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Detecting diesel particulate matter using real time monitoring under the influence of an exhaust fan system

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DETECTING DIESEL PARTICULATE MATTER USING REAL TIME MONITORING UNDER THE INFLUENCE OF AN EXHAUST FAN SYSTEM

by

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ABSTRACT

Diesel Particulate Matter (DPM) is a complex mixture of diesel exhaust gas that consists of carbon, ash, metallic abrasion particles, sulfates and silicates. The diesel soot particle includes a solid core made of elemental carbon, and organic carbon compound attached to the surface of the soot particle. The main source of DPM is diesel exhaust gas. The National Institute for Occupational Safety and Health (NIOSH) and the Environmental Protection Agency (EPA) have determined that DPM is the source of most of the emissions of carbon monoxide, carbon dioxide, oxide of nitrogen, and hydrocarbons in underground coal, metal and non metal mines. It has become a significant health issue, particularly in underground mines where diesel engines are more active in confined areas. The studies have shown that exposure to DPM is the main risk for lung cancer and other lung diseases. Providing an accurate underground ventilation plan can help to dilute the concentration of emissions. Diesel particulate matter should be monitored constantly to ensure it does not exceed MSHA's emission standards. This paper will show the behavior of diesel exhaust emission under the influence of exhaust fan with different speeds, and how the DPM can be detected by using a real time personal sampler. The experiment was conducted in the experimental mine at Missouri University of Science and Technology (MS&T). It is shown that there is a variance of the concentration of elemental carbon depending on the type of diesel source and the speed of exhaust fan. Understanding the relationship between the source and the ventilation system can give a better understanding of what ventilation plan is appropriate to keep the emission concentration as low as possible while taking into account the other affecting factors such as leakage. Some of the tests have not shown a good dilution of the gas but they can suggest other factors to be used for a high probability of reducing emissions. These other factors are recommended in this paper for more research.

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1. INTRODUCTION

1.1. BACKGROUND

Diesel Particulate Matter (DPM) has been a critical issue during the last decade in underground mines. This problem is threatening the personnel health of mine workers, as well as the mine's productivity. It has been confirmed that the diesel engine exhaust is the main source for the diesel particulate matter (DPM), and that it has the highest impact in raising carbon monoxide, carbon dioxide, oxide of nitrogen, and hydrocarbons rates in the underground environment according to (MSHA, 2015). Miners who are exposed to this kind of emission are at high risk for developing lung cancer and other lung diseases. Therefore, the Mine Safety and Health Administration (MSHA) has issued a standard rules to regulate diesel emissions in underground mines. The final ruling confirmed in 2008 states that the total carbon should not exceed 160 $\mu g/m^3$.

Monitoring DPM in underground mines has been important since then to control high concentrations of emissions. There are many different types of DPM monitoring systems that are being used since DPM has become a significant factor in health issues. Two methods are typically used for DPM sampling: the personal sampling method or the direct exhaust sampling method, which takes a direct sample from the engine's tailpipe. Yet, many mines do not recommend the direct exhaust sampling method since it involves complex measuring equipment and procedures, as well as the issue that is not regulated in the United States or Canada. Thus, the personal sampling method is the preferred method to be used when taking DPM samples. Even this method includes many variations, such as the Respirable Combustible Dust (RCD) method and the method devolved by the National Institute for Occupational Health and Safety (NIOSH 5040).

The NIOSH 5040 method is the preferred method overall because it gives more accurate measurements compared to the other methods. This method does not allow organic carbon sources other than those coming from diesel engine exhausts to interfere with the measurements, which otherwise would lead to overestimating the actual amount of the DPM in the mine environment. An impactor feature in the cassette, which holds the samples in the instrument, characterizes this method. This impactor does not allow particles more than 0.9 microns to be collected in the cassette filter. The cassette is then taken to the laboratory to analyze and determine the concentrations of organic carbon (OC), elemental carbon (EC), and total carbon (TC). Lately, the National Institute for Occupational Safety and Health (NIOSH) has developed a new instrument that can use the same concept of NIOSH 5040, but with instant measurements of elemental carbon. It utilizes laser radiation with the cassette so it can give a real time measurement. The real time measurements give instant information about the underground environment that will allow the mining engineer to take immediate action and enact plans instead of waiting for results from the laboratories where NIOSH 5040 method may take several weeks to get the measurements.

There are many ways to dilute and control diesel particulate matter emissions in underground mines. Providing a proper ventilation plan is the most important since it is the main factor for diluting any contaminant then. Using other dilution and controlling methods such as installing diesel particulate filters, providing new engines with the lowest possible emission levels, and by buying diesel engines that meet the regulation standards, can support the controlling and diluting plans in underground mines.

1.2. PROBLEM STATEMENT

Diesel particulate matter (DPM) has become a significant health issue in the last decade. There is limited research on monitoring and controlling these exhaust emissions in relation ventilation plans with emission dilution. Ventilation in underground mines can be very complicated depending on the layout and design of the mine. The primary objective to ventilate any mine is to let fresh air reach working faces while removing contaminants out of the sites in the simplest way with the lowest cost. Stoppings, regulators, and doors are important equipment supports to managing the airflow underground and they must be taken into account. However, reducing the numbers of these additions as much as possible can save more money and help avoid complicated plans. The goal of integrating these equipment supports is to ensure that the polluted air being prepared to be removed from the mine, does not contaminate fresh air.

The ventilation plans have a significant effect on diluting gas emissions and reducing other risks in underground mines such as heat, dust, humidity, and radiations. Subsurface ventilation systems contain major components to get the air in and out of the mine. The main intake shaft where the air enters the mine enhanced by a main surface fan which boosts its inside flow. The air flows through the intake airways to supply the working faces with fresh air. Then air will then take contaminants through the return airways to prepare for exit through the up cast shaft where, typically, there is a main exhaust shaft to assist pulling the unwanted air out of the mine (McPherson, 1993). The ventilation design will also include an auxiliary fan system to be placed inside the mine in order to blow or pull air. The purpose of these auxiliary systems is to help feed working places with fresh air in large mines where the intake shafts alone are not enough. They are also efficient in sucking polluted air away from the working faces and directing it to the return airways.

1.3. LOCATION OF THE STUDY

The study took place in the experimental mine at Missouri University of Science and Technology, Rolla, Missouri. The location consists of two underground mines and two small quarries on Missouri S&T property, approximately 76890 m^2 and operated by two full time employees. The experimental mine possesses a variety of equipment for research and instructional purposes (Feledi, 2014). It is located between 37° 56` 13.9`` N and 91° 47` 27.0`` W (Google maps, 2015). (Figure 1.1)

The experimental mine serves all Mining and Nuclear Engineering departments, as well as their faculty and students for research and enhancing student understanding through practical application and training. Additionally, it is available to graduate students who need apply new applications in support of their studies and research.

Figure 1.1. The location of Missouri S&T experimental mine (Google maps, 2015)

1.4. OBJECTIVE

Since there is limited research regarding diesel particulate matter emissions in underground mines this research will concentrate on the behavior of diesel particulate matter under the influence of particular ventilation scenarios and relate it to the efficiency of using real time DPM monitoring method. Doors, stoppings, main portals, and main shafts have been utilized to regulate the intake and outtake airways to simulate the real mine situation and provide more effective measurements through this research. Also, consideration will be given to the effectiveness of using a real time measurement method by using an Airtec instrument to determine the elemental carbon emitted from the source. Results will be correlated and compared in order to understand the contaminant airflow mechanism and provide solution and recommendations for more research opportunities.

2. LITERATURE REVIEW

2.1. DIESEL PARTICULATE MATTER (DPM)

The correlation between serious health issues and exposure to diesel particulate matter has brought up serious concerns, which are instigating the need for increased research in many areas regarding DPM. The U.S. Occupational Safety and Health Administration has defined the diesel particulate matter as a complex mix of diesel exhaust, which consists of soot particles made up of carbon, ash, metallic abrasion particles, sulfates and silicates. The diesel soot particle consists of solid core made of an elemental carbon and organic carbon compound attached to the surface of the soot particle. (Figure 2.1)

Figure 2.1. Illustration the component of the DPM. (MSHA, 2001)

The main source of DPM in underground mines is the diesel engine exhausts. The National Institute for Occupational Safety and Health (NIOSH) and the Environmental Protection Agency (EPA) have found that diesel engines are the most prolific contributors to elevations in the emissions of carbon monoxide, carbon dioxide, oxide of nitrogen, and hydrocarbons in underground coal, metal and non-metal mines. (Office of Mine Safety and Health Research, 2015)

2.2. HEALTH ISSUES CAUSED BY DPM

Exposure to diesel particulate matter has raised very significant health concerns regarding underground mines. The DPM is considered as the most hazardous contaminant to health because DPM particles are typically less than one micron. These can be inhaled deeply into the lungs, significantly increasing the probability that they will to remain in the walls of the alveoli. Furthermore, the fibrous nature of the soot particles enables them to adsorb a range of polynuclear and aromatic hydrocarbons. (Waytulonis, 1988). The adult male can typically inhale about 10 m^3 of air per day where this inhalation may be susceptible to a toxic component, which can be found in the air, as a result of pollution activities such as vehicle exhaust emissions. Breathing these pollutants can lead to adverse health problems such as inflammation, innate and acquired immunity, oxidative stress, lung cancer, and death due to high exposure to DPM. (Ristovski and others, 2012)

According to Kuhar a study conducted by researchers from National Cancer Institute (NCI) and the National Institute for Occupational Safety and Health (NIOSH) for more than 12,000 non-metal miners in the United States, they determined that heavy exposure to diesel exhaust increased the risk of death from lung cancer. The study took place in eight non-metal mines because of their characteristics. Non-metal mines are lower in overall exposure elements that may be related to lung cancer. The mines were selected based on their heavy use of diesel equipment, which generated exhaust emission frequently. Diesel exhaust emission samples in the air were collected from each mine, and they have been combined with historical exposure information so as to quantify the exposure level for each worker. The same data has been used in cohort and case-control analyses. Some external factors were taken into consideration, such as smoking and other lung damage related factors, in order to estimate lung cancer risk. This study showed that the observed risk of lung cancer among heavily exposed workers was five times greater than that of the observed risk for lung cancer in the lowest exposure division. On the other hand, the study was done by (Kuhar, 2012) study was applied on a small number of non-smoking workers who were exposed to the highest level of diesel exposure, and it showed that they were seven times more likely to die from lung cancer than those who were exposed to the lower exposure level.

The Air Resources Broad, a section of the California Protection Agency, performed a study, which demonstrated that DPM contains toxic chemical materials, which can contribute to the mutation of genetic material (DNA), as well as contributing cause of cancer. The U.S. Environmental Protection Agency (U.S.EPA) and the International Agency for Research on Cancer (IARC) have classified some of the polycyclic aromatic hydrocarbons as probable human carcinogens. After exposure to DPM, the compounds can be adsorbed into the bloodstream and damage the cells within living tissues such as the lungs. Leukemia is another serious disease which can be caused by exposure to Benzene, which is the first contaminant listed by the state of California in diesel exhaust, which is not only present in the gaseous phase of exhaust gases, but also in the DPM itself. The study strongly links that DPM as a primary casual factor of causing more than 250 cancer cases per year in California. Based on the epidemiologic study, DPM is associated with a 40% increase in cancer risk overall. (California Environmental Protection Agency, 2004). Furthermore, a study conducted by (Sharp, 2003) showed that exposure to DPM in Canada has the potential to cause about 13,600 Canadians to develop cancer over their lifetimes. Similarly, underground miners face a 33% to 47% increase in risk of developing lung cancer due exposure to DPM emissions.

Due to the concerns resulting from the risk of diseases associated with diesel exhaust engines, and the need to use those engines in many industries and the underground mining industries in particular, new legislation has been put into place where new limits which must not be exceeded have been stated in order to reduce potential health issues.

Due to the serious health effects caused from exhaust emissions, many environmental and health agencies around the world have put together some recommendations so as to reduce these emissions as stated below:

- Establish policies to reduce the use of heavy-duty vehicles.

- Purchase diesel powered equipment to meet the standard regulations of DPM emissions.
- Provide good maintenance for diesel engines to reduce any hazardous emissions.
- Install diesel particulate filters that can reduce up to 95% of harmful soot.
- Limit speeds and use of one way travel routes
- Develop ventilation systems to reduce high concentrations of DPM

With this in considerations, the Mine Safety and Health Administration (MSHA) put out the final rule limit for DPM exposure in 2008. The rule currently states that the total carbon (TC), which is the sum of the elemental carbon (EC) and organic carbon (OC), should not exceed 160μg/m^3. Initially in May 2006, MSHA approved a final exposure limit of elemental carbon at 308μg/m^3. The limit was then set in January 2007 to regulate total carbon limit at 350μg/m^3 until the final limit was set on May 20, 2008 to regulate the exposure limit of total carbon as well as elemental carbon to be 160μg/m^3 in all metal and non-metal mines (Pallasch, 2008).

According to the Australian Institute of Occupational Hygienists in 2012, the Western Australia Department of Mines and Petroleum issued a guideline which recommend the exposure limit of 0.1mg/m^3 of elemental carbon measured as a time weighted average over eight hours, based on their recommendations in 2007.

In Canada, each province has its own regulation to govern the use of diesel engines in underground mines except the province of Prince Edward Island, which has no mines. Most provinces require the limit of 1.5-mg/m^3. Some provinces, such as Manitoba and Newfoundland, are using the limits put out by the American Conference of Governmental Industrial Hygienists (ACGIH) who proposed a threshold limit value (TLV) of 0.15-mg/m^3 for diesel exhaust in 1995.

2.3. DPM MONITORING

Throughout the past several years, DPM has become a serious issue within underground mines. Due to this issue the necessity to monitor and control DPMs are very important to provide a more comfortable and less hazardous working atmosphere for miners. Many monitoring methods and instruments have been developed to give appropriate readings of diesel particulate matter and its components, such as elemental carbon and organic carbon. DPM sampling can verify the efficiency of a ventilation system or any diesel emission treatment that is attached to the equipment.

There are many different methods, which can be used to collect and analyze DPM data. According to Grenier, and others (2001), there are two methods, which are more commonly used for sampling and monitoring DPMs.

2.3.1. Personal Exposure Monitoring. It is the most commonly used type of DPM within Canada alone it has been regulated form more than 10 years in several mining provinces. The samples should be taken depending on the personal exposure and worker selections. Workers who are exposed to a high concentration of diesel particulate matter should be sampled. It is important to sample as many high risk employees as possible, including diesel equipment operators, mechanics, and other employees who work in places where diesel machines are used intensively. The selection of sampled employees relies on the location, shift time, and number of individuals in a group. In large groups, the personal sample should be selected randomly. For smaller groups that are less than 10 employees, however, all of them should be sampled to monitor their exposure (Grenier, and others, 2001).

2.3.1.1. Respirable combustible dust method (RCD) (Canada). This method was developed in Canada to estimate the DPM emissions in non-coal mines according to several experts (Hews, and Rutherford, 1973; Watts, and Ramachandran, 2000). This method consists of 10-mm nylon cyclone tubes where the sample passes through at a flow rate of 1.7-L/min, which is being controlled by using a personal sampling pump. The sample is then collected in a 0.8-µm silver membrane or glass fiber filter, which is called cassette (Figure 2.2). The collected dust can be determined by measuring the weight of the membrane, or the fiberglass filter, before and after collecting samples. The RCD is determined gravimetrically by removing the material from the cassette through controlled combustion at 400°C for silver membranes and 500 °C for fiberglass filters. The sampling devices can be fitted on a worker (Watts, and Ramachandran, 2000; Grenier, and others, 2001).

The RCD consists of all combustible materials collected on filters such as drill oil mist, the soluble organic fraction of DPM, and elemental carbons. (Watts, and

Ramachandran, 2000).

Figure 2.2. The concept of RCD collecting sample devise.

This method is inexpensive and simple to use. Therefore, analytical services are available in most laboratories. However, the RCD method can be affected by any source of carbon such as cigarette smoke, drill oil mist, and more. These sources can lead the instrument to overvalue the amount of actual DPM present. As well, some mineral dusts, mines with high sulphide ore body, or mines which use high sulphur content fuel can underestimate the amount of DPM exposure leading to inaccurate readings yet again.

2.3.1.2. Elemental carbon method (EC). This method is quite similar to the RCD method with respect to collecting samples. The only difference with regards to the sampling devise in this method is that the submicron impactor attached to the cyclone, where the air flows through the impactor, prevents respirable dust particles larger than 0.9 micron in size to enter into the filter cassette (Figure 2.3). This helps to eliminate the non-diesel particles to be analyzed as diesel particulates since the diesel particles are less than 0.9 micron. (Geriner and others, 2001)

Figure 2.3. Illustrates the difference between RCD and EC collecting sample device. (Levin, 2013)

NIOSH has developed a thermal-optical method called NIOSH 5040. This method, however, is more complicated than the RCD method as it utilizes the thermal separation of elemental carbon and organic carbon, and the controlled temperature and analytical cell atmosphere to measure both of them separately. Laser light is used in the instrument to measure the light transmittance through the filter to determine the proportions of elemental and organic carbon accurately. The combustion process of the dust in the instrument is controlled; this dust burning produces carbon dioxide that can be measured and then the masses of elemental and organic carbon are extracted. The flow rate and the sampling time are then used to calculate the concentration of diesel particulate matter. (Geriner and others, 2001)

The NIOSH 5040 method gives accurate readings. Unfortunately, it is not widely used and only few instruments are available since it is not specified in Canadian or

American mining regulations. However, as long as new MSHA's rules are applied, this will increase the demand for analytical processes as well as more laboratories. The new MSHA regulations for metal and non- metal mines require eliminating particles larger than 0.9 micron from being analyzed, thus a new component has been added to personal samplers. This component is a disposable impactor. It is recommended to be used while taking samples, even though it does not eliminate large particles completely, nevertheless, it reduces the potential for other carbon compounds to overlap with the sample analysis (Geriner and others, 2001).

2.3.1.3. Previous studies. Much research has been done in both the RCD and NIOSH 5040 methods, yet the majority of researchers did not prefer using the RCD method because it did not give as accurate measurements due to its potential of foreign interactions and interferences with other carbon and sulfide sources causing it to overestimate the amount of carbon in the DPM survey.

A study has been done to compare sampling and analytical methods exposure to diesel exhaust in a railroad work environment (Verma, and others, 1999), where they examine both the RCD and NIOSH 5040 methods in tow maintenance shops at a large Canadian railroad company. These locations were identified as Yard 1, which was located in central Canada, and Yard 2, which was located in western Canada. Most of the samplings were taken in Yard 1, where it contains a very large maintenance shop. Locomotives were brought into Yard 1 where they let them run briefly during testing in the turnaround area and release the exhaust into the shop, the area which has the highest potential of diesel exposure. The second location monitored in Yard 1 was the heavy repair area, which is considered the second highest potential for diesel exposure because locomotives may or may not be working in this area. A limited number of samples were taken from Yard 2 in similar locations as Yard 1. A total of 215 samples were collected between April and July.

The use of both methods in this study showed that the obtained concentrations by using RCD method are 12 to 53 times higher than those obtained using the EC NIOSH 5040 method. They found that the EC method is more selective, has the ability to differentiate the elemental and organic carbon and this method is relatively inexpensive. However, they see that the accuracy of this method needs improvement.

The RCD method used in this study has shown that it is neither selective nor sensitive and the measurement limit is higher than the EC method. The RCD measurements include both elemental and organic carbon, which means that this method does not differentiate them. Additionally, this study acknowledges that other organic carbon affects this method, such as uncombusted diesel fuel, oil mist, cigarette smoke, and pollen. The researchers of this study suggested that the RCD method might be suitable for underground mining measurement where the respirable dust level may be much higher than the combustible dust, which is approximated as 10 to 20 % of respirable dust in a hard rock mining environment.

A report submitted to the Diesel Emission Evaluation Program (DEEP) in 2000 by Winthrop F. Watts showed in a study conducted in Canadian mines by University of Minnesota, center of diesel research to statistically compare diesel particulate matter sampling methods. The researchers used three methods to measure DPM emission. These methods were the respirable combustible dust method (RCD), size selective sampling (SS), and elemental carbon method (EC) using NIOSH 5040 to analyze EC samples.

The study concluded that the intercept in the RCD method was 25.5-$\mu g/m^3$. That means that when the RCD gives this reading, the EC method will then read zero due to the interfering materials, which affect the RCD method but not the EC method. It also demonstrated that the EC method is the most sensitive and specific marker of diesel exhaust. Because its high the sensitivity, a small change in DPM concentration will be that can be measured by a method at a specified confidence level (Watts, 2000).

