Real-time monitoring of DPM, airborne Dust and correlating Elemental Carbon measured by two methods in underground mines in USA

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In underground mines Diesel Particulate Matter (DPM) and airborne dust are considered to be the major causes of a large number of occupational diseases [1-3]. Long term and continuous exposure to DPM and respirable dust can result in severe health issues which include respiratory disease, lung cancer, reduced lung capacity and heart disease [1-4]. The US National Institute of Occupational Safety and Health (NIOSH), the US Mine Safety and Health Administration (MSHA) and others are working to improve understanding and measuring techniques for both DPM and mine dust. Most regulations consider shift average based exposure to define and determine Permissible Exposure Limits (PEL) for underground miners as MSHA relies on shift average based measurement for compliance determinations in underground mining. MSHA is currently reducing the shift averaged PEL regulation limit for respirable coal dust from 2.0 to 1.5 mg/m^3 with final effect August, 2016. Continuous or real-time monitoring of DPM and dust is vital to gain understanding of fast and frequent changes in the mine atmosphere contamination levels due to the limitations of shift average based measurements. From March 2016 MSHA will require the use of Continuous Personal Dust Monitor (CPDM) to measure real-time respirable dust exposure under certain circumstances. Real-time monitors quantify the level of pollutants in the mine air and allow the implementation of control strategies at the time of high exposure. Real-time monitoring provides insights into the mine environment during different mine activities. The current study focuses on determinations of DPM and respirable dust levels in underground mines in the USA. The Personal Dust Monitor (PDM) was used for real-time dust determination whereas real-time DPM was measured by FLIR Airtec monitors. The shift average DPM level was determined by the NIOSH 5040 method. The relationship between shift average based Elemental Carbon (EC) from real-time and shift average instrumentation was established.

Keywords: Diesel particulate matter, Respirable dust, Permissible exposure limit, Pollutants, Personal dust monitor.

1. Introduction

Ventilation is a critical aspect of underground mining. The ventilation network in many modern mines changes as development is extended. Maintaining an understanding of the ventilation network is a big challenge for the ventilation engineer. An important task of underground mine ventilation engineer is to provide a clean and sufficient quantity of air. In most of non-gassy underground mines DPM and dust are the important sources of air pollution. Limitations involved with shift average measurement methods have promoted the concept of real-time monitoring of mine atmosphere. Continuous monitoring of dust and DPM is vital in understanding frequent changes in the mine atmosphere. Instrumentation development is allowing improved real-time monitoring of ventilation parameters with particular emphasis on gases, respirable dust, and DPM. Ventilation expenditure can also affect mine production as comfortable and pleasant work environments could return in increased miner productivity.

This paper principally focuses on the monitoring of dust and DPM in underground mines in the USA. Dust and DPM measurements were taken in both metal and nonmetal mines. The personal dust monitor was used for continuous dust determinations. Real-time graphs of the dust concentrations were plotted during various mining activities. DPM was measured by two types of equipment. The FLIR Airtec DPM monitor was used to measures real-time component of DPM and SKC air sampling pumps were used for measuring MSHA approved NIOSH 5040 shift average DPM levels. The Airtec monitor also provides the time weighted average (TWA) value of elemental carbon. In order to compare DPM results using real-time monitoring with the NIOSH 5040 method approach both instruments were installed side by side at each measuring station. DPM samples were collected during performing various activities and the results from both measurement approaches were analyzed. A correlation equation was developed between shift average EC content measured by the two methods discussed and a very good correlation coefficient was obtained.

2. Respirable Dust Monitoring

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The International Standardization Organization (ISO) describes dust as small solid particles which settle out under their own weight but which may remain suspended for some time [4]. Dust particles are usually in the size range from about 1 to 100μm diameter and settle slowly under the influence of gravity [5]. However, in referring to particle size of airborne dust, the term "particle diameter" alone is an over simplification, since the geometric dimensions of a particle do not fully explain how it behaves in its airborne state [6]. Therefore, the most appropriate measure of particle size for many occupational hygiene situations is particle aerodynamic diameter. This can be defined as "the diameter of a hypothetical sphere of density 1 g/cm^3 having the same terminal settling velocity in calm air as the particle in question, regardless of its geometric size, shape and true density" [4].

Miners are exposed to high level of mine dust and there are several factors which influence the effects of inhaled dust particles. Particle size is usually the critical factor that largely determines approximately where in the respiratory tract that particle may be deposited [4]. The settling of dust in the lungs could be increased by acute dust exposures and deep breaths. Miners suffer from a variety of illnesses caused by inhaled dust during work activities. For practical purposes some types of lung diseases caused by the inhalation and deposition of mineral dusts in the lungs are covered by the general term "pneumoconiosis." This term simply means "dusty lung [7]."

2.1 Personal Dust Monitor (PDM)

The PDM is a respirable dust sampler and a gravimetric equivalent analysis instrument. The main components of the device include a cap lamp and sample inlet located on the end of an umbilical cord, a belt-mounted enclosure containing the respirable dust cyclone, sampling, and mass measurement systems, and a charging and communication module used to transmit data between the monitor and a computer. The PDM gives real-time readings. The monitor internally measures the particle mass collected on its filter and results do not exhibit the same sensitivity to water spray droplets as optically based approaches [8-9]. The technology that forms the heart of the PDM is unique. It collects suspended particles on a filter while simultaneously determining the accumulated mass. The technique achieves microgram level mass resolution even in the hostile mine environment. The PDM is currently being adopted for statutory mine respirable dust determinations in the USA. By using this device miners and mine operators have the ability to view both cumulative and projected end-of-shift mass concentration values, as well as a short term 5, 15 or 30 minutes running averages. The instrument has particular application for determining high dust source locations and efficiency of engineering means of suppression and other approaches to handling the mine dust. Being a personal dust monitor, the instrument measures the airborne dust from the breathing zone, so it has many advantages over instruments which measure from a fixed-point locations. It is also believed to be the first personal dust monitor instrument that reliably delivers a real-time reading [8]. The PDM is shown in figure 1 below.

Figure 1. Personal Dust Monitor

2.1 Monitoring in Metal Mines

2.2.1 Measurement during mucking

As an illustration of the use of the PDM, dust sampling was conducted in a metal mine entry during normal mine operations. The PDM was placed in a particular mine entry during mucking activity over about six hours. The peak dust value based on 15 minutes concentration was 3.1 mg/m^3 whereas, based on 30 minutes concentration the peak recorded value was 3.0 mg/m^3. During monitoring over a shift, records were made of more than sixty diesel operated equipment units by maintaining a vehicle log at the recording passage. In the beginning of an activity the dust concentration was low, with the passage of time it started accumulating in the mine entry due to the less air flow at the face the concentration finally reached to its peak value at about 10:50am. From 10:55am to 11:55 am there was a gap in the activity which was followed by decrease in dust. This decrease in dust concentration can be seen in figure 2. High dust concentration was observed with high vehicle frequency as initially four haul trucks were involved in dumping, after the gap one dumper was removed and only three dumpers were left for mucking. The dust concentration started accumulating again and it can be seen in figure 2. Both 15 and 30 minutes dust concentrations were plotted against time and the graphs are shown in figure 2.

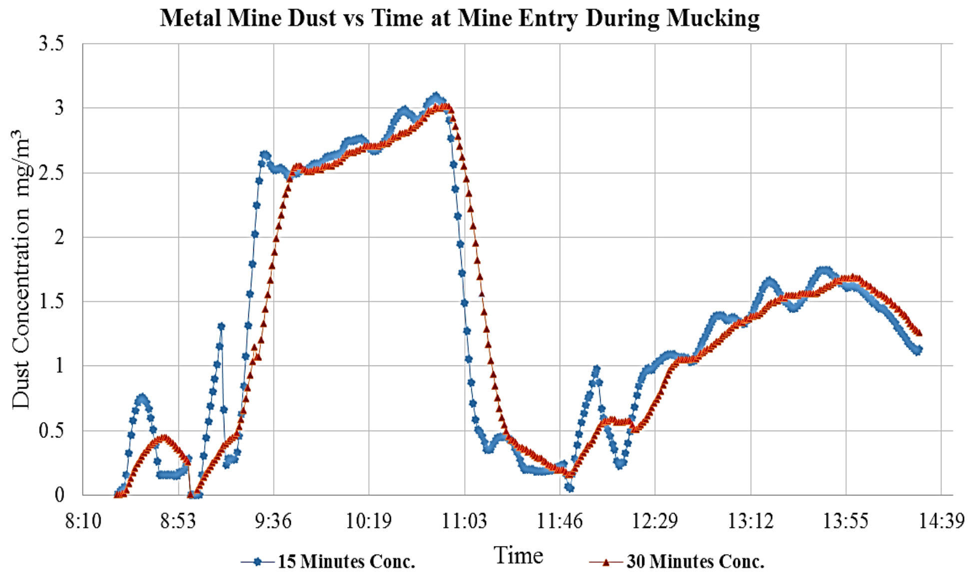

Fig 2. Real-time measured dust concentrations versus time over 15 and 30 minutes

2.2.2 Measurement at the face during loading

Another dust sample was collected in a metal mine. The PDM was hung at the face during loading operation where a front end loader (FEL) was loading the dumpers. One front end loader and three dumpers were involved in the activity. Total monitoring period was five hours and thirty minutes. This monitoring time includes a 90 minutes idle time (break time) near the middle. During the idle time the dust concentration was reduced, that reduction could be observed in figure 3. The peak recorded dust value based on 15 minutes concentration was 3.0 mg/m^3 whereas based on 30 minutes concentration the peak recorded value was 2.9 mg/m^3. The 30 minutes dust concentration graph is more consistent as compared to dust concentrations recorded at 15 minutes interval. During monitoring period forty dumpers were loaded by the FEL. Both 15 and 30 minutes dust concentrations were plotted against time. The real-time dust concentration graph is shown in the figure 3 below.

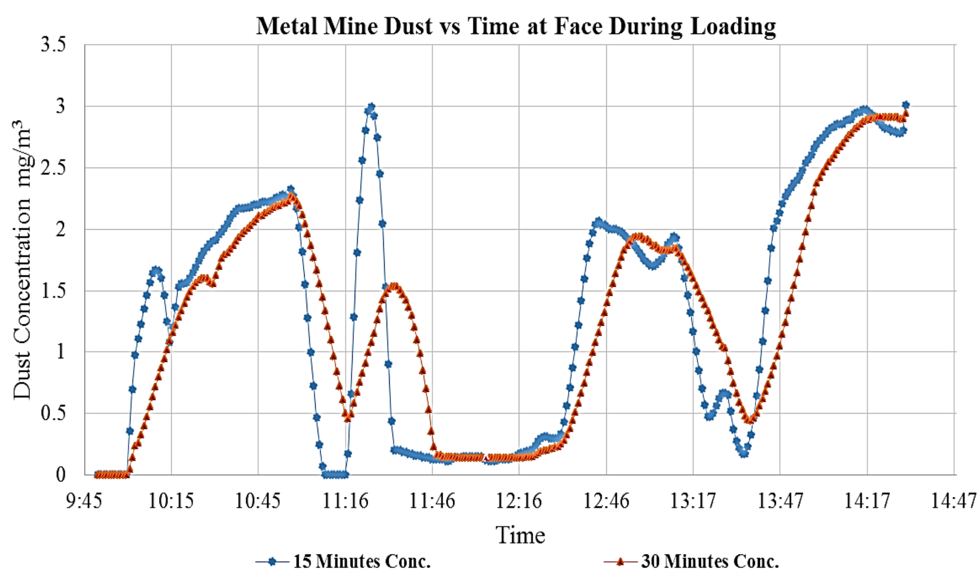

Fig 3. Real-time measured dust concentrations versus time over 15 and 30 minutes

2.2.3 Measurement during face drilling

Dust sample was also collected during drilling operation in another metal mine. The PDM was installed at the mine face where a 224kW jumbo drill was operating. Monitoring period was five hours and thirty minutes. The recorded peak dust value based on 15 minutes concentration was 2.9 mg/m^3 and based on 30 minutes concentration the peak recorded value was 2.7 mg/m^3. During the monitoring period all additional activities of vehicles or machinery in the area of monitoring were observed and noted. One 97 kW diesel powered hydraulic mechanical scalar was also working during the whole monitoring time period at another face in a nearby entry. Low dust values were recorded at commencement of monitoring. At the face the air velocity was quite low so the dust started accumulating at the face with time. Both 15 and 30 minutes dust concentrations were plotted against time. The real-time graph of dust concentration is shown in figure 4.

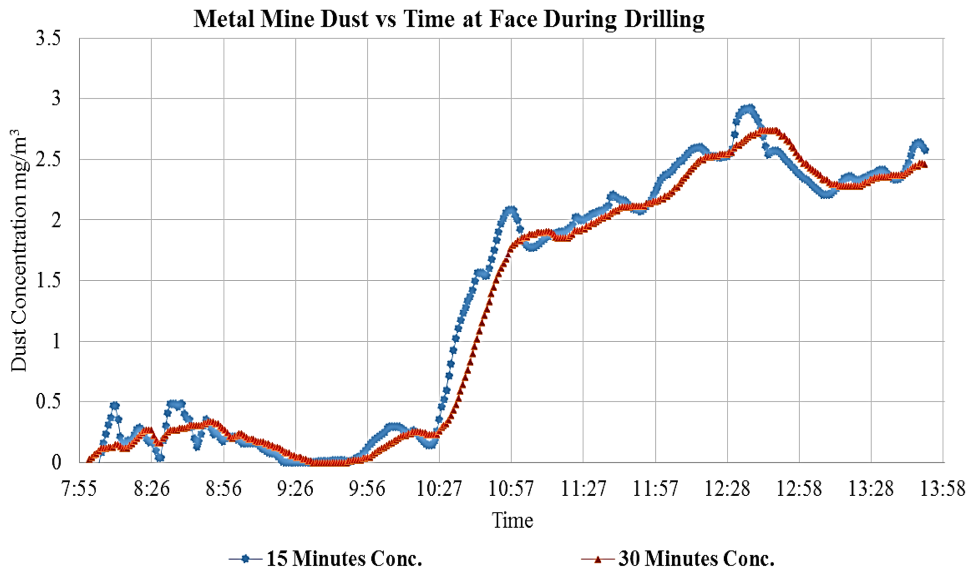

Fig 4. Real-time measured dust concentrations versus time over 15 and 30 minutes

2.3 Monitoring at Nonmetal Mine

2.3.1 Measurement in conveyor belt entry

Dust sampling was performed in a nonmetal mine entry of a long wall operation. PDM was installed in the conveyor belt entry. Monitoring continued for about eight hours. The peak dust value based on 15 and 30 minutes concentrations were 7.0 mg/m^3 and 6.4 mg/m^3 respectively. The belt was not in operation in the beginning of measurement so no dust concentration was recorded. The belt started at 9:45am and an exponential increase in dust concentration can be seen in figure 5. The real-time dust concentrations for complete monitoring time is shown below in figure 5.

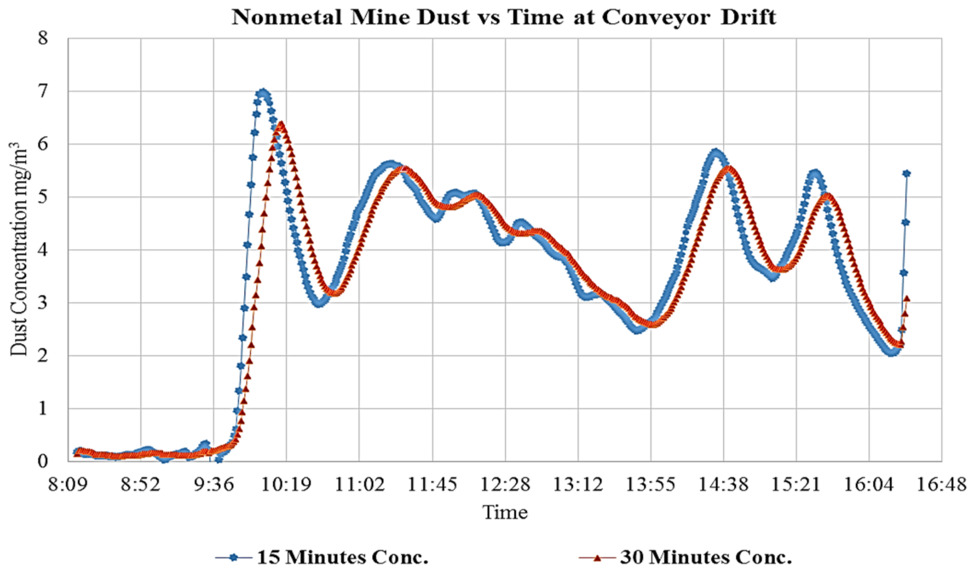

Fig 5. Real-time dust concentrations versus time over 15 and 30 minutes

3. Diesel Particulate Matter Monitoring

Diesel equipment has the ability to convert a large fraction of available energy into useable work. The diesel engine's high efficiency, ruggedness, economical operation and ease of maintenance makes it an attractive option for use in underground mines. It is very common for diesel engines in heavy duty trucks to have a life of 1,600,000 km [10]. Generally diesel equipment provides good maneuverability in underground mining operations. Diesel powered equipment offers more flexibility as compared to other available options, which makes it the first choice of underground mine operators. The underground mining industry is very likely to maintain its reliance on diesel powered equipment keeping in mind the recent developments in other energy alternatives [11].

Use of Diesel fuel is harmful to humans. Diesel particles are very small in size. The size of diesel particles is generally one order of magnitude smaller than the respirable dust aerosols in underground mines and predominantly less than one micron [12]. Force of gravity has less effect on DPM due to its small particle size. The phenomenon of less gravitational attraction increases the settling and residence time of DPM in the mine atmospheres. High residence time of DPM as compared to other mechanically generated particles increases its chances of deposition in the human respiratory tract. The small sized diesel aerosols penetrate deeply into regions of the human lung [13], which increase the health risks associated with long term exposure to diesel aerosols. Published studies documented the adverse health effects of DPM exposure [14]. The NIOSH regarded diesel exhaust as carcinogenic and continuous and long term DPM exposure can result in several other occupational diseases including respiratory disease, reduced lung capacity, and heart disease. NIOSH also declared that the reductions in DPM exposure would reduce cancer risks [15].

DPM measurement is a challenging task and it is becoming a matter of serious concern due to the harmful health effects linked with the exposure of DPM. DPM is mainly composed of EC, Organic Carbon (OC) and Inorganics [16]. EC constitutes a large fraction of the diesel particulate mass and it can be used as a measure of DPM [17]. The NIOSH 5040 method is an established technique for measuring DPM and it can quantify DPM even at very low concentrations. MSHA employs NIOSH 5040 DPM sampling for compliance purpose in mines. The NIOSH 5040 sampling method requires that an exposure sample should be submitted to a laboratory for analysis. This process fundamentally involves a significant time lag before an accurate exposure determination can be made and during which time miners are potentially overexposed to airborne levels of DPM [9]. The issue of lag time can be addressed by using real-time DPM monitors. Various real-time DPM monitors are used in the mining industry [18, 19].

3.1 Results of DPM Monitoring

DPM data has been collected from different metal and nonmetal mines by employing two different measuring methods, namely real-time and shift average method. The Airtec monitor which was used for real-time monitoring also provided shift averaged elemental carbon concentration measurements. The EC component of NIOSH 5040 method measurements were correlated with shift averaged EC values obtained from the Airtec monitors (figure 6). A correlation equation with a very good value of coefficient of determination (R^2) was established. The developed correlation equation (I) is given below:

$$y = 0.839x - 8.099 \qquad \text{(I)}$$

$$R^2 = 0.99$$

Where:

y = EC by NIOSH 5040 (μg/m^3)

x = EC by Airtec monitