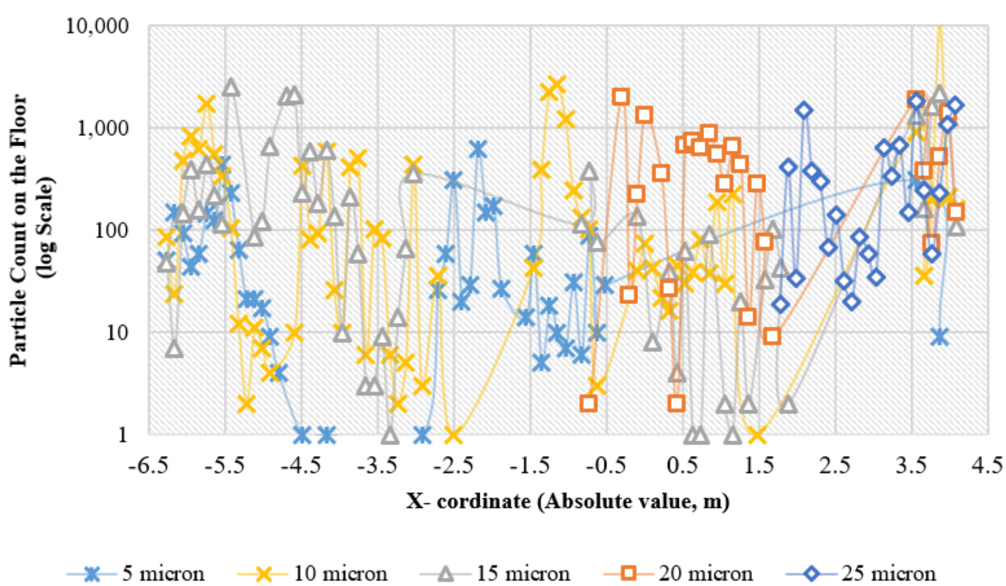


Figure 4.5: Lateral displacement of the dust particles by count on the mine floor

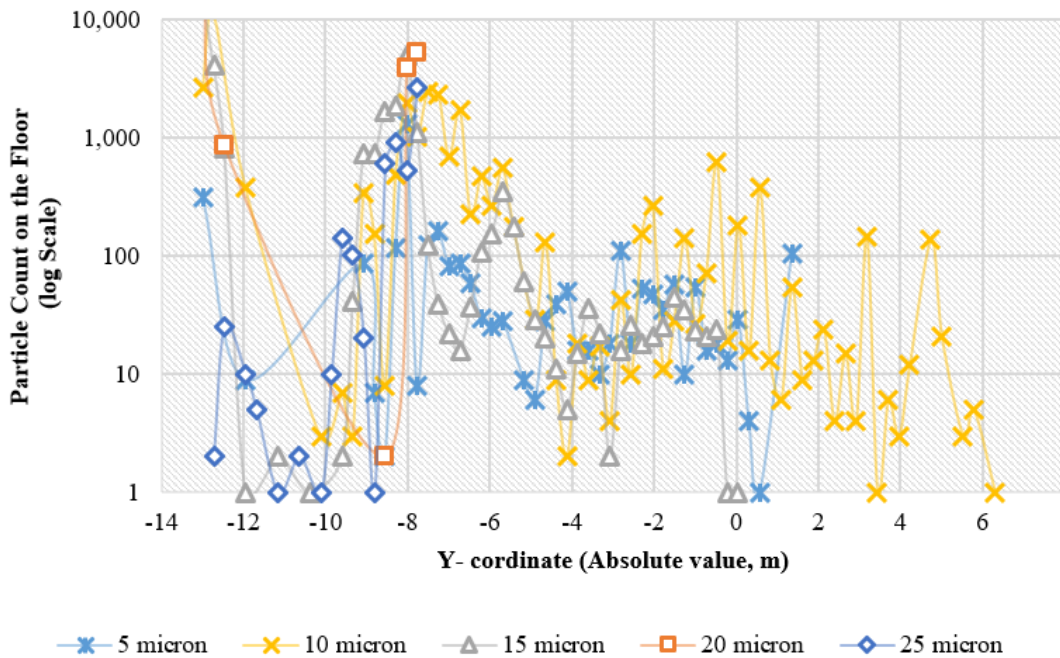


Figure 4.6: Lateral displacement of the dust particles towards the exhaust airway out of the mine

To predict the distance of dust particles of different densities, and how they would travel under the influence of gravity, a simple pseudo-2D model was created to scale the results to full-scale. This was done to imitate the distance dust particles could travel under different ventilation air stream flows, and therefore the motion of particles the in third dimension was considered insignificant. The optimized model measures 7 ft. in height, and is 300 ft. long. Flow volume thickness was designated as 1.0 in. To reduce the number of mesh elements, two layers of grid elements were assigned in the third dimension. Surface mesh in the flow volume is shown in Figure 4.7.

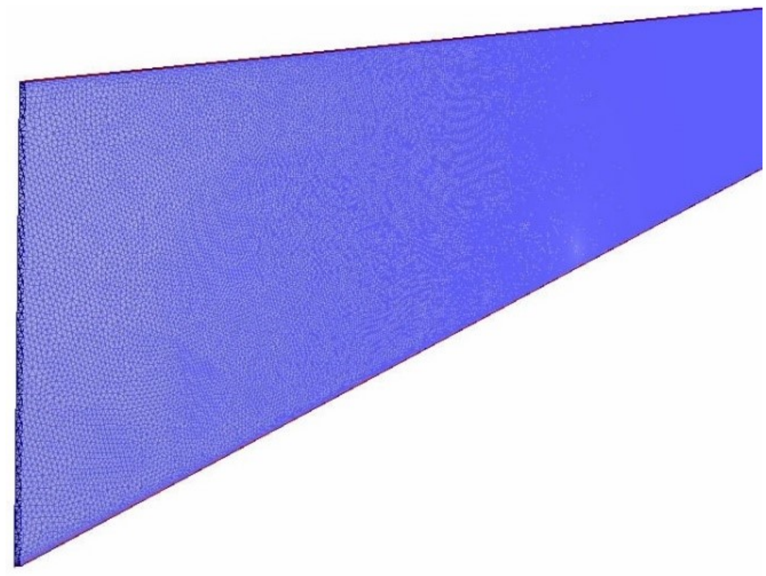


Figure 4.7: Surface mesh on the isometric projection of the pseudo-2D flow volume, spanning 7' X 300'

To account for the different average airflow speeds, steady-state models were generated first. Restart files of those models were used to initiate particle tracking simulations.Particles of size 75.0 microns 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, lateral displacement. The Newtonian forces were calculated at every time step, and the particles were tracked until they hit the floor. The location of particles of different densities is shown Figure 4.8,

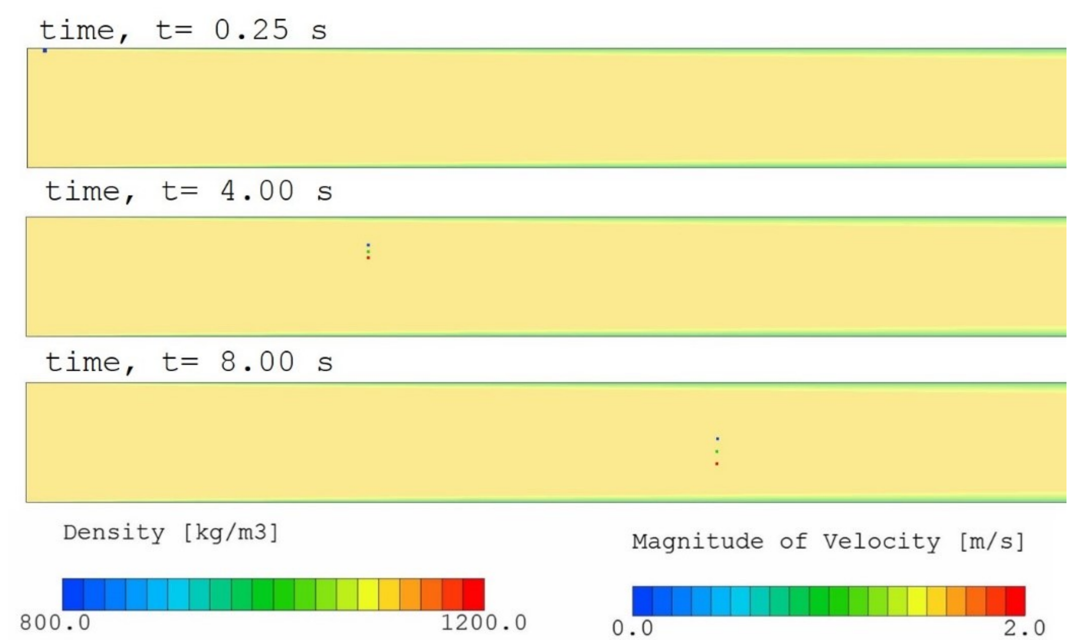


Figure 4.8: Position of the particles colored by their density

and Figure 4.9 shows the surface plot of lateral displacement of all particles.

