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

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Introduction

Background

Diesel Particulate Matter (DPM) has been a critical issue during the last decade in underground mines. This problem is threatening the 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 in the underground environment. Miners who are exposed to this kind of emission are at high risk for developing lung cancer and other lung diseases. The Mine Safety and Health Administration (MSHA) has issued standard rules to regulate diesel emissions in underground mines. The final ruling confirmed in 2008 that the total carbon should not exceed 160 $\mu g/m^3$. (MISHA, 2008)

Monitoring DPM in underground mines has become important to ensure compliance with the MSHA regulations. There are many different types of DPM monitoring systems that are currently being used in underground mines. 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. Many mines do not recommend using the direct exhaust sampling method since it involves complex measuring equipment and procedures, as well as it is not regulated in the United States or Canada. Thus, the personal sampling method is the preferred method in many mines 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. Since the diesel particles are less than 0.9 micron, this impactor does not allow particles more than 0.9 microns to be collected in the cassette filter. The cassette is then analyzed in a lab and the concentrations of organic carbon (OC), elemental carbon (EC), and total carbon (TC) are determined. 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.

Problem statement

Diesel particulate matter (DPM) has become a significant health issue in the last decade. There is limited research on monitoring these exhaust emissions in relation to 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.. However, reducing the numbers of these additions as much as possible can save money and help avoid complicated ventilation plans. The goal of integrating these equipment supports is to ensure that the polluted air being removed from the mine, does not contaminate the fresh air being drawn into the mine.

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

Ventilation has 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 is enhanced by a main surface fan which boosts the inside flow. The air flows through the intake airways to supply the working faces with fresh air. The air will then take contaminants through the return airways to prepare for exit through the exhaust shaft where, typically, there is a main exhaust fan to assist in pulling the unwanted air out of the mine (McPherson, 1993). The

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ventilation design might 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 faces 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.

Exposure to diesel particulate matter has raised very significant health concerns in underground mines. DPM is considered the most hazardous contaminant to health because DPM particles are typically less than one micron in size. Particles this small can be inhaled deeply into the lungs, significantly increasing the probability that they will 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 typically inhales about 10 m^3 of air per day. These inhalations may be susceptible to toxic components, 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, oxidative stress, lung cancer, and death due to high exposure to DPM. (Ristovski et al. 2012)

The Air Resources Board, 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 (California Environmental Protection Agency, 2004). 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 (OSHA, 2013). 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. This study strongly links that DPM as a primary casual factor for 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 to exposure to DPM emissions.

DPM monitoring

Throughout the past several years, DPM has become a serious issue within underground mines due the better understanding of the danger of DPM. 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 (EC) and organic carbon (OC). 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), personal exposure monitoring and direct exhaust samplings are the commonly used methods for sampling and monitoring DPMs.

Elemental carbon method (EC) is one of the personal exposure monitoring methods. The sampling devise in this method consists of the submicron impactor attached to the cyclone, where the air flows through the impactor that prevents respirable dust particles larger than 0.9 micron in size to enter into the filter cassette (Figure 1). 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 et al. 2001)

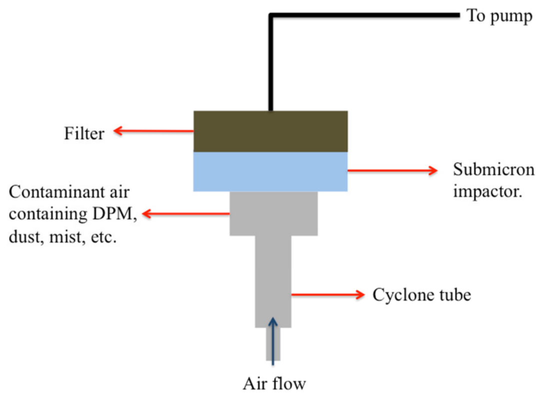

Figure 1. Illustrates the Elemental carbon collecting sample device.

The elemental carbon (EC) method was developed by NIOSH and it is called NIOSH 5040 method. The NIOSH 5040 method gives accurate readings. Unfortunately, it is not widely used and only few instruments are available. However, as long as new MSHA's rules came to regulate the exposure limits of DPM, 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 et al. 2001).

NIOSH has developed a thermal-optical method. This method 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 (EC) and organic carbon (OC) 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)

This thermal-optical method allows a real time monitoring. This method is quite similar to the NIOSH 5040 method, but in real-time. The real time monitoring gives an instant measurement and readings with almost the same accuracy as NIOSH 5040 method.

Wu, Gillies, Volkwein, and Noll (2009) conducted a study to test the accuracy of the real time monitoring approach in underground mines. The research was conducted in six Australian mines designated 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 good results. The DPM information obtained by real time monitoring can provide a greater understanding of the underground environment and for engineering evaluation exercises.

Arnott, Arnold, Mousset-Jones, and Shaff (2008) also 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, at two sites within declining drifts at Barrick Goldstrike Meikle gold mine in Nevada, USA. They used different real time instruments to determine the DPM components. The Dusttrak Nephelometer was used to determine the total carbon, and a Photoacoustic measurement was used 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.

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.