Another approach was developed by NIOSH to measure the elemental carbon instantly by using real time monitors. The instrument, by NIOSH (Airtec) gives an instantaneous determination of diesel particulate matter in the air. The data can be stored and furthermore provides miners information of major factors of overexposure; allowing engineers to take immediate action to control these emissions (Noll, and Janisko, 2013).

According to Noll, and Janisko (2013), the real time DPM commercial instrument (Airtec) was found to meet the NIOSH accuracy criteria and showed no statistical differences between the standard method NIOSH 5040, and the real time method. Moreover, the instrument was found to be unaffected by the dust and humidity.

Wu, Gillies, Volkwein, and Noll (2009) conducted a study to test the accuracy of the real time montoring approach in underground mines. The research was conducted in six Australian mines named A to F, using both the real time monitors and NIOSH 5040 method. The project discussed how the monitors performed evaluating DPM during various phases of Long Wall equipment moves. The results of the comparison between the NIOSH 5040 method and the real time method in this research have shown that the real time mentoring technique gave reasonable results. The DPM information obtained by real time monitoring can provide a greater understanding of the underground environment and for engineering evaluation exercises.

A complimentary study was performed by Noll, and Janisko (2013) to evaluate the differences between using the NIOSH 5040 method and the real time monitoring instrument, Airtec. The results have shown that the differences obtained in the data from both methods were similar to the observed data when duplicate NIOSH 5040 samples were taken. The Airtec instrument in this study also proved its resistance to dust and high humidity in the field.

On the other hand, Arnott, Arnold, Mousset-Jones, and Shaff (2008) conducted a comparison study between the use of real time monitoring and the NIOSH 5040 method. They placed DPM samplers for the NIOSH 5040 method, and instantaneous samplers for real time method, in two sites within declining drift at Barrick Goldstrike Meikle gold mine in Nevada, USA. They used different real time instruments to determine the DPM components, such as the Dusttrak Nephelometer, to determine the total carbon, and a Photoacoustic measurement to determine the elemental carbon. The results showed that the total carbon measurements obtained by the Dusttrak Nephelometer were 50% greater than those obtained by the NIOSH 5040 method. However, the elemental carbon results obtained by the Photoacoustic were similar when compared to NIOSH 5040 method.

2.3.2. Direct Exhaust Sampling. It is another approach to measuring the personnel exposure levels to diesel particulate matter. As described by Grenier, and others (2001), this method involves complex equipment and pressure from a tailpipe of the engine in order to assess the engine's health and accuracy, as well as enhancing the underground mine environment. This method is not routinely used in mines since it is not required in Canada or the United States. More detailed information about this method is described in the Diesel Emission Evaluation Program report of 2001 under the title of "Samples for Diesel Particulate Matter in Mines."

2.4. VENTILATION PLANS TO DILUTE DIESEL PARTICULATE MATTER

Good ventilation plans have a significant impact on diluting and controlling many contaminants that may be found in underground mine environments. Even though it is not the only method to control underground emissions, the ventilation plan must be considered to assist with any other controlling methods. There are many studies, which have been executed to test the efficiency of various ventilation plans, and observe how those compounds behaved to give a better understanding and recommendation on these matters.

A study was done by Noll, Patts, and Grau (2008) to test the efficiency of ventilation and enclosed cabs in reducing DPM emissions and exposure. The study was conducted in two stone mines that used both ventilation and enclosed cabs to reduce DPM exposure. Both of the mines were able to deliver airflow to the working face using long pillars or brattices. The van anemometer was used to obtain ventilation measurements in several locations within the mines, like return areas and some locations near the face. The elemental carbon monitors and three SKC DPM cassettes (NIOSH 5040 method) were placed in baskets on tripods and operated for six hours. These samples were collected in several locations within the stone mines to determine the DPM concentration levels, as well as examine the effect of current ventilation plans. The stone mines also used conditioned and filtered enclosed cabs to prevent or reduce miners' exposure to DPM. Two baskets containing elemental carbon monitors and three SKC DPM cassettes (NIOSH 5040 method) were prepared to evaluate the efficiency of cabs to reduce DPM exposure. One of the baskets was strapped to the loader while the other basket was placed inside the cab, where the miner was operating the machine. The sampling lasted for six hours of production shifts over the course of five days.

The obtained results from this study concluded that the ventilation control plan was good enough to reduce the DPM concentrations to a level that will allow the use of more options for controlling DPM exposure. With such an option, the enclosed cab was indicated to be over 90% efficient in reducing DPM exposure in one mine, as long as windows and doors of the cab are closed.

Sometimes there is a difficulty to find an extra ventilation capacity to utilize air for contaminant dilution in the mine. C. Pritchard has discussed a variety of alternative ways to supply mines with adequate amounts of air for a healthier and more comfortable working environment. He suggested some solutions, which discussed in detail in his paper “methods to improve mine ventilation system efficiency”. One of the discussed case studies in this paper was in a room and pillars mine. The working activities were advanced further from the mine shaft where the contaminated air and leakage have a negative effect on the air flow to the face. It was found that the mine level airflow was 236-m^3/s, while the shop airflow was 24-m^3/s. The recommended solution was to supply the mine area with air from the shop area instead of send to the return airway.

The monitoring system was installed to monitor the carbon monoxide levels in the shop intake, end of shop bay, and the mixing point of the shop and east mine intake split.

19-m^3/s of the 24-m^3/s from the shop area was saved and sent to the mine production area. Actual shop airflow volume increased from 24-m^3/s to 38-m^3/s when opened up as a parallel intake, and provided a more efficient route for air to flow. The author concluded that finding extra air source in some mine areas, and placing them in parts of the mine when there is no extra ventilation capacity, can reduce consuming power and cost. Taking into account the entire system of the mine, and making adequate changes, will lead to a reduction in any pollutant within a working place, and provide a healthy and clean environment for miners.

The National Institute for Occupational Safety and Health (NIOSH) conducted a research in various mines to improve working conditions for miners in the United States of America. The research was conducted to determine an appropriate method to estimate the adequate air quantity to dilute diesel particulate matter (DPM), choosing appropriate fans, and mine layout, particularly in mine entry areas with large sectional spaces. NIOSH has been developing a method in non-metal mines with large entries. These researchers indicated that utilizing preventative measures with appropriate ventilation could effectively reduce the air contaminants, such as dust and DPM. However, the common ventilation methods and techniques are not adequate in large opening non-metal mines, where the large entries reduce the ventilation resistance and allow for more air quantity to flow with small static pressure. Many mines, especially in large opening mines, depend on the natural ventilation by utilizing auxiliary fans for ventilation inside the mine. Yet, the natural ventilation alone is unreliable since it changes frequently in magnitude and direction due to the differences in densities between the air column in the mine and the outside air depending on temperature. The ventilation system through the entire mine should be considered to improve overall mine air quality. The ventilation system consists of mechanical main fans, auxiliary fans, and mine layout using a device called air walls to direct and control the air. All these parameters should be considered for utilization to promote better air quality. Moreover, the split mine method where the mine is split into two parts (intake fresh air and pollutant return air), is appropriate to dilute and split the contamination based on NIOSH recommendations.

3. METHODOLOGY

3.1. INSTRUMENTATION

There were many instruments used in this research to collect as much information as possible in the underground mine's atmosphere such as temperature, duct dimensions, air velocity, and DPM and gas concentrations.

The vane anemometer was used to determine the air velocity through the underground ducts (Figure 3.1). In this instrument an extended rod is attached to the vane anemometer to allow covering of the duct dimensions for convenient measurements. A stopwatch is used while taking velocity measurements so as to limit the measurement time to 100 seconds in an effort to simplify correction factors.

Figure 3.1. Manual vane anemometer with a stopwatch.

Rotated hygrometers, which consist of wet and dry bulb thermometers, were used to determine the temperature in both wet and dry conditions (Figure 3.2).

The gas detector IBRID MX6 was used to detect gas concentrations in the mine while research was being conducted. Industrial Scientific manufactures the IBRID MX6, which is capable of detecting up to 19 kinds of toxic gases including combustible gases and volatile organic compounds (Figure 3.3).

Figure 3.2. Hygrometer to determine wet and dry temperatures.

Figure 3.3. IBRID MX6 gas detector.

A real time monitoring instrument, Airtec, was used to measure the diesel particulate matter in the mine. This instrument measures the elemental carbon that comes out of an exhaust engine instantly. The Airtec is closely correlated to the NIOSH 5040 method results, which also capture the particles in real time by using a light transmission method. The Airtec is manufactured by FLIR instruments, and is powered by a lithium-ion battery that can last for 12 hour of continuous operation (Figure 3.4).

Figure 3.4. Real time DPM measurement instrument (Airtec).

Dimension and distance measurements were taken by using a laser tape measure. It conveniently provide precise measurements, was easy to use, and it saved time and effort (Figure 3.5).

Figure 3.5. Laser tape measure.

3.2. MINE PREPARATION

An appropriate approach in any mine, as discussed earlier, is to split the mine into two main parts with, the intake airways where the fresh air enters the mine so as to ventilate the working and active faces, while the return airways allow the contaminated air to exit out of the mine. In large mines, the use of an auxiliary fan system is needed to enhance the airflow in the mine, whether it is to push it further through the airway or to pull it out. However, this research has been conducted in a relatively small mine, and therefore was in no need of auxiliary fans usage before examining the efficiency of the main ventilation systems. The initial setup was to split the mine into two separate parts so as to prevent the air from mixing. Seven stoppings were installed to separate the two parts of the mine conveniently for research scenarios (Figure 3.6).

Additionally, four doors were installed in the mine. While the doors and stopping both control airflow, the doors allow for access to different locations of the mine as they provide short cuts from one area to another. In addition, they can efficiently change the ventilation plan as needed. They can be opened to allow airflow through and change the way it flows (Figure 3.7).

Figure 3.6. Mine stopping in the experimental mine.

Figure 3.7. Illustration of one of the installed doors in the mine.

A brattice was installed in one station near Wheeler main portal. A brattice is a temporary plastic partition used to control the mine ventilation. The installation is easy and fast, and it can provide an efficient way of stopping air leaks. Moreover, they can provide an instant solution for complex ventilation control. Uses of a brattice in this mine provide an immediate solution to preventing fresh air from interfering with the diesel emissions coming from the source (Figure 3.8).