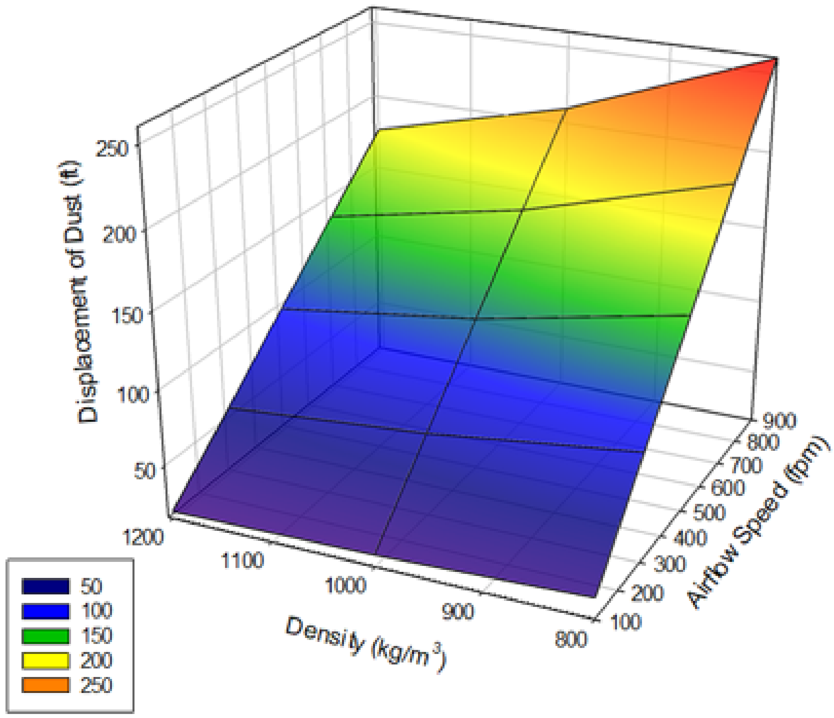


Figure 4.9: A 3D surface plot of horizontal distance the particles are displaced laterally when released in known airflow speeds

4.3 MATLAB Program for Calculating Dust Deposition Behavior

MATLAB is a matrix based language used by millions of engineers and scientists world wide. MATLAB allows matrix manipulations; plotting of functions and data; implementation of algorithms; creation of user interfaces; interfacing with programs written in other languages, including C, C++, Java, and FORTRAN; analyzing data; developing algorithms; and creating models and applications. It has numerous built-in commands and math functions that help you in mathematical calculations, generating plots, and performing numerical methods.

The program takes input from csv file which has the network coordinates of the mine. Program is designed to work on imperial units. The program uses assumption and works on the basis of CFD results gathered in the previous section. The typical output of the program is shown in Figure 4.10 and the code has been included in the Appendix at the end of thesis.

MATLAB Command Window

```
>> trial_script

 Program for dust migration in a mine
 Enter atkinson coeff (Imperial, No units)  :  2
Enter height of entry (ft.)  :  7
Enter width of entry (ft.)   :  20

 Resistance of the branch is : 0.000199
 Enter the airflow at the entry (cfm)   : 3000

 Average velocity in the branch is 21.428571 (ft/min)

 Density of coal particle (kg/m^3)   : 1.22

 Average distance travelled by particle is 21.428571 (ft)
 >>
```

Figure 4.10: Typical output of the program

4.4 Using MFIRE to Model Dust as Fire Contamination

MFIRE was first introduced in 1990 by Chang et al. to accommodate dynamic state modeling of fire, accommodating the transient-state modeling problem [96]. This program provided useful information for fighting a mine fire as well as planning evacuation routes. In addition to estimating the air quantity and pressure distributions in the steady state condition from a regular mine ventilation network analysis program, MFIRE also outputs information about the propagation of time dependent air temperature and concentrations of gases (including mine gases or products of combustion) [97].

4.4.1 MFIRE Program Structure

The MFIRE program contains four sections to perform mine ventilation analysis [97].

(i) **Network calculation section:** This performs the basic network calculation like airflow rates and pressure-loss calculations as a result of fans, branch resistances and ventilation network connection patterns and controls;

(ii) **Temperature calculation section:** This section calculates temperature distribution such as mean temperature in each airway and temperature at each junction needs to be known in order to evaluate natural ventilation pressure and choke effects. In the temperature section, the temperature distribution is calculated based on the airflow distribution obtained from the network calculation section;

(iii) **Transient-state simulation section:** This can be induced by mechanical disturbance. In the transient state simulation (or non-steady state simulation) of MFIRE, users can specify a series of time increments within a time period of interest. This follows with the airflow in the system divided into corresponding air segments. With the aid of a heat transfer model, the temperature distribution in a system can be obtained in an airway-by-airway advancing process; and

(iv) **Quasi-equilibrium simulation Section:** This simulation predicts the ventilation pattern at a quasi-steady state condition. The ventilation system reaches a more or less steady state condition after a relatively long period of time has elapsed from the starting of a fire. The processing procedure is similar with that of the temperature calculation.

4.4.2 Convective Diffusion Model for the Transport and Deposition of Dust in Mine Airways

Bhaskar and Ramani described a convective diffusion model for the transport and deposition of dust in mine airways [98]. Using this model, the spatial and temporal characteristics can be evaluated in terms of dust concentrations in the mine atmosphere. McGrattanal modeled convective motion of fume using a large eddy simulation [99]. The convective diffusion model for dust has led to the assumption that dust transportation can be modeled as fume transportation.

4.4.3 Sensitivity Analysis for Fume Concentration in MFIRE Network Model

The basis of the simulation of mine fires is the MFIRE model; the model consists of airways, junctions, fans, and fires. Each airway is associates with two junctions: a 'starting' and 'ending' junction that is based upon the airflow direction. The network model used for sensitivity analysis in MFIRE is shown in Figure 4.11.

