SME Annual Meeting
Feb. 21 - 24, 2016, Phoenix, AZ

Preprint 16-037

REAL-TIME DIESEL PARTICULATE MATTER MONITORING IN MINES A REVIEW

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ABSTRACT

Diesel exhaust is a major cause of large number of occupational diseases. Acute and continuous exposure to Diesel Particulate Matter (DPM) can cause numerous health issues including respiratory disease, reduced lung capacity, heart disease etc. The National Institute of Occupational Safety and Health (NIOSH) and the International Agency for Research on Cancer (IARC) consider diesel engine exhaust as carcinogenic. In large underground metal and nonmetal mining operations, regulatory compliance regarding miner's exposure to airborne particles especially DPM is a big challenge. Complex mine networks add more difficulties in controlling DPM. MSHA relies on the NIOSH 5040 method for DPM compliance. The NIOSH 5040 method is a shift average based method which inherits some limitations. Due to these inherent limitations of the NIOSH 5040 method the concept of real-time DPM monitoring is promoted in the mining industry. Several real-time DPM monitors have been used by the researchers and efforts still continues to improve their measuring techniques and understanding. Real-time monitoring of DPM is vital to gain understanding of rapid changes in the mine atmosphere. The current study highlights the advancement in real-time DPM monitoring and mainly covers a review of several studies in which DPM concentrations were measured by utilizing real-time DPM monitors.

INTRODUCTION

Ventilation of underground mines is an important aspect of mining operations. Mining is a continuous activity and the ventilation networks in modern mines change with extended developments. Proper understanding of the ventilation network is a key design factor of an optimum mine ventilation plan. An important task of underground mine ventilation engineers is to provide clean air with sufficient quantity to the underground miners (Khan M. U. and Gillies A.D.S. 2015). The amount of fresh air supplied to the mine should be adequate to dilute the concentrations of contaminants present in the mine atmosphere.

In the United States it is estimated that diesel powered equipment is used in thousands of mining operations (Stephenson D. J. et al. 2006). Use of diesel powered equipment is an attractive option in underground mines due to its several advantages over other available alternates. Diesel engines are rugged, dependable and fuel efficient (McKinnon 1999). It is common for diesel engines in heavy duty trucks to have a life of 1.6 million kilometers (McKinnon 1999). Looking at the developments in other energy alternatives, it can be assumed that the underground mining industry will maintain its reliance on diesel powered equipment (Anon 2001).

DPM is an important source of mine air contamination in many non-gassy underground mines (Khan M. U. and Gillies A.D.S. 2015). Diesel exhaust is harmful for humans. Acute and continuous exposure to diesel exhaust concentrations can cause several health issues. Some of the health diseases caused by DPM exposure are respiratory diseases, reduced lung capacity, heart disease, and lung cancer (National Research Council. 1981, Mine Safety. 2005). In addition, NIOSH regards diesel exhaust as "potential carcinogen" (Centers for Disease Control 1988) and IARC has declared that "diesel engine exhaust is carcinogenic to humans" (IARC 2012). NIOSH has also declared that the reductions in DPM exposure would reduce cancer risks (Centers for Disease Control 1988).

NIOSH 5040 method is a standard method employed for DPM compliance determination in metal and non-metal mines of US. NIOSH 5040 method is a shift average based measurement method. Thus it inherently involves an issue of "lag time" as it requires a lab analysis for DPM determination. It may take two weeks to get the results from the laboratory and miners could be potentially overexposed to DPM during those two weeks. Like any other shift average based measurement method, NIOSH 5040 method cannot depict changes in DPM levels for short although significant time periods which makes it unsuitable to determine the effect of any specific activity on mine environment. These issues associated with NIOSH 5040 method can be efficiently addressed by the use of real-time DPM monitoring devices. Real-time DPM monitors can almost instantly quantify the DPM concentrations and highlight mine situations where DPM levels are relatively high for substantial time periods (Gillies A.D.S. et al. 2014). Instrumentation developments are allowing improved real-time monitoring of ventilation parameters with particular emphasis on gases, respirable dust and DPM (Khan M. U. and Gillies A.D.S. 2015).