Figure 3.8. Illustration of the installed brattice in the experimental mine.

Two main shafts were used. One of them was the intake shaft, which allowed fresh air to enter the mine, while the other was the exhaust shaft, which pulled the contaminated air out of the mine. One main fan was used in the entire research and that was the exhaust fan. No blowing fan was used since the goal of this research was to examine the exhaust fan and its effectiveness in diluting the diesel particulate matter emissions within the mine.

Missouri University of Science and Technology, Department of Mining and Nuclear Engineering, owns the refereed to fan, which was purchased and installed in 2011. Spendrup Fan Company manufactured this fan and equipped it with a 12 kw motor fan, diffuser screen, and inlet cone (Figure 3.9).

Figure 3.9. The exhaust fan in the experimental mine at Missouri S&T.

3.3. EXPERIMENTAL METHOD

Eleven different scenarios were applied in this experiment based on the different main exhaust fan speeds, diesel sources, and locations. The real time monitor (Airtec) was placed at an elevation of 1.20 m in all stations. Two diesel sources were used throughout experiments: 1) a bobcat loader, which was used for approximately 40 kw (Figure 3.10), and 2) an air compressor that puts out up to 700 Kpa of air (Figure 3.11).

The bobcat was used in drifts A and B, but was unable to be used in drift C since it is bigger than the main portal that leads to this location. Thus, the air compressor was used in drift C instead. The air compressor was also used in drift B, but not in drift A since the air compressor was wider than the door which leads to drift A.

The emissions from these sources will be compared in each scenario and related to the efficiency of the main exhaust fan. Each scenario will be explained in this section.

The air velocities were taken in each station using the manual vane anemometer as well as the dimension of the station in order determine the air quantity in each station by finding the sectional area then multiply it by the average air velocity. Also the temperature was taken using hygrometer. This information might not be needed but they are necessary to explain any unusual readings might found.

Figure 3.10. Diesel source (bobcat). Was placed in one of mine’s drifts.

Figure 3.11. Diesel source (air compressor). Was placed in drift C.

3.3.1. Scenario 1. The bobcat was placed in drift B near the Kennedy portal with the bobcat's facing toward the drift and the exhaust shaft. The main intake shaft was opened to allow fresh air to enter the mine without any influence from the blowing fan. However, the main exhaust shaft, equipped with an exhaust fan was operated at speed of 500 rpm. Both main portals and all doors were closed to regulate the airflow through drifts A and B without any effect from air coming from another duct. The real time instruments were placed in eight stations to measure the elemental carbon during the experiment. Also, velocity, dimension, and temperature measurements were taken at each of the eight stations (Figure 3.12).

Figure 3.12. Mine setup map for Scenario 1.

3.3.2. Scenario 2. The bobcat (diesel source) was placed in drift A close to the intake shaft. When the air entered the mine, it was contaminated immediately by the diesel emission under the intake shaft, where it traveled through drift A and entered drift B, after which it continued until it reached the exhaust shaft and was pulled out of the mine by the exhaust main fan at the speed of 500 rpm. Both main portals were closed, and the doors inside the mine were also closed in order to regulate the airflow in the ducts. The real time monitors (Airtecs) were placed in 11 stations starting from the intake shaft and ending at the outtake shaft. All required measurements like air velocity, dimensions, and temperature, were taken in each station (Figure 3.13).

Figure 3.13. Mine setup map for scenario 2.

3.3.3. Scenario 3. This scenario used the same set up as Scenario 1, However, the number of stations in this scenario were reduced from eight to six stations due to the following: stations 1-2 and 1-3 results were identical, and as such station 1-3 was removed, and station 1-6 was removed due its location between two stoppings, where therefore, it was better to examine the elemental carbon levels before and after those stoppings for difference in results instead. The only other difference in this scenario was that the main exhaust fan was turned to the maximum speed of 1550 rpm. All required parameters (dimensions, air velocity, and temperature) were taken at each station (Figure 3.14).

Figure 3.14. Mine setup map for scenario 3.

3.3.4. Scenario 4. This scenario is exactly the same as Scenario 1, with eight stations to detect the level of elemental carbon using a real time monitor. The air speed of the main exhaust fan in this station was reduced from the maximum speed of 1550 rpm in Scenario 3 to a speed of 1000 rpm in this scenario. Both main portals were closed as well as all inside doors. All parameters were taken at each of the eight stations (Figure 3.15).

Figure 3.15. Mine setup map for scenario 4.

3.3.5. Scenario 5. The air compressor was placed in drift C near the Wheeler main portal as it was to be the diesel source in this experiment. Both main shafts were opened with no blowing fan at the intake shaft. The exhaust shaft was enhanced by the main exhaust fan at a speed of 500 rpm to pull air out of the mine. The Wheeler portal was opened during the experiment so that the fresh air entered the mine from this portal to pass through drift C. The main intake shaft was also opened so that fresh air would pass through drift A and B to the exhaust shaft. However, the Kennedy main portal was closed during the experiment. The inside door between stations 5-4 and 5-5 was opened to allow air to go through. A plastic brattice was installed between stations 5-2 and 5-3 as an instant solution to control airflow. A total of six stations were installed to measure the level of elemental carbon using the real time monitors. All required parameters were taken at each of the six stations (Figure 3.16).

Figure 3.16. Mine setup map for scenario 5.

3.3.6. Scenario 6. This scenario used exactly the same set up as scenario 5, however, the main exhaust fan was turned to a speed of 1000 rpm. The station numbers remained the same. All required parameters were taken during this experiment (Figure 3.17).

Figure 3.17. Mine setup map for scenario 6.

3.3.7. Scenario 7. Similar to Scenarios 5 and 6, this scenario has the same set up but with an altered main exhaust fan speed, which was turned to the maximum of 1550 rpm. Changing the fan's speed was done to compare the level of the diesel emissions. All stations remained the same, as did the parameters, which were taken at each station (Figure 3.18).

Figure 3.18. Mine setup map for scenario 7.

3.3.8. Scenario 8. This scenario is similar to Scenario two, where the bobcat loader was placed in drift A beside the intake shaft. The exhaust main fan was set at speed of 1000 rpm to pull the contaminated air out of the mine. The diesel exhaust poisoned the air once it entered the mine. All main portals were closed, as were all inside doors to isolate drift C from drifts A and B. The real time instruments were placed in a total of 11 stations. All the required parameters were taken during this experiment (Figure 3.19).

Figure 3.19. Mine setup map for scenario 8.

3.3.9. Scenario 9. This scenario, as well as the next two scenarios, was repeats of what was done in Scenarios 1, 3, and 4. The difference in scenarios 9, 10, and 11 was that the air compressor was used instead of the bobcat loader in an effort to examine both of the diesel sources emitting DPM. Both of the main portals were closed, as were the inside doors, to isolate drift C. However, the main intake shaft remained open to allow natural air inside the mine. The outtake shaft was open with a main exhaust running at 500 rpm. The real time instruments were installed in a total of 7 stations. All required parameters were taken for better interpretation (Figure 3.20).

Figure 3.20. Mine setup map for scenario 9.

3.3.10. Scenario 10. This scenario has a setup similar to Scenario 9, where the air compressor was placed near the Kennedy portal. The main exhaust fan was turned on at a speed of 1000 rpm. Both of the main portals were closed, as well as the inside doors to isolate drift C. Real time instruments were placed in a total of 7 stations to measure the elemental carbon during the experiment. All required parameters were taken for better interpretation (Figure 3.21).

Figure 3.21. Mine setup map for scenario 10.

3.3.11. Scenario 11. This scenario also has the same setup, with the air compressor placed close to the Kennedy portal, both of main portals closed, as well as the inside doors so as to isolate drift C. The main exhaust fan was turned on to a maximum speed of 1550 rpm. The real time instruments were placed in a total of 8 stations during this experiment. All required parameters were taken for better interpretation (Figure 3.22).

Figure 3.22. Mine setup map for scenario 11.

4. RESULTS AND DISCUSSION

4.1. INTRODUCTION

This section will review the most important results obtained from this research so as to give an opportunity to compare these results and explain the gas's behavior in the subsurface opening. As mentioned earlier, there are some factors affecting this behavior such as temperature and the quantities. Therefore, the experiment was divided into scenarios and each scenario was then divided into stations. The gas measurements were taken in each station by a real time instrument (Airtec). Additionally, temperature and calculations of quantity were taken in each station based on the air velocity and the station's dimensions. These measurements may vary between scenarios, as is demonstrated in the following subsections.

4.2. SCENARIO RESULTS

4.2.1. Scenario 1. The amount of elemental carbon obtained in this scenario did not exceed the legal U.S. minimum of 160-$\mu g/m^3$. In stations 1-1 and 1-3 the elemental carbon coming from the bobcat exhaust remained at average of 70.16- $\mu g/m^3$(Figure 4.1 & 4.2). These results are considered to be low and that there is no real threat to the workers even though the main exhaust fan speed was as low as 500 rpm.

Figure 4.1. Elemental carbon results obtained from station 1-1 in $\mu g/m^3$.

Figure 4.2. Elemental carbon results obtained from station 1-3 in μg/m^3.

In station 1-4 the elemental carbon observed was initially reduced to 50-μg/m^3 and rises to approximately 79-μg/m^3 with an average of 50-μg/m^3(Figure 4.3).

Figure 4.3. Elemental carbon results obtained from station 1-4 in μg/m^3.

In station 1-5 the average of elemental carbon has increased by approximately 2-μg/m^3 (Figure 4.4).

Figure 4.4. Elemental carbon results obtained from station 1-5 in $\mu g/m^3$.

In station 1-6 the concentrations decreased again, reaching an average of 50-$\mu g/m^3$ of elemental carbon (Figure 4.5).

Figure 4.5. Elemental carbon results obtained from station 1-6 in $\mu g/m^3$.

The elemental carbon increased again in station 1-7 by roughly 7-$\mu g/m^3$ than it was in station 1-6 (Figure 4.6), however, the concentration dropped to the lowest amount of elemental carbon in the last station 1-8 to be around 30-$\mu g/m^3$ (Figure 4.7). The reason for such a low amount of elemental carbon was due to station 1-8 being right under the exhaust shaft and having the highest air compared to the other stations (Table 4.1). This indicates that the relationship between the main exhaust fan speed and the diesel particulate matter source is quite strong in this scenario, and able to maintain a safe underground atmosphere. However, the goal was to reduce the exhaust emission to as low as possible, and therefore, more main fan speeds would be applied.