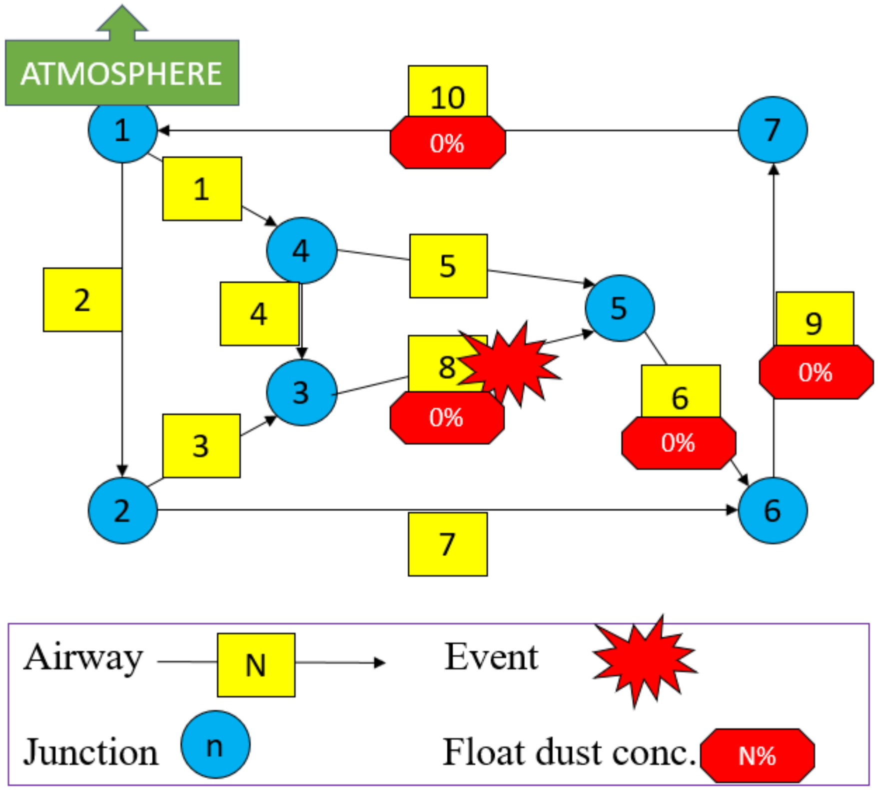
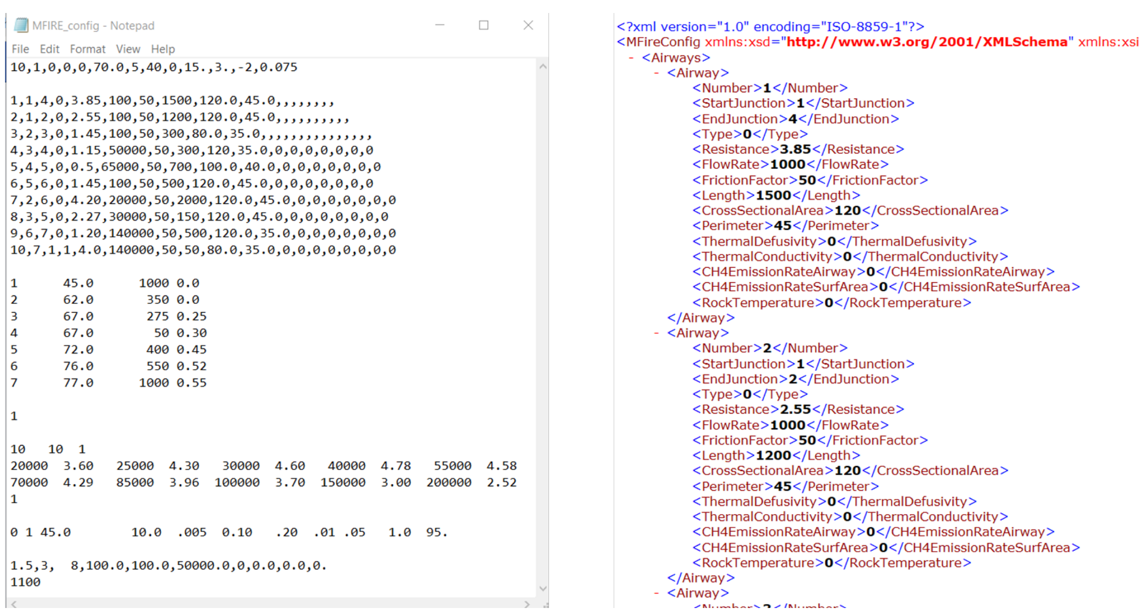


Figure 4.11: MFIRE network model

To run the simulation in MFIRE, the first step is to load the MFIRE configuration, which is either in legacy text or XML format, as shown in Figure 4.12.



```
MFIRE_config - Notepad
File  Edit  Format  View  Help
10,1,0,0,0,70.0,5,40,0,15.,3.,-2,0.075

1,1,4,0,3.85,100,50,1500,120.0,45.0,,,,,,,,
2,1,2,0,2.55,100,50,1200,120.0,45.0,,,,,,,,,,
3,2,3,0,1.45,100,50,300,80.0,35.0,,,,,,,,,,,,,,,
4,3,4,0,1.15,50000,50,300,120,35.0,0,0,0,0,0,0,0
5,4,5,0,0.5,65000,50,700,100.0,40.0,0,0,0,0,0,0,0
6,5,6,0,1.45,100,50,500,120.0,45.0,0,0,0,0,0,0,0
7,2,6,0,4.20,20000,50,2000,120.0,45.0,0,0,0,0,0,0,0
8,3,5,0,2.27,30000,50,150,120.0,45.0,0,0,0,0,0,0,0
9,6,7,0,1.20,140000,50,500,120.0,35.0,0,0,0,0,0,0,0
10,7,1,1,4.0,140000,50,50,80.0,35.0,0,0,0,0,0,0,0,0

1       45.0      1000 0.0
2       62.0       350 0.0
3       67.0       275 0.25
4       67.0        50 0.30
5       72.0       400 0.45
6       76.0       550 0.52
7       77.0      1000 0.55

1

10   10  1
20000  3.60   25000  4.30   30000  4.60   40000  4.78   55000  4.58
70000  4.29   85000  3.96  100000  3.70  150000  3.00  200000  2.52
1

0 1 45.0        10.0  .005  0.10   .20  .01 .05   1.0  95.

1.5,3,  8,100.0,100.0,50000.0,0,0.0,0.0,0.
1100
```