Use of real-time DPM monitors is relatively new and several real-time DPM monitoring devices are currently used in mining industry. This study will focus on recent studies which used real-time DPM monitoring devices for determining DPM concentrations in the laboratory and in underground mines throughout the world.

MSHA DPM REGULATION

The Mine Safety and Health Administration (MSHA) implemented DPM Personal Exposure Limit (PEL) in May 2008. MSHA measures DPM by measuring Total Carbon (TC), where TC is defined as the sum of Elemental Carbon (EC) and Organic Carbon (OC) when both EC and OC are measured by NIOSH 5040 method. The PEL of DPM exposure based on TC concentration for eight hours working shift is 160μg/m^3. Considering the error factors (EF) in determining miner's exposure to DPM, TC value greater than 160μg/m^3 times the EF will result in miner's overexposure. MSHA summarized the miner's overexposure to DPM as follows; (MSHA 2006).

i. $EC > 160 \times EF$
ii. $TC > 160 \times EF$ & $EC\ (TC/EC) > 160 \times EF$.

Where EC and TC are measured by NIOSH 5040 method.

MERITS OF REAL-TIME DPM MONITORING

Because of the issue of lag time and inability of the shift average based method to illustrate the DPM concentration for significant but short time periods, the concept of real-time monitoring has evolved. Real-time monitors can address the limitations linked with the standard shift average based DPM measuring methods. Various real-time DPM monitors are used in the mining industry and the research still continues to check their efficacy, reliability and applicability. Real-time DPM monitoring is beneficial in many ways, some of the merits of real-time DPM monitoring are discussed as follows.

Real-time DPM monitors can;

- Identify high DPM exposure zones.
- Almost instantly quantify the level of DPM.
- Provide DPM trend information throughout a working shift.

- Help to understand the fast changes in the mine atmosphere.
- Optimize the number of pieces of diesel powered equipment in any active stope.
- Allow efficient modification of mine ventilation system to reduce underground miner's DPM exposures.
- Quantify the effects of DPM control measures and help in better implementing different DPM control strategies.
- Drastically reduce the cost of DPM monitoring which could lead to an improved mine environment by allowing an increase of DPM sampling in active underground mine openings.

REAL-TIME DPM MONITORING

In 2006 Stephenson D. J. et al. conducted a study in an underground precious metal mine in the western part of the US. The total production of the mine was 25000 tons of ore per day and the mine was approximately 80% mechanized. Mine area sampling was conducted by using MSHA approved DPM sampling method and a TSI DustTrak™ real-time aerosol monitor. The TSI DustTrak™ is a 90° light scattering device which directly measures particulate mass concentration in mg/m^3. For this study the DustTrak™ was configured using a sampling head having a 50% cut point of 1μm and the logging interval of each DustTrak™ for estimating average particulate mass concentration was set at one minute. The pump flowrate associated with each DustTrak™ was 1.7 liters per minute (lpm) and all post-calibration flow rates were found within 5% of error. DPM was measured at various locations in the mine. The researchers investigated the presence of correlation between a TSI DustTrak™ real-time aerosol monitor and the TC by NIOSH 5040 method and found a linear correlation. Established correlation equation (I) is given below:

$$y = 0.2316x + 32.699 \qquad \text{(I)}$$

$R^2 = 0.91$

Where:

y = TC by NIOSH 5040 method in μg/m^3.
x = DustTrak™ mass concentration in μg/m^3.