Figure 4.6. Elemental carbon results obtained from station 1-7 in µg/m^3.

Figure 4.7. Elemental carbon results obtained from station 1-8 in µg/m^3.

Table 4.1. Parameters of Scenario number 1.

Station	Average velocity m/s	Average width m	Average height m	Sectional area m^2	Air quantity m^3/s	Wet bulb temperature ℃	Dry bulb temperature ℃
1-1	0.73	3.97	2.38	9.45	6.91	19.5	18
1-2	1.08	2.95	2.03	5.99	6.47	-	-
1-3	1.08	2.44	2.25	5.49	5.93	-	-
1-4	0.97	2.99	2.24	6.71	6.51	-	-
1-5	1.02	2.87	2.33	6.69	6.82	17	16
1-6	1.03	2.56	2.00	5.12	5.27	-	-
1-7	1.56	2.04	1.98	4.04	6.30	-	-
1-8	1.69	2.45	2.09	5.13	8.67	15.5	15

The elemental carbon averages were put together in one graph to analyze the diesel emission behavior through the duct under the influence of a 500 rpm exhaust fan speed (Figure 4.8). It showed that the elemental carbon started at a maximum of 70-µg/m^3 and then decreased to 50-µg/m^3 in the second station. However, that result may be the impact of leakage from the stoppings before station 2 as the concentration returned to 70-µg/m^3 in station 3 before it again reduced, where it to remained nearly constant until it dropped to the lowest concentration of 30-µg/m^3 in station 8 (which is the last station in this scenario and has the exhaust fan affecting the concentration of emission to be low).

Figure 4.8. Diesel emission behavior through the duct in Scenario 1.

4.2.2. Scenario 2. The contaminated air in this experiment will travel through drifts A and B, starting from the intake shaft area and leaving the mine through the exhaust shaft with the help of the main exhaust fan at a speed of 500 rpm. Even though some of the stations gave illogical readings, all results will be displayed and explanations provided based on the observations during this experiment.

The initial station recorded an average of about 37-μg/m^3 of elemental carbon, with a slight increase by 4-μg/m^3 in the next station as shown in Figure 4.9 and 4.10.

Figure 4.9. Elemental carbon results obtained from station 2-1 in μg/m^3.

Figure 4.10. Elemental carbon results obtained from station 2-2 in μg/m^3.

The concentrations then increase by approximately 20% in the next two stations (3 and 4) to reach an average of 63 and 62-μg/m^3 respectively (Figure 4.11 and 4.12). Surprisingly, the initial thought was that there would not be any elemental carbon concentration in station 4 since the air quantity is the lowest in that station (Table 4.2). However, it was found that air pushes gas further more to station 4 before turning around to the other airway where the contaminated airflow enters drift B.

Figure 4.11. Elemental carbon results obtained from station 2-3 in μg/m^3.

Figure 4.12. Elemental carbon results obtained from station 2-4 in μg/m^3

Table 4.2. Parameters of Scenario number 2.

Station	Average velocity m/s	Average width m	Average height m	Sectional area m^2	Air quantity m^3/s	Wet bulb temperature ℃	Dry bulb temperature ℃
2-1	1.27	2.25	2.06	4.64	5.89	14.5	13
2-2	0.96	2.49	2.09	5.2	4.99	14.5	13
2-3	1.22	2.15	2.07	4.45	5.41	19	15.5
2-4	0.39	2.16	2.06	4.45	1.74	18.5	15
2-5	0.44	3.93	3.14	12.34	5.41	13.3	12.5
2-6	0.91	3.74	2.25	8.42	7.66	14	13
2-7	1.15	2.44	2.25	5.49	6.29	15.5	14
2-8	1.04	2.99	2.24	6.71	6.97	13.5	13
2-9	1.14	2.87	2.33	6.69	7.63	14	12.5
2-10	1.74	2.04	1.98	4.04	7.03	13	12.5
2-11	1.71	2.45	2.09	5.13	8.71	14	13

The concentration of the elemental carbon decreased in station 5 to reach an average amount of 46-$\mu g/m^3$(Figure 4.13), and then gradually increased through station 6 and 7 to attain an average amount of 55-$\mu g/m^3$ (Figure 4.14 and 4.15).

Figure 4.13. Elemental carbon results obtained from station 2-5 in $\mu g/m^3$.

Figure 4.14. Elemental carbon results obtained from station 2-6 in $\mu g/m^3$.

Figure 4.15. Elemental carbon results obtained from station 2-7 in $\mu g/m^3$.

The elemental carbon level dropped again in station 8 to approach what it was in station 6 before dropping dramatically in station 9 to reach an average amount of 20-$\mu g/m^3$ (Figure 4.16 and 4.17).

Figure 4.16. Elemental carbon results obtained from station 2-8 in $\mu g/m^3$.

Figure 4.17. Elemental carbon results obtained from station 2-9 in $\mu g/m^3$.

The levels spiked quickly in the next two stations (10 and 11) to reach a maximum average amount of 65-$\mu g/m^3$ in station 11. This appears illogical since it was expected to be the lowest in the last station due the influence of the exhaust fan near it (Figure 4.18 and 4.19). More investigation is needed in this case; however, this did not occur in this study due to a time limitation.

Figure 4.18. Elemental carbon results obtained from station 2-10 in µg/m³.

Figure 4.19. Elemental carbon results obtained from station 2-11 in µg/m³.

All average amounts have been put together in one graph to provide a better picture of how the main exhaust fan performed in this scenario. It was concluded that the main exhaust fan did not perform well in this scenario, and the real time monitors indicate relatively low performance in giving steady readings in some stations (Figure 4.20).

Figure 4.20. Diesel emission behavior through the duct in Scenario 2.

4.2.3. Scenario 3. This scenario consists of six different stations; each one has a DPM real time monitor installed to measure the elemental carbon levels and concentrations. The first station recorded the highest average amount of elemental carbon with a maximum observed peak reaching 63-$\mu g/m^3$. This amount is considered to be low with respect to the DPM standard regulations, which means there was no serious hazard at that time (Figure 4.21).

Figure 4.21. Elemental carbon results obtained from station 3-1in $\mu g/m^3$.

There was no elemental carbon concentration recorded in station two, which led to questions for the reason of this result. The interpretation might have been due to the relationship between the leakage from the stopping adjacent to the station, the low emission from the engine exhaust, and the speed of the exhaust fan, which was at the maximum speed of 1550 rpm. Thus, it was concluded that the monitor could not record any concentration of elemental carbon at station 2.

The results obtained from station 3 showed relatively low concentrations of elemental carbon and recorded an average of 11-$\mu g/m^3$ with a peak reaching a maximum of 66-$\mu g/m^3$ (Figure 4.22).

Figure 4.22. Elemental carbon results obtained from station 3-3 in $\mu g/m^3$.

At the next station the average concentration increased by approximately 6-$\mu g/m^3$ with a relatively lower maximum concentration than the previous station, recording a maximum of 63-$\mu g/m^3$ (Figure 4.23).

Figure 4.23. Elemental carbon results obtained from station 3-4 in $\mu g/m^3$.

The concentration level dropped to the lowest in station 5 with an average of 9-$\mu g/m^3$, fluctuating between zero and a maximum of 23-$\mu g/m^3$ as shown in Figure 4.24. This may be due to the high air speed in that station according to Table 4.3.

Figure 4.24. Elemental carbon results obtained from station 3-4 in μg/m^3.

Table 4.3. Parameters of Scenario number 3.

Station	Average velocity m/s	Average width m	Average height m	Sectional area m^2	Air quantity m^3/s	Wet bulb temperature ℃	Dry bulb temperature ℃
3-1	2.65	3.74	2.25	8.42	22.3	17.5	19.5
3-2	3.65	2.95	2.03	5.99	21.86	17	18
3-3	3.27	2.99	2.24	6.71	21.9	17	17.5
3-4	3.86	2.87	2.33	6.69	25.8	17	18
3-5	5.5	2.04	1.98	4.04	22.2	17	17.5
3-6	5.35	2.45	2.09	5.13	27.45	16	16.5

Even though the last station has high air quantity as well as a relatively high air speed (Table 4.3), the elemental carbon concentration here was recorded to be the highest based on the calculated average concentration of 18-μg/m^3. The readings fluctuated between zero and a maximum of 32-μg/m^3 (Figure 4.25).

Figure 4.25. Elemental carbon results obtained from station 3-6 in μg/m^3.

The following graph illustrates the emission behavior through the duct from the source until the outtake shaft (Figure 4.26). It showed unstable recordings of elemental carbons, as displayed when it dropped from the twenties in station 1 to recording zero in the station 2. It then starts to increase significantly in the next two stations before it drops slightly and then increases to reach the maximum amount of elemental carbon. It seems that the high amount of elemental carbon in this station is because of the influence of the high speed exhaust fan where it gathers all contaminants in the airways at a final station before taking them out of the mine. The maximum speed of the main exhaust fan improved efficiency to keep the levels of the elemental carbon emissions coming from the bobcat very low.

Figure 4.26. Diesel emission behavior through the duct in Scenario 3.

4.2.4. Scenario 4. This scenario has the same set up as the previous one. One difference in this experiment was that the main exhaust fan speed was lower than Scenario 3, set at 1000 rpm. The only other difference made was the addition of two stations, to reach a total of eight stations that were equipped with real time monitors. The first station recorded the highest amount of elemental carbon with an average of 34-$\mu g/m^3$(Figure 4.27). Then the concentration reduced to its lowest average level of 15-$\mu g/m^3$(Figure 4.28). The concentrations later increased to reach an average elemental carbon of 30-$\mu g/m^3$ (Figure 4.29).

Figure 4.27. Elemental carbon results obtained from station 4-1 in μg/m^3.

Figure 4.28. Elemental carbon results obtained from station 4-2 in μg/m^3.

Figure 4.29. Elemental carbon results obtained from station 4-3 in μg/m^3.

Starting from station 3, the levels decrease continuously until reaching 18−$\mu g/m^3$, which is the minimum concentration in this scenario (Figure 4.30, 4.31, and 4.32).