The National Institute for Occupational Safety and Health (NIOSH) conducted a research study in various mines to improve working conditions for miners in the United States. 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, 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 both natural ventilation, and utilization of auxiliary fans for ventilation inside the mine. Yet, 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 (Krog et al. 2004). The ventilation system through the entire mine should be considered in order 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 also appropriate to dilute and split the contamination based on NIOSH recommendations. (Krog et al. 2004)

Objective

This research will concentrate on the behavior of diesel particulate matter under the influence of a particular ventilation scenario and relate it to the efficiency of using a real time DPM monitoring method. Doors, stoppings, main portals, and main shafts have been utilized to regulate the intake and outtake airways to simulate a real mine situation and provide more accurate measurements through this research. Also, consideration will be given to the use of 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.

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 2)

The Experimental Mine serves the Mining and Nuclear Engineering department, 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 to apply new applications in support of their studies and research.

Figure 2. The location of Missouri S&T experimental mine (Google maps, 2015)

Methodology

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. 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.

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

A real time monitoring instrument, Airtec, was used to measure the diesel particulate matter in the mine. This instrument instantly measures the elemental carbon that comes out of an exhaust engine The Airtec design is similar to the NIOSH 5040 method 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. The Airtecs were positioned at elevation of about 4 m in all stations, which is in the middle of the drift height. (Figure 3).

Figure 3. Real time DPM measurement instrument (Airtec).

Dimension and distance measurements were taken using a laser tape measure.

Mine preparation

An appropriate approach in any mine, as discussed earlier, is to split the mine into two main parts: 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 occurs 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 for the research scenario.

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.

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 12 kW exhaust fan (Figure 4). 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.

Figure 4. The exhaust fan at the Experimental Mine at Missouri S&T.

EXPERIMENTAL METHOD

The scenario was applied in this experiment under three different main exhaust fan speeds (500, 1000, and 1550 rpm). An air compressor that puts out up to 700 kPa of air was placed in the head of one of the drifts in the mine to emit diesel through that drift and allow for DPM measurements. (Figure 5). The real time monitor (Airtec) was placed at an elevation of 1.20 m in all stations.

(Figure 5). Diesel source (air compressor).

The emissions from this source were compared in the scenario and related to the efficiency of the main exhaust fan. 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. The temperature was taken using a hygrometer. This information

Scenario setup

The air compressor was placed in drift B near the Kennedy portal, 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 three different speeds of 500, 1000, and 1550 rpm respectively. 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 through the drift to measure the elemental carbon during the experiment. Also, velocity, dimension, and temperature measurements were taken at each of the eight stations. (Figure 6).

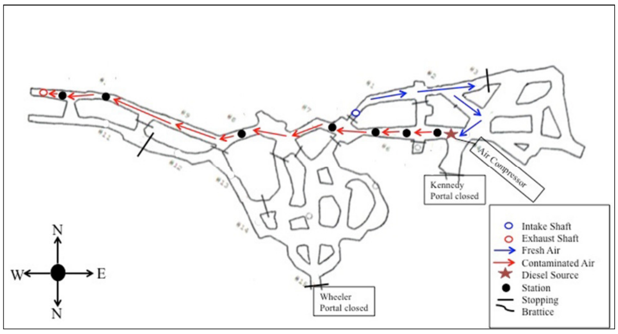

Figure 6. Mine setup.

Results and discussion

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.

The air compressor emitted large concentrations of diesel particulate matter, as measured by the Airtec instrument at all stations_. At station 1, which was located about 5 m away from the compressor, then the Airtecs were placed around 20 m away from each other. The concentrations reached nearly 300-$\mu g/m^3$ under the influence of a 500 rpm exhaust fan speed. When increasing the fan speed to 1000 rpm, the concentrations were reduced to 160-$\mu g/m^3$ and below. The fan showed good capability at a maximum speed of 1550 rpm in reducing the concentrations below 140-$\mu g/m^3$ to ensure a safe environment. Figure 6 shows the DPM concentrations under the influence of three exhaust fan speeds. It illustrates the impact of the exhaust fan on reducing the concentrations. The real time monitors performed well in this experiment as they gave steady readings with high emission form the diesel source. However, the average readings from first stations in all scenarios were the lowest between the others before the DPM concretions spiked to the highest concentrations. Even though the first station was the closest to the diesel source, but the only interpretation that the resistance was low at this station because of the air leakage and other additional fresh air source that keep the DPM concentrations at the lowest amount.

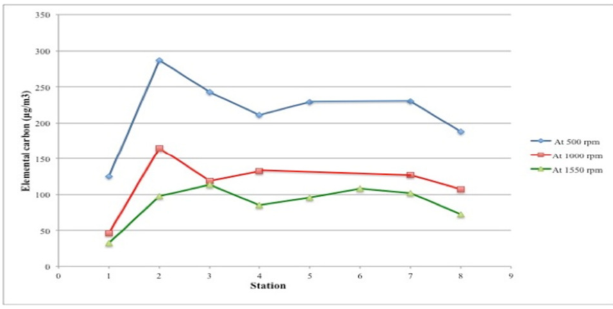

Figure 6. Comparison results at three different exhaust fan speeds.

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), with the use of real time monitoring system.

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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