Arnott A. et al. 2008 determined DPM in Nevada gold mines by utilizing the NIOSH 5040 and real-time monitoring method. A photoacoustic monitor was used for determining Black Carbon (BC) whereas total scattering particulate matter with submicron size (denoted by dPM1) was measured by a Dusttrak Nephelometer. BC by photoacoustic monitor and dPM1 by Dusttrak Nephelometer are akin to EC and TC measured by the NIOSH 5040 method respectively. The TC and EC values obtained by NIOSH 5040 method were found to be 50% of the respective values obtained from real-time Dusttrak Nephelometer and photoacoustic monitors. In this study they also compared the Dustrak TC and photoacoustic EC directly. The authors observed that the real-time values of TC and EC are 42% and 49% larger than those from filter samples (NIOSH 5040) whereas the ratio of EC/TC is similar for both methods. Finally the authors recommended that in-mine analysis of real-time EC and TC measurement using photoacoustic and Dusttrak, instruments should be calibrated to provide the same results as an equivalent EC and TC measurement by the NIOSH 5040 method for compliance applications.

In 2008 Janisko S. and Noll J. D. used an "EC monitor" and NIOSH 5040 method to determine EC concentrations. EC monitor used a laser diode absorption technique. Four key components of the EC monitor are an impactor, a filter, a pump, and an optical measuring circuit. The air is drawn at a set flow rate through an impactor. The mixture of air and DPM then passes through a filter within the instrument and EC from the air sample is collected onto the filter. The intensity of light transmitted through the filter is measured by an optical sensing circuit. The absorbance of the light decreases with increase in EC accumulation on the filter cassette and the output voltage of the light sensor decreases. This drop in voltage is compared with a calibration curve to relate laser absorption to EC concentration. The calibration curve is given below in equation (II). The data logger records these changes in voltage and a microcontroller calculates and displays the output on an LCD screen of the instrument in real-time. In this study various tests including drop testing and sensitivity, personal sampling, loaders' cab efficiency and mine area sampling were conducted in an active stone mine. This study concludes that the real-time EC monitor is not prone to interference from sudden shock or from dropping. In mine area sampling the real-time EC monitor gave slightly higher values of Time Weighted Average (TWA) EC concentrations as compared to the NIOSH 5040 method. Cab efficiency was also determined in this study and the authors concluded that an error in understanding the DPM results can occur in standard (NIOSH 5040) test when averaging over an eight hour time period.

Calibration equation (II) is as follows:

$$y = 188.88x \qquad \text{(II)}$$

$R^2 = 0.9984$

Where:

y = NIOSH 5040 EC μg/filter.
x = Laser Adsorption (AU).

Another study in 2008 conducted by Noll J. D. et al. determined DPM in two stone mines for sub-micrometer EC by using SKC DPM cassettes (analyzed by NIOSH 5040) and a near real-time instrument. In this study, the effect of ventilation control and environmental cab on DPM concentration was determined. The concentration of EC at the working areas was at or below 400μg/m^3 for both mines, whereas the EC concentrations in returns were about 166μg/m^3 and 251μg/m^3. In this study the effectiveness of the environmental cab in reducing DPM concentration was determined by measuring EC concentrations both inside and outside of a loader's cab. When checking the effect of ventilation on DPM, this research endorsed the concept that an effective ventilation system can efficiently reduce DPM content. The authors also concluded that cab efficiency is variable and it depends upon the proper use of cab, as opening of a window can cause substantial decrease in cabs' efficiency. This research also showed that the loader's cab was over 90% effective in reducing DPM as long as the cab system was properly maintained and doors and windows were closed.

Gillies A.D.S. and Wu H. W., 2008; Wu H. W., and Gillies A.D.S. 2008; and Gillies A.D.S. 2009; measured real-time DPM in several coal mines in Australia by using a modified personal dust monitor to determine real-time DPM concentrations. The real-time DPM monitor (D-PDM) was developed on the basis of the successful Personal Dust Monitor (PDM) unit. 'Thermo Fisher Scientific' has undertaken structural changes to the PDM to convert it to a submicron real-time monitoring underground instrument. The 'Pittsburgh Research Laboratories' of NIOSH has undertaken laboratory evaluation of the concept. The submicron size-selective inlet selected for D-PDM potential field instrument was the BGI 1μm sharp-cut cyclone. The D-PDM instrument was at prototype stage. By utilizing D-PDM and NIOSH 5040 method the authors correlated D-PDM mass concentration with TC and EC obtained by NIOSH 5040 method and proposed several mine specific correlation equations. The differences in correlation equations were suspected to be due to variations from mine to mine in aspects such as mine atmospheric contamination, vehicle fleet variations, fuel type, engine maintenance, engine combustion efficiency, engine behavior and interference from other submicron aerosols. Linear correlations were found with good correlation coefficients. Established correlation equations are given in table 1.