Figure 4.30. Elemental carbon results obtained from station 4-4 in $\mu g/m^3$.

Figure 4.31. Elemental carbon results obtained from station 4-5 in $\mu g/m^3$.

Figure 4.32. Elemental carbon results obtained from station 4-6 in $\mu g/m^3$.

The elemental carbon increased by approximately 1-$\mu g/m^3$ in station eight before spiking to reach 20-$\mu g/m^3$ in the last station just prior to the exhaust fan taking the contaminated air out of the mine through the outtake shaft (Figure 4.33 and 4.34).

Figure 4.33. Elemental carbon results obtained from station 4-7 in $\mu g/m^3$.

Figure 4.34. Elemental carbon results obtained from station 4-8 in $\mu g/m^3$.

For a better understanding, the elemental carbon averages have been put together in Figure 4.35 to show how they behaved under experiment conditions It observed that the elemental carbon in Scenario 4 is reduced more than Scenario 1 when the exhaust fan speed was on 500 rpm. While that is higher than Scenario 3, where the fan speed was at the maximum of 1550 rpm, this scenario showed more stable behavior at 1000 rpm.

Figure 4.35. Diesel emission behavior through the duct in Scenario 4.

4.2.5. Scenario 5. As described earlier in section 3, this scenario has a different set up than the previous. The experiment has been moved to drift C to examine the diesel particulate matter emitted from an air compressor that was put at the head of the duct near the Wheeler main portal. The results showed very high concentrations of elemental carbon, which exceeded the regulated limit of DPM, under the influence of the main exhaust fan at a speed of 500 rpm. This scenario consisted of 6 stations, which were distributed along the drift.

The first station, which was right after the air compressor, recorded an average of 227-μg/m^3 of elemental carbon, and a maximum concentration around 308-μg/m^3 (Figure 4.36).

Figure 4.36. Elemental carbon results obtained from station 5-1 in μg/m^3.

The next station recorded a lower elemental carbon average at 206-μg/m^3. This station was quite close to station 1. The maximum observed peak was reaching approximately 261-μg/m^3 (Figure 4.37). The air compressor had less effect on the concentrations level in the current station than at station 1.

Figure 4.37. Elemental carbon results obtained from station 5-2 in μg/m^3.

The concentration level in station 3 increased by approximated 11-μg/m^3 with a maximum of approximately 270-μg/m^3 (Figure 4.38). The station after that then showed a dramatic increase of elemental carbon to reach an average of 271 μg/m^3 with maximum recordings of 359-μg/m^3 (Figure 4.39). These numbers are the maximum recorded in this scenario even though the air quantity and velocity were normal and quite close to the other quantities and velocities in other stations (Table 4.4). An observation is that this station was in a transition area where there was a door opened between stations 4 and 5, which could possibly have raised the concentrations before passing through.

Figure 4.38. Elemental carbon results obtained from station 5-3 in μg/m^3.

Figure 4.39. Elemental carbon results obtained from station 5-4 in μg/m^3.

Table 4.4. Parameters of Scenario number 5.

Station	Average velocity m/s	Average width m	Average height m	Sectional area m^2	Air quantity m^3/s	Wet bulb temperature ℃	Dry bulb temperature ℃
5-1	1.16	1.92	2.12	4.05	4.7	21.2	25.5
5-2	1.22	2.34	1.72	4.02	4.9	20.5	23.5
5-3	1.41	2.4	2.04	4.9	6.84	20.5	23
5-4	1.49	2.01	2.1	4.22	6.29	19.5	22
5-5	1.54	1.74	2.2	3.83	5.9	19.5	21.5
5-6	1.93	2.45	2.09	5.13	9.9	16.5	17.5

The elemental carbon decreased significantly in station 5 to reach a minimum average of 201-μg/m^3 in this scenario; however, the maximum records in this station remain high and reached 335-μg/m^3 (Figure 4.40). The concentration increased again in the last station to reach an average of 250-μg/m^3. Yet, the maximum recorded was 453-μg/m^3 and considered to be the highest since this experiment started (Figure 4.41).

Figure 4.40. Elemental carbon results obtained from station 5-5 in $\mu g/m^3$.

Figure 4.41. Elemental carbon results obtained from station 5-6 in $\mu g/m^3$.

The next graph (Figure 4.42) shows the behavior of DPM emission through drift C. Even though there are declines and rises, they are minor, which indicates that the emission acted steady under the effect of a 500 rpm main exhaust fan speed. The increase of elemental carbon in the last station is not known at the moment, but since this phenomenon was observed in prior scenarios, it is assumed to be normal for levels to increase before the outtake shaft depends on the exhaust fan speed.

Figure 4.42. Diesel emission behavior through the duct in Scenario 5.

4.2.6. Scenario 6. This repeats the same scenario as Scenario 5, but sped up the main exhaust fan to a middle speed of 1000 rpm. Since the high elemental carbons were observed in the previous scenario, this one will examine the effect of the exhaust fan at 1000 rpm and monitor the elemental carbon behavior and levels.

It is observed that the concentrations in this scenario remain high even though there is a significant reduction by approximately 50 to 100-$\mu g/m^3$. These concentrations are hazardous and need to be reduced as much as possible to provide a clean and healthy underground environment.

The highest concentration was recorded in the first station with an approximated average of 220-$\mu g/m^3$before it dropped to around 140-$\mu g/m^3$ in the next station (Figure 4.43 and 4.44). The first two stations had some rising peaks, showing the maximum readings obtained in this experiment at 300 and 175-$\mu g/m^3$ respectively.

Figure 4.43. Elemental carbon results obtained from station 6-1 in $\mu g/m^3$.

Figure 4.44. Elemental carbon results obtained from station 6-2 in µg/m^3.

The concentration level has increased again in the third station by approximately 24-µg/m^3 and continued to decrease and increase in the following two stations, remaining between 145 and 170-µg/m^3 with almost no difference in the maximum reading between stations 4 and 5 at roughly 200-µg/m^3 (Figure 4.45, 4.46, and 4.47).

Figure 4.45. Elemental carbon results obtained from station 6-3 in µg/m^3.

Figure 4.46. Elemental carbon results obtained from station 6-4 in µg/m^3.

Figure 4.47. Elemental carbon results obtained from station 6-5 in µg/m^3.

Unlike scenario 5, it was observed that the concentration of elemental carbon reduced in the last station compared to the other stations in the current scenario (Figure 4.48). Figure 4.49 illustrates the behavior of the emission during this experiment and demonstrates steady levels with some moderate drops and rises except for the first big drop from station 1 to 2.

Figure 4.48. Elemental carbon results obtained from station 6-6 in µg/m^3.

Figure 4.49. Diesel emission behavior through the duct in scenario 6.

4.2.7. Scenario 7. This experiment was run with a maximum exhaust fan speed of 1550 rpm. This speed resulted in a good reduction in average DPM compared to the previous scenario where the average concentrations were reduced below 100-$\mu g/m^3$ with some peaks reaching above 140-$\mu g/m^3$. The first station of this scenario that recorded the highest average to be approximately 140-$\mu g/m^3$with maximum recording of 204-$\mu g/m^3$(Figure 4.50).

Figure 4.50. Elemental carbon results obtained from station 7-1 in $\mu g/m^3$.

The average concentrations decreased immediately at stations 2 and 3 to maintain averages between 90 and 95-$\mu g/m^3$ with some peaks displaying a maximum amount of 132-$\mu g/m^3$and 145-$\mu g/m^3$ respectively (Figure 4.51 and 4.52). This immediate drop was likely caused by the large amount of leakage coming from the plastic sheet brattice located adjacent to station 2, which barley kept sealed under the pressure of high air velocity (Table 4.5).

Figure 4.51. Elemental carbon results obtained from station 7-2 in $\mu g/m^3$.

Figure 4.52. Elemental carbon results obtained from station 7-3 in μg/m^3.

Table 4.5. Parameters of Scenario number 7.

Station	Average velocity m/s	Average width m	Average height m	Sectional area m^2	Air quantity m^3/s	Wet bulb temperature ℃	Dry bulb temperature ℃
5-1	2.52	1.92	2.12	4.05	10.21	21.5	25
5-2	3.82	2.34	1.72	4.02	15.36	22	20
5-3	3.91	2.4	2.04	4.9	19.16	19.5	21.5
5-4	4.29	2.01	2.1	4.22	18.1	19.5	21
5-5	4.4	1.74	2.2	3.83	16.85	19	20
5-6	5.83	2.45	2.09	5.13	29.91	17	17.5

The average concentration decreased to 86-μg/m^3 in station 4, with some maximum recordings to remain at nearly 140-μg/m^3(Figure 4.53). The levels then began to increase again slightly in the last two stations, 5 and 6, which maintained an amount between 90 to 97-μg/m^3 with a relatively significant maximum hit of 156-μg/m^3 in the last station (Figure 4.54).

Figure 4.53. Elemental carbon results obtained from station 7-4 in $\mu g/m^3$.

Figure 4.54. Elemental carbon results obtained from station 7-6 in $\mu g/m^3$.

This scenario showed steady flow through drift C. The contaminant concentrations in this scenario started slightly high than 140-$\mu g/m^3$ before decreasing immediately to remain between 80 and 100-$\mu g/m^3$ for the whole experiment. Even though there was positive reduction compared to scenarios 5 and 6, this reduction amount was not enough to provide maintenance of a healthy and comfortable working environment for underground workers. On the other hand, the main exhaust fan showed beneficial performance with the diesel source, and provided steady and smooth airflow without any turbulence like that, which occurred in the first few scenarios of this research (Figure 4.55).

Figure 4.55. Diesel emission behavior through the duct in Scenario 7.

4.2.8. Scenario 8. This scenario was made to compare results with scenario two using the same diesel source, the small bobcat loader. This scenario was influenced by a 1000 rpm exhaust fan speed, where scenario 2 was affected by the 500 rpm exhaust fan speed. The average concentrations were relatively decreased to remain below 50-$\mu g/m^3$. Important observations of elemental carbon concentrations will be described in this scenario for easier comparison.

The concentration in the first station near the intake shaft appears to be an average of 20-$\mu g/m^3$, approximately. Most of collected samples in this station give zeros with a few peaks reaching the maximum of 80-$\mu g/m^3$ (Figure 4.56).

Figure 4.56. Elemental carbon results obtained from station 8-1 in $\mu g/m^3$.

The average concentration level then slightly increased in the second station with a maximum of 101-$\mu g/m^3$ and some peaks remained between 50 and 51-$\mu g/m^3$ (Figure 4.57). The average level dropped down again at the third station to roughly 11-$\mu g/m^3$. The initial measurements in this station remained as low as zero before they suddenly jumped to a maximum around 82-$\mu g/m^3$ (Figure 4.58).

Figure 4.57. Elemental carbon results obtained from station 8-2 in $\mu g/m^3$.

Figure 4.58. Elemental carbon results obtained from station 8-3 in $\mu g/m^3$.

The highest average concentration of elemental carbon was recorded in station 4 with a maximum of approximately 55-$\mu g/m^3$ (Figure 4.59). The parameter measurements in that station showed that there was very low air velocity and quantity (Table 4.6), which causes the elemental carbons to concentrate in that area without any adequate amount of air reaching that station to clean it from contaminants.

Figure 4.59. Elemental carbon results obtained from station 8-4 in $\mu g/m^3$.

Table 4.6. Parameters of Scenario number 8.

Station	Average velocity m/s	Average width m	Average height m	Sectional area m^2	Air quantity m^3/s	Wet bulb temperature ℃	Dry bulb temperature ℃
8-1	2.25	2.25	2.06	4.64	10.44	14.5	16.5
8-2	1.68	2.49	2.09	5.20	8.74	14	16
8-3	2.26	2.15	2.07	4.45	10.11	14	16
8-4	0.75	2.16	2.06	4.45	3.34	14	15.5
8-5	0.79	3.93	3.14	12.34	9.72	13.5	15
8-6	1.73	3.74	2.25	8.42	14.57	13.5	14
8-7	2.44	2.44	2.25	5.49	13.41	13.5	14.5
8-8	1.99	2.99	2.24	6.71	13.33	13.5	14
8-9	2.36	2.87	2.33	6.69	15.75	13.5	14
8-10	3.53	2.04	1.98	4.04	14.26	13.5	14
8-11	3.40	2.45	2.09	5.13	17.44	13.5	14

The contaminated air was reduced by approximately 10-μg/m^3 in the transition station between drift A and drift B, which called station 5 in this scenario. The maximum amount recorded in this station was relatively lower than the others at around 54-μg/m^3 (Figure 4.60).

Figure 4.60. Elemental carbon results obtained from station 8-5 in μg/m^3.

The average level fell at station 6 to the lowest in this scenario, and in the entire experiment, where only one peak showed a maximum of approximately 83-μg/m^3 and the rest of collected samples were measured as zeros. The average amount of this station was calculated to be around 3-μg/m^3 (Figure 4.61). There is no observed evidence that can explain the reasons behind this result. The only thought is that the real time monitor did not perform well in this station.

Figure 4.61. Elemental carbon results obtained from station 8-6 in μg/m^3.

The elemental carbon levels were raised in station 7 to 18-μg/m^3 with a maximum of 55-μg/m^3 before they again declined to about 15-μg/m^3 with a higher maximum peak of 82-μg/m^3. (Figure 4.62, and 4.63).

Figure 4.62. Elemental carbon results obtained from station 8-7 in μg/m^3.

Figure 4.63. Elemental carbon results obtained from station 8-8 in μg/m^3.

The average concentrations levels again increased and remained almost at the same levels for the last three stations between 20 and 24-μg/m^3. Only a few peaks showed in stations 9, 10 and 11 with the highest maximum amount of 168-μg/m^3 in the last station itself (Figure 4.64, 4.65, and 4.66).

Figure 4.64. Elemental carbon results obtained from station 8-9 in $\mu g/m^3$.

Figure 4.65. Elemental carbon results obtained from station 8-10 in $\mu g/m^3$.

Figure 4.66. Elemental carbon results obtained from station 8-11 in $\mu g/m^3$.

The diesel particulate matter or the elemental carbon specifically performed a turbulent movement through drifts A and B. A few real time monitor results, such as the ones in stations 3 and 6, did not perform accurately under the conditions of this scenario or with the enhancement of the diesel source (small bobcat loader), which was located adjacent to the intake shaft. The overall observation was that the concentrations of elemental carbon were reduced compared to the related scenario (Scenario 2). The following graph illustrates the drops and rises that were recorded during this scenario by the real time monitors (Figure 4.67).

Figure 4.67. Diesel emission behavior through the duct in Scenario 8.

4.2.9. Scenario 9. This scenario has the same set up as scenarios 1, 3, and 4. The air compressor was used instead of the small bobcat loader, where it was placed near the Kennedy main portal. 500 rpm main exhaust fan speed was utilized to examine the diesel reduction and levels in the mine. The diesel source emitted a lot of diesel through the duct where they exceeded the permitted concentration of diesel particulate matter.

The results from the first station, which was right behind the diesel source, showed a relatively moderate average concentration at approximately 125-μg/m^3 with a maximum is around 50-μg/m^3 more than the average (Figure 4.68).

Figure 4.68. Elemental carbon results obtained from station 9-1 in μg/m^3.

The concentration in the second station jumped dramatically to cross the boundary of 200-μg/m^3. The average was found to be around 290-μg/m^3 with the maximum recorded at approximately 430-μg/m^3 (Figure 4.69). These amounts are extremely high with respect to the mine size that this experiment was conducted in.

Figure 4.69. Elemental carbon results obtained from station 9-2 in μg/m^3.

The average concentration reduced in the third station by almost 50-μg/m^3 to reach an average of roughly 240-μg/m^3. The maximum recording eventually decreased to remain between 300 and 400-μg/m^3 (Figure 4.70).

Figure 4.70. Elemental carbon results obtained from station 9-3 in µg/m^3.

The average level of elemental carbon reduced more in the fourth station, by approximately 30-µg/m^3, to get an average of 211-µg/m^3. There are several peaks shown in the following graph (Figure 4.71), they represent the highest level of elemental carbon where the maximum level reached around 340-µg/m^3.

Figure 4.71. Elemental carbon results obtained from station 9-4 in µg/m^3.

The average concentrations increased by approximately 20-µg/m^3. It remains at 230-µg/m^3 in both stations 5 and 6 with almost the same maximum amount recorded in these stations. Some peaks appeared in both stations, showing a maximum amount reached between a range of 230 to 240-µg/m^3 (Figure 4.72 and 4.73).

Figure 4.72. Elemental carbon results obtained from station 9-5 in $\mu g/m^3$.

Figure 4.73. Elemental carbon results obtained from station 9-6 in $\mu g/m^3$.

The elemental carbon concentrations remain almost at the same range in station 7 as the last two scenarios. However, the average concentration has dropped to roughly 190-$\mu g/m^3$ with a maximum of about 290$-\mu g/m^3$ (Figure 4.74).

Figure 4.74. Elemental carbon results obtained from station 9-7 in $\mu g/m^3$

The following graph (Figure 4.75) is showing how the diesel emission reacted through the drift. It shows how the concentration jumped from the first station to the second and then decreased continuously until station 4. The levels have slightly increased in the next two stations before it passed through a small reduction in the last station at the outtake shaft. The flow of the emission in this scenario is steady with no real turbulence under the influence of both the 500 rpm main exhaust fan speed and the high emissions coming from the air compressor.

Figure 4.75. Diesel emission behavior through the duct in Scenario 9.

4.2.10. Scenario 10. Elemental carbon has shown good reduction in this scenario under the enhancement of 1000 rpm exhaust fan speed. Even though it is not enough reduction to keep the concentrations at or below the regulated limit of 160-$\mu g/m^3$. The elemental carbon concentrations were seen to be reduced by dilution as the exhaust fan speed increased.

The first station recorded the lowest range to be between 70 to 80-$\mu g/m^3$ with an average of approximately 46-$\mu g/m^3$. There is one peak at a maximum measurement of about 152-$\mu g/m^3$ (Figure 4.76).

Figure 4.76. Elemental carbon results obtained from station 10-1 in μg/m^3.

The concentrations increased in the second station to keep between 160-μg/m^3 to a maximum of 230-μg/m^3 with an average of approximately 165-μg/m^3 (Figure 4.77).

Figure 4.77. Elemental carbon results obtained from station 10-2 in μg/m^3.

The average concentration decreased in station 3 of this scenario to approximately 120-μg/m^3. Most of the concentrations were between the ranges of 70 to 170-μg/m^3 with one peak at the maximum concentration of roughly 235-μg/m^3. This maximum peak showed up when the measurement began in this station before it dropped down and kept between the mentioned ranges (Figure 4.78).

Figure 4.78. Elemental carbon results obtained from station 10-3 in $\mu g/m^3$.

The elemental carbon then increased again in station 4 to record an average of roughly 133-$\mu g/m^3$. The elemental carbons measured by the real time monitor were between 150 to a maximum of 210-$\mu g/m^3$ (Figure 4.79).

Figure 4.79. Elemental carbon results obtained from station 10-4 in $\mu g/m^3$.

Station 5 was cancelled due an issue with the monitor installed at that station. Therefore, the measurement will continue from station six. The results from station six showed an increasing in the average concentration that was recorded to be approximately 130-$\mu g/m^3$. The elemental carbon ranges were between 119-$\mu g/m^3$ to a maximum of 187-$\mu g/m^3$ (Figure 4.80).

Figure. 4.80. Elemental carbon results obtained from station 10-6 in $\mu g/m^3$.

The last station results, showed a reduction in the elemental carbon levels to be mostly in a range between 60 and 135-$\mu g/m^3$ with an average of around 108-$\mu g/m^3$. The maximum amount of elemental carbon was about 200-$\mu g/m^3$ as represented in one peak in the following graph (Figure 4.81).

Figure 4.81. Elemental carbon results obtained from station 10-7 in $\mu g/m^3$.

The average amounts of elemental carbons in all stations of this scenario were reduced more than the previous scenario. With 1000 rpm exhaust fan speed; there was no turbulence in the contaminated airflow except for a minor one observed through stations 1, 2 and 3 according to (Figure 4.82). The following graph illustrates how the diesel particulate matter flew through the drift with steady flow and a small reduction at the last station.

Figure 4.82. Diesel emission behavior through the duct in Scenario 10.

4.2.11. Scenario 11. This scenario is repeating scenarios 9 and 10 but increasing the exhaust fan speed to a maximum of 1550 rpm. Another station was added to this scenario to get as many readings as possible to make any clear deduction in the drift.

The first station has recorded the lowest elemental carbon concentrations with an average of 32-$\mu g/m^3$approximately. There were few volatile readings according to Figure 4.83. The maximum reading was at the beginning of the measurements and was estimated at 75-$\mu g/m^3$with lowest reading found to be around 15-$\mu g/m^3$.

Figure 4.83. Elemental carbon results obtained from station 11-1 in $\mu g/m^3$.

The elemental carbon level increased in the second station to reach an average of approximately 98-$\mu g/m^3$. Most of the samples concentrations captured by the real time monitor were between 80 and 140-$\mu g/m^3$ except one peak showed a maximum reading of 165-$\mu g/m^3$ (Figure 4.84).

Figure 4.84. Elemental carbon results obtained from station 11-2 in μg/m^3.

The concentration kept increasing in the third station to keep mostly between 100 and 150-μg/m^3 with an average of 113-μg/m^3, approximately. One peak showed up at the end of the measurement to reach nearly 200-μg/m^3 (Figure 4.85).

Figure 4.85. Elemental carbon results obtained from station 11-3 in μg/m^3.

The concentration level has decreased in station 4 to be between 85-μg/m^3 and a maximum amount of 140-μg/m^3 with an average of 85-μg/m^3. One peak was found to represent the lowest recorded concentration of around 45-μg/m^3 (Figure 4.86).

Figure 4.86. Elemental carbon results obtained from station 11-4 in $\mu g/m^3$.

The elemental carbon average slightly increased in station 5 more than the previous station to get an average concentration of about 56-$\mu g/m^3$. Most of the measured concentrations were between 90-$\mu g/m^3$ and a maximum of nearly 150-$\mu g/m^3$ (Figure 4.87).

Figure 4.87. Elemental carbon results obtained from station 11-5 in $\mu g/m^3$.

The results obtained from station 6 of this scenario illuminate fluctuation in the readings, which is illustrated in Figure 4.88. The average concentration was found to be around 108-$\mu g/m^3$ with a maximum concentration of approximately 150-$\mu g/m^3$ and lowest reading to be around 105-$\mu g/m^3$.

Figure 4.88. Elemental carbon results obtained from station 11-6 in μg/m^3.

There was a very small reduction in the average concentration of elemental carbons in station 7 which were estimated to be 102-μg/m^3. The overall concentrations were between 100-μg/m^3 to a maximum of 156-μg/m^3 (Figure 4.89).

Figure 4.89. Elemental carbon results obtained from station 11-7 in μg/m^3.

Incompatible readings were found in the last station (Station 8). These contradictory readings might be due to the effect of the high-speed exhaust fan at that station, where it is adjacent to the exhaust shaft. However, the average concentration was reduced to reach approximately 73-μg/m^3. The maximum reading was in excess of 160-μg/m^3 before it dropped to the lowest concentration of 40-μg/m^3 (Figure 4.90). This occurrence was unexpected and there is no clear explanation for it.

Figure 4.90. Elemental carbon results obtained from station 11-8 in µg/m^3.

The overall average concentrations through the drift in this scenario were reduced below 120-µg/m^3. The high exhaust fan speed performed well in reducing the concentrations below the regulated limit of 160-µg/m^3 even though the target was to reduce it more than 120-µg/m^3. The lowest average in this scenario was at the first station, before it increased in the next stations and then reduced again in the last one (Figure 4.91).

Figure 4.91. Diesel emission behavior through the duct in Scenario 11.

4.3. CONCLUSION

The main exhaust fan performed well in reducing the diesel contamination in the underground mine. The real time monitors (Airtec) gave relatively good readings in detecting the elemental carbon emitted from the sources. Yet, the monitors have shown some weaknesses in measuring the concentrations of elemental carbon coming from the small bobcat loader, which emitting a low quantity of diesel emissions. On the contrary, stable and more reliable readings were found when the air compressor was used in some scenarios because of high diesel quantities that were being emitted form it.

For more understanding, the average graphs from related scenarios will be complied together in one graph to observe the effect of different exhaust fan speeds with respect to the diesel source type and how well the monitors performed.

In scenarios 1, 3 and 4, the mine setups were the same, where the small bobcat loader was used as a diesel source to supply drift B with diesel emission. It was placed near the main Kennedy portal. Three different exhaust fan speeds were used: 500 rpm in Scenario 1, 1550 rpm in Scenario 3, and finally 1000 rpm in Scenario 4. The emission from the bobcat was not high and did not exceed 70-μg/m^3. Therefore, the main exhaust fan was able to reduce the concentration by 10 to 50-μg/m^3. There was some turbulence in the readings in Scenario 1 under the influence of 500 rpm main exhaust fan. The readings showed more steady flow in Scenario 4 when the speed of the exhaust fan was at 1000 rpm. More reductions were observed at 1550 rpm in Scenario 3, which were at and below 20-μg/m^3 with little more turbulence than that displayed in Scenario 4 but less than Scenario 1 (Figure 4.92).

Figure 4.92. The comparison of Scenarios 1,3, and 4.

The small bobcat loader was moved to drift A where it was placed adjacent to the intake shaft. The natural fresh air enters the mine through the intake shaft and is contaminated immediately by the diesel emission coming out of the bobcat. The contaminated air would then flow through drift A, then B, and was pulled by the main exhaust fan attached at the surface of the exhaust shaft. Scenarios 2 and 8 were applied in this setup, where Scenario 2 was influenced by a 500 rpm exhaust fan speed and Scenario 8 was influenced by a 1000 rpm exhaust fan speed. The concentrations of elemental carbon detected by the real time monitors were very low, below 70-$\mu g/m^3$. Even though there was a reduction by approximately 10 to 40-$\mu g/m^3$, there was high turbulence in both scenarios as shown in Figure 4.93.

Figure 4.93. The comparison of Scenarios 2 and 8.

The diesel source was then changed to use the air compressor instead of the bobcat. It was placed in drift C near the main Wheeler portal. It was observed that the elemental carbon concentrations emitted were very high and reached more than 250-$\mu g/m^3$. Three scenarios were set up based on the main exhaust fan speed while both the main intake shaft and the main Wheeler portal were opened to allow fresh air to enter the mine. Scenario 5 was influenced by the 500 rpm main exhaust fan. The speed then increased to 1000 rpm in Scenario 6. It was at the maximum of 1550 rpm in Scenario 7. There was little flow turbulence in the drift in Scenario 5 before it became steadier in Scenarios 6 and 7. Eventually, the main exhaust fan was able to reduce the concentrations of elemental carbon below the regulated limit of 160-$\mu g/m^3$ at 1550 rpm. However, it might need more air source or influence to reduce more of these concentrations (Figure 4.94).

Figure 4.94. The comparison of Scenarios 5,6, and 7

The last set of experiments was to use the air compressor in drift B, where it was placed near main Kennedy portal. This set is similar to the first discussed set in this conclusion (Scenario 1,3, and 4). The difference is the diesel source as the air compressor emitted much larger concentrations of diesel particulate matter. The concentrations reached nearly 300-μg/m^3 in Scenario 9 under the influence of a 500 rpm exhaust fan speed. When increasing the fan speed to 1000 rpm in Scenario 10, the concentrations were reduced to 160-μg/m^3 and below. The fan showed good capability at a maximum speed of 1550 rpm in Scenario 11 in reducing the concentrations below 140-μg/m^3 to ensure a safe environment. For more reduction, more fresh air sources may be needed, such as blowing fan (Figure 4.95).

Station

Figure 4.95. The comparison of Scenarios 5,6, and 7.

5. CONCLUSION

Diesel particulate matter has represented a lot of concerns in the mining industry in the last decade. It became a serious health issue after observation of workers who are highly exposed to diesel emissions and became severely ill. The medical researchers have found that exposure to diesel emissions can cause diseases as those, the lung diseases. Lung cancer is most likely to happen when a miner is overexposed to diesel emission, which can be lethal.

To ensure a safe and comfortable underground environment, many mining agencies have got together to set up regulations and rules to avoid potential hazards in the underground environment. Therefore, the final rule came up in 2008 by the Mine Safety and Health Administration (MSHA) to regulate the diesel emission and the Diesel Particulate Matter that must not exceed 160-$\mu g/m^3$ for both elemental carbon (EC) and total carbon (TC) that contains elemental and organic carbon.

Since this regulation it has become vitally important to find a way to dilute the diesel particulate matter and diesel emission. By monitoring through the use of portable sampling and analyzing instruments to maintain emissions to the lowest level possible in underground openings. Ventilation also plays an important role in this situation by utilizing air to push contaminants away and clean the openings. Using helpful tools to enhance the air inside the mine is particularly preferred in large mines as well. Fan systems are furthermore a significant element in any ventilation plan than is able to regulate the airflow in a mine as well as dilute any hazardous contaminant.

This research examined the effect of the exhaust fan alone in diluting diesel emissions in the experimental mine (which was a small mine), and the overall efficiency of the real time monitor in giving an accurate readings.

The research was conducted at Missouri University of Science and Technology's Experimental Mine. Eleven scenarios were applied in the mine based on the diesel sources and exhaust fan speeds. Real time monitors (Airtec) were used in all scenarios to monitor and give instant readings of elemental carbon concentrations.

The small bobcat loader emitted low concentrations of diesel particulate matter and elemental carbon. The main exhaust fan alone was able to dilute the concentrations of elemental carbon, even though there was some turbulence in the gas flow itself through drifts, as described in the related graphs in Section 4. However, the real time monitors might not be adequate in situations that may give unclear results under a condition of low emission of diesel particulate matter with higher ventilation flow.

On the other hand, the air compressor released a large amount of diesel particulate matter and elemental carbon, which exceeded the regulated limit approved by the Mine Safety and Health Administration (MSHA). The real time monitors performed well under this large emission, and gave clear readings about the traveling gas concentrations through drifts. Yet, the exhaust fan alone was not enough to reduce the concentrations with the air compressor. The exhaust fan’s maximum and moderated speeds were able to dilute the concentrations below the regulated limit, yet the objective was to reduce it to the lowest possible amount. To achieve that, the research suggests another fresh air source may be needed. For instance, the main blow fan might be helpful in pushing more fresh air through the drift and cleaning it from contaminates. Also, opening the main portals can affectively reduce the contaminants and may even eliminate them. These suggestions should be consider at the basis for conducting further research and experimentation on this matter.

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