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<MFireConfig xmlns:xsd="http://www.w3.org/2001/XMLSchema" xmlns:xsi
- <Airways>
  - <Airway>
      <Number>1</Number>
      <StartJunction>1</StartJunction>
      <EndJunction>4</EndJunction>
      <Type>0</Type>
      <Resistance>3.85</Resistance>
      <FlowRate>1000</FlowRate>
      <FrictionFactor>50</FrictionFactor>
      <Length>1500</Length>
      <CrossSectionalArea>120</CrossSectionalArea>
      <Perimeter>45</Perimeter>
      <ThermalDefusivity>0</ThermalDefusivity>
      <ThermalConductivity>0</ThermalConductivity>
      <CH4EmissionRateAirway>0</CH4EmissionRateAirway>
      <CH4EmissionRateSurfArea>0</CH4EmissionRateSurfArea>
      <RockTemperature>0</RockTemperature>
    </Airway>
  - <Airway>
      <Number>2</Number>
      <StartJunction>1</StartJunction>
      <EndJunction>2</EndJunction>
      <Type>0</Type>
      <Resistance>2.55</Resistance>
      <FlowRate>1000</FlowRate>
      <FrictionFactor>50</FrictionFactor>
      <Length>1200</Length>
      <CrossSectionalArea>120</CrossSectionalArea>
      <Perimeter>45</Perimeter>
      <ThermalDefusivity>0</ThermalDefusivity>
      <ThermalConductivity>0</ThermalConductivity>
      <CH4EmissionRateAirway>0</CH4EmissionRateAirway>
      <CH4EmissionRateSurfArea>0</CH4EmissionRateSurfArea>
      <RockTemperature>0</RockTemperature>
    </Airway>
  - <Airway>
```

Figure 4.12: Inputs for MFIRE software in legacy and XML format

This configuration can be changed to simulate other complex network models. A fire contaminant can be added in a MFIRE simulation by varying parameters in the text and XML file. The vital parameters controlling the dynamic simulation of the fire in MFIRE are listed below:

(i) Airway: The airway at which the fire has started;

(ii) Contamination flow rate: Volume flow rate of contaminated gas inflow ft^3/min, metric units are m^3/sec;

(iii) Contamination concentration: Concentration of contaminant in gas inflow in percent;

(iv) Heat input: Air flow rate defining fire characteristics in imperial unit Btu/min, metric unit is watt;

(v) O_2 concentration leaving fire: Oxygen concentration of air current leaving fire zone in percent;

(vi) Contamination per cubic feet O_2: Contaminant production per ft^3 of oxygen delivery in imperial unit ft^3/ft^3 O_2, metric units are m^3/m^3 O_2; and

(vii) Heat per cubic feet O_2: Heat production per ft^3 of oxygen delivery in imperial units are Btu/ft^3 O_2, metric units are kJ/m^3 O_2.

Taking these parameters into account, MFIRE runs simulations with resulting output as network calculation results, data for concentration and temperature calculation, and the concentration of fumes at every airway as shown in Figure 4.13.

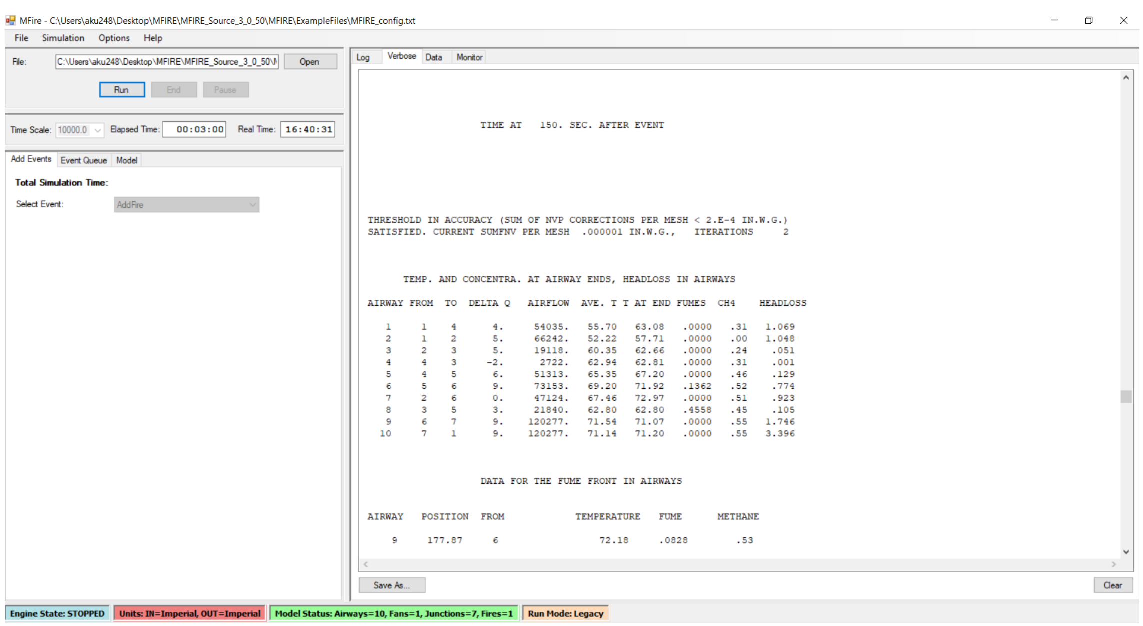


Figure 4.13: Output from simulations of MFIRE

Assuming the fumes transportation behavior is same as dust, dust transportation can be simulated in MFIRE using the parameters listed above. The default example model, as shown in Figure 4.11 was simulated and sensitivity analysis was performed to find the relationship between the fume concentrations in the airway. The parameter heat input was set to low at 50 Btu as higher heat input resulted in higher changes in airflows throughout the network, which is not suitable for dust modeling. This was also done to avoid zero error in the program. The other parameters O_2 concentration leaving fire, contamination per cubic feet O_2, and heat per cubic feet O_2 were set to zero as these thermodynamic calculations were not important for transportation of dust. Contaminant flowrate was varied in steps and the transportation of fumes showed a linear relationship with the transportation of fumes in the network airway as shown in Figure 4.14. Therefore, the contaminant flow rate was the parameter that could be related to dust source generation. It was found that contamination concentration also had a linear relationship to fume concentration downstream; therefore, it was kept to 100 % during all simulations.

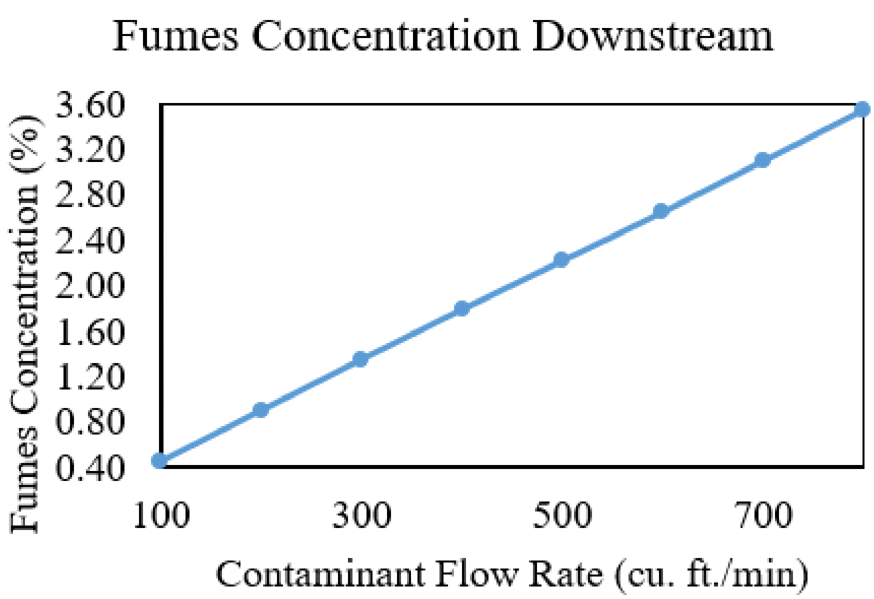


Figure 4.14: Relationship between contaminant flowrate and fumes concentration

Contamination flow rate in a mine can be related to dust sampling results, and this is shown in Table 4.1.

Table 4.1: Projected value of contamination flowrate and fumes concentration to known value of float coal dust concentration

Float coal dust (%) or Fume concentration (%)	Contamination flowrate input (ft^3/min)
1	223
5	1134
10	2269
15	3403
20	4542
25	5677

The float coal dust percentage obtained by TGA will result in nearly the same fume concentration obtained by the simulations. The corresponding contamination flowrate input, which follows a linear relationship, has been shown in Equation 4.4.

$$y = 0.0044x + 0.0175 \tag{4.4}$$

where y = float coal dust (%) and x = contamination flowrate input (ft^3/min). Table 4.1 shows the projected values of contamination flow rate for known float dust or fume concentration. The fume concentrations calculated by MFIRE at time 180 second after the event, shown in Figure 4.15 verbose report, indicate float dust concentrations as fumes.

```
TIME AT   180. SEC. AFTER EVENT

THRESHOLD IN ACCURACY (SUM OF NVP CORRECTIONS PER MESH < 2.E-4 IN.W.G.)
SATISFIED. CURRENT SUMFNV PER MESH  .000003 IN.W.G.,   ITERATIONS    2

      TEMP. AND CONCENTRA. AT AIRWAY ENDS, HEADLOSS IN AIRWAYS
```

AIRWAY	FROM	TO	DELTA Q	AIRFLOW	AVE. T	T AT END	FUMES	CH4	HEADLOSS
1	1	4	10.	54079.	55.70	63.08	.0000	.31	1.071
2	1	2	14.	66297.	52.22	57.71	.0000	.00	1.050
3	2	3	5.	19135.	60.35	62.66	.0000	.24	.051
4	4	3	0.	2725.	62.94	62.81	.0000	.31	.001
5	4	5	11.	51354.	65.35	67.20	.0000	.46	.129
6	5	6	15.	73213.	69.19	71.90	.3018	.53	.775
7	2	6	9.	47163.	67.46	72.97	.0000	.51	.924
8	3	5	5.	21859.	62.80	62.80	1.0100	.45	.106
9	6	7	24.	120376.	73.08	73.76	.1836	.55	1.759
10	7	1	24.	120376.	71.44	71.20	.1836	.55	3.393

Figure 4.15: MFIRE simulation output for contaminant flow rate 223 (ft^3/min)

The output from the program is in the range measured in the mine, calibrating the model's input values. Changes to the ventilation network will make changes to the float dust concentration (i.e. fumes), and the float dust measure in the branch can be predicted as the mine is developed.

The model can be edited to change the dust generation source (i.e. active mining face) and can be used to predict the float coal dust concentration throughout the ventilation network. The transportation of the float dust concentration from one airway to another in the default simulated example model 180 seconds after the event is shown in Figure 4.16.

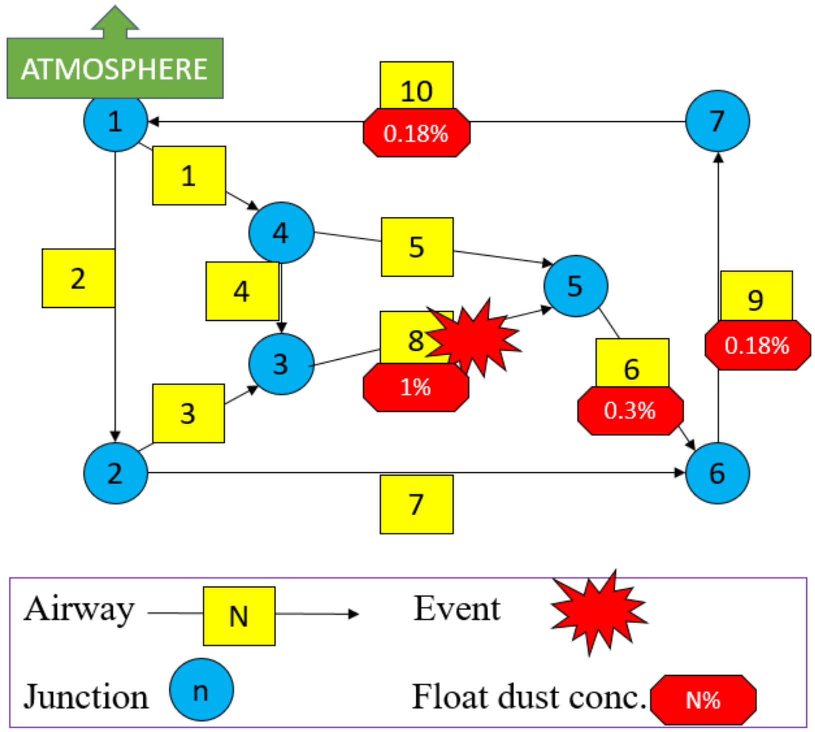


Figure 4.16: Float dust concentration in the model 180 seconds after the event

Particle transportation was modeled in a reduced scale model of a room and pillar coal mine. In such a mine the the flow is highly turbulent and 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. Particles less than 1.0 micron in size were observed in the streamlines of airflow, whereas 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 has known dimensions, similar random distribution of the float dust has been observed in coal mines, as discussed in previous chapter.

The MFIRE model showed that the fumes traveling from one airway to other airway depends on contamination flowrate and other parameters such as airway resistance, volumetric flowrate of air in the branch, and temperature in the branch. The research specifically examined the effect of contamination flowrate on fume concentration downstream. The simulation show that fume concentration downstream depends linearly on the contaminant flowrate into the ventilation circuit. Dust sample collected from the physical mine can be used to calibrate the simulation in MFIRE using physical mine inputs, these results will give a better estimation of dust transportation in the mine, which mine operators could make use to aid in scheduling rock dusting in mines.

Chapter 5 Major Conclusions and Future Work

This research was aimed to model the dispersion of dust in mine ventilation network models and develop an easy-to-use tool for scheduling rock dusting in underground mines. Mine airways of room and pillars, as well as a longwall panels, were sampled systematically. With the samples in this research, measurement of float coal dust deposition using TGA analysis indicated no apparent dependence of predicted deposition rate in terms of location and origin of dust source within the mine network. Return airways in the mine had somewhat higher float coal dust deposition, but no definite trends could be identified. These results show that local remedial measures could be the most effective dust alleviation technique.

Analysis of many samples showed that carbon content in the scooped dust from floor, roof and ribs did not follow any trends. This is attributed to the fact that dust generation zone in an active coal mine is not a controlled environment. The particles are transported in regions with varying geometrical, roughness and flow characteristics. Dust particles, which might settle in a region, could be moved further by numerous activities, including vehicular movement and change in dust characteristics due to moisture addition or simply agglomeration.

CFD analysis of dust particle transportation in a reduced scale model of a room and pillar coal mine showed no conclusive evidence of deposition trends within a known particle range when measured from the source of generation. This was because the dust particles were generated randomly on the surfaces marked as active mining faces. This was done to mimic a continuous sweeping action of the continuous miner drum. However, computer models, generated to predict the distance dust particles travel when released from 7-ft high coal seam, clearly indicated that lighter particles released in a fast moving airstream were found to travel furthest.

MFIRE software was developed to predict smoke transportation and dilution along the ventilation network. Smoke is analogous to float dust, and the software-predicted measurements were presented. Because MFIRE calculates fume transportation linearly, based on contamination flowrate, this parameter can be calibrated using physical mine dust sampling inputs to approximate dust transportation in an underground mine. Mine operators will get amount of time to transport the dust from the MFIRE output as well as expected concentrations. Those calculations will change as the ventilation network changes with the mining process, giving the mine planner more information for rock dust scheduling. .

5.1 Avenues of Future Work

The following points enumerate a few avenues for further investigation

(i) Investigation of more economic methods dust sampling and analysis techniques from an underground coal mine could be done to calibrate simulations of MFIRE;

(ii) Computational fluid dynamics analysis of dust transportation modeling with dynamic mine environment could be analyzed to establish more accurate dust deposition trends; and

(iii) Gravimetric dust sampling in a dynamic mine environment could be performed to validate the MFIRE model for dust transportation.

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Appendix

This MATLAB code was used to translate the CFD results to calculate float coal dust deposition behavior using physical mine inputs.

```
P=1.225; % Desnity of air :kg/m3
%program begins
%importing coordinate from csv file
load xyz.csv;
% x=xyz(:,1); code for calling full rows and columns
% y=xyz(:,2);
% z=xyz(:,3);

x1=xyz(1); %code for calling and storing single elements from the csv file
y1=xyz(5);
z1=xyz(9);
x2=xyz(2);
y2=xyz(6);
z2=xyz(8);
b1=sqrt((x1-x2)*(x1-x2)+(y1-y2)*(y1-y2)+(z1-z2)*(z1-z2));
prompt= 'Enter atkinson coeff (Imperial, No units)  :  ';
k=input(prompt);
prompt1= 'Enter height of entry (ft.)  :  ';
h=input(prompt1);
prompt2= 'Enter width of entry (ft.)   :  ';
w=input(prompt2);
A= w*h;    % Area of the cross section
R=k*P*(2*(h+w)*b1)/(A*A*A);
fprintf ('\n Resistance of the branch is : %f ',R);
prompt3='\n Enter the airflow at the entry (cfm)   : ';
q=input(prompt3);
AV=q/A;
fprintf ('\n Average velocity in the branch is %f (ft/min) \n ',AV);
prompt4='\n Density of coal particle (kg/m^3)   : ';
pd=input(prompt4);
dx=AV*0.196;
fprintf ('\n Average distance travelled by particle is %f (ft) \n ',dx);
```

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Education

M.Tech, Mining Machinery Engineering (2017)
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Thesis title: Numerical analysis of headgear structure using STAAD.PRO V8i.
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Summer Internship May - July 2016
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TATA Power Limited, Jamshedpur

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Uranium corporation of India Limited, Jamshedpur

Awards

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Peer Reviewed Conference Proceedings

- Kumar, A.R., **Kumar,A.**, and Schafrik, S. (2019). CFD modeling of dust transportation and deposition under Newtonian forces in the reduced scale model of a typical room and pillar mine. Annual Conference and Expo.(Preprint). Denver, CO: Society of Mining, Metallurgy, and Exploration.

- **Kumar, A.**, Schafrik, S., and Kumar, A.R. (2019). Float coal dust sampling and preliminary thermogravimetric analysis. Annual Conference and Expo.(Preprint). Denver, CO: Society of Mining, Metallurgy, and Exploration.

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Professional Presentations

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Research Posters Presentations

- **Kumar, A.**, Kumar, A.R., Schafrik, S. (2019). Computer modeling and laboratory testing of maintenance free Vortecone for dust-capture. Environmental division poster, SME Annual Conference and Expo. Denver. CO.

- **Kumar, A.**, Kumar, A.R., Schafrik, S. (2019). Computational fluid dynamics modeling and lab testing of a self-cleaning impingement filter screen. MPD division student poster, SME Annual Conference and Expo. Denver. CO.

- **Kumar, A.**, Kumar, A.R., Schafrik, S. (2019). Laboratory testing of a non-clogging filter screen for dust capture. Graduate student research poster.SME Annual Conference and Expo. Denver. CO.

Professional Affiliations/ Synergistic Activities

- Society of Mining, Metallurgy and Exploration (SME), [Student Member]
- The American Society of Mechanical Engineers (ASME), [Student Member]
- Society of Automotive Engineers, [Student Member]