In 2010 Takiff L. and Aiken G. used an EC real-time DPM monitor to determine DPM on a vehicle and concluded that the EC real-time DPM monitor can effectively determine real time DPM concentrations

In 2010 Janisko S. and Noll J. D. used a beta prototype (supplied by ICx technologies) near real-time EC measuring portable monitor for DPM measurements. This instrument can provide DPM measurements quickly and continuously in an underground mine and also provides charted outputs of DPM concentration changes over time. This portable device relies on a rolling average to measure DPM levels. When used as an area sampler or a personal sampler, it provides a measurement of the average concentrations of DPM over the previous five, ten and fifteen minutes as well as the time-weighted average exposure measurement (TWA) for an eight hour shift. In this study the authors provided a practical approach to use real-time DPM measurements for the selection and evaluation of effective DPM controls. The researchers also concluded that the ability to perform well-executed tests and to interpret the information that real-time monitors provide is an essential part of sophisticated DPM measurements.

Table 1: Mine Dependent Correlation Equations

Mine	Equation	Correlation Coefficient
Mine 1	D-PDM = 1.65TC	$R^2 = 0.91$
	D-PDM = 1.85EC	$R^2 = 0.90$
Mine 2	D-PDM = 1.16TC	$R^2 = 0.99$
	D-PDM = 1.55EC	$R^2 = 0.97$
Mine 3	D-PDM = 1.03TC	$R^2 = 0.99$
	D-PDM = 1.23EC	$R^2 = 0.98$
Mine C	D-PDM = 1.34TC	$R^2 = 0.90$
	D-PDM = 1.96EC	$R^2 = 0.99$
Mine D	D-PDM = 2.22TC	$R^2 = 0.75$
	D-PDM = 1.13EC	$R^2 = 0.98$
Mine E	D-PDM = 0.92TC	$R^2 = 0.98$
	D-PDM = 1.27EC	$R^2 = 0.97$
Mine F	D-PDM = 1.21TC	$R^2 = 0.97$
	D-PDM = 1.46EC	$R^2 = 0.98$
Combined 8 Mines	D-PDM = 1.07TC	$R^2 = 0.96$
	D-PDM = 1.34EC	$R^2 = 0.95$

Where:
D-PDM is mass concentration by real-time monitor in (mg/m^3).
TC and EC are in (mg/m^3) by NIOSH 5040 Method

Griffith J. and MS. IH., in 2012 determined DPM using real-time and NIOSH 5040 method and showed that real time DPM monitor's accuracy decreased with more usage and high level of Organic Carbon (OC). In this study protection factor of environmental cab from DPM was determined by testing cab efficiency. The cab was found to be 25% efficient in reducing DPM concentration. The researchers also found that the results obtained by real-time monitor were within a 5% difference when compared to NIOSH 5040 method.

Noll J. D. et al. in 2013 conducted detailed laboratory analysis of the commercial version of Airtec. This analysis included calibration curve, NIOSH accuracy criteria, limit of detection (LOD), limit of quantification (LOQ), dynamic range and responses to potential interferences on Airtec performance. The Airtec monitor mainly measures light extinction which incorporates the effects of light absorption and scattering. Considering the accumulation of DPM particles, the light absorption will be the dominant effect on light extinction. Whereas if other scattering aerosols are collected with the DPM, light scattering may have more influence. The Airtec measures the EC component of DPM. The Airtec device can be used for both area and personal sampling. A pre selector is used to make a size cut of 1µm. A diaphragm pump draws air at a set flow rate. EC reaches the Teflon membrane filter through a conductive tubing without sticking to the tubing walls. The Teflon membrane filter is kept in a specially designed cassette that has a defined volume chamber as well as a carefully constructed flow path to achieve uniform distribution of EC on the Teflon filter. A 650nm wavelength laser penetrates through the sample while collecting DPM. Optical density is converted to mg of EC collected on the filter using a calibration curve. The Airtec displays the five minutes rolling average EC concentration. A data point is collected every minute which represents the average concentrations over the previous five minutes. The Airtec monitor also records and displays the eight-hour TWA EC concentration. This study also evaluated the effect of potential interferences like dust, humidity, cigarette smoke, and oil mist on Airtec in the laboratory. The results showed that mineral dust can interfere with the Airtec only when no size selector was used, however using a submicron size selector removed the influence of the dust on the Airtec. Oil mist as well as humidity was found not to interfere with the Airtec. The Airtec did not detect the presence of cigarette smoke unless DPM was on the filter. The study also concludes that the multi-scattering of the cigarette smoke particles increase the opportunity of light absorption from the DPM on the filter. When sampling was done in enclosed cabs where the equipment operator was smoking the concentrations of cigarette smoke resulted in a bias to the Airtec. This study also showed that the Airtec instrument meets the NIOSH accuracy criteria in the laboratory testing.

In 2013 Noll J. D. and Janisko S. determined the potential interferences of dust, humidity and oil mist on Airtec monitor performance in limestone and granite mines. The authors of this research concluded that the Airtec readings were equivalent to the NIOSH method 5040 values. The results of this study showed that dust and high humidity did not affected the Airtec reading when an impactor was used. The study concluded that besides the known potential interferences the presence of some other submicron aerosols in the monitoring environment could potentially cause a bias in the Airtec results.

In 2014 Gillies A.D.S. et al. discussed several ambient monitoring practices currently used in underground mines in Australia, US and South Africa and concluded that real time diesel particulate matter ambient monitoring practices in underground mines are gradually being accepted as an engineering tool to optimize the DPM control strategies.

In 2015 Khan M. U. and Gillies A.D.S. determined DPM in metal and non-metal mines in USA by using Airtec monitor and NIOSH 5040 method. In this study the researchers identified high DPM sources in the mines and found that in the metal mine, front end loaders and dumpers were the main sources of DPM whereas in non-metal mine, LHDs were major DPM contributors.

In another study conducted in 2015, Khan M. U. and Gillies A.D.S. used the NIOSH 5040 method and Airtec real-time monitor for determining DPM and observed that the TWA EC concentrations obtained by the Airtec monitor were usually higher than the TWA EC concentrations obtained by NIOSH 5040 method. A correlation equation between shift average EC measured by both, Airtec and NIOSH 5040 method was developed in this research. The developed correlation equation (III) could be used for more accurate determination of EC by Airtec method. Equation (III) is given below:

$$Y = 0.839x - 8.099 \qquad \text{(III)}$$

$R^2 = 0.99$

Where:

y = EC by NIOSH 5040 (µg/m^3).
x = EC by Airtec monitor (µg/m^3).

CONCLUSIONS AND RECOMMENDATIONS

Due to the several advantages over shift average based measuring methods, real-time DPM monitoring is becoming important in the mining industry. Recent technological improvements allow better estimation of real-time DPM concentrations. Numerous studies which used different real-time DPM monitoring devices are described. The Airtec real-time DPM monitor was used by several researchers and its performance was reported satisfactory. Airtec monitor estimates real-time DPM concentrations more accurately compared to other real-time DPM monitors. Differences in EC concentrations determined by Airtec monitor and NIOSH 5040 method were also reported. Extensive DPM field measurements by Airtec monitor and its comprehensive comparison with NIOSH 5040 method is recommended.

ACKNOWLEDGEMENT

The authors wish to acknowledge the Saudi Mining Polytechnic (SMP) Institute, the Mining & Nuclear Engineering Department of Missouri University of Science & Technology for funding support, and the University of Engineering and Technology, Lahore, Pakistan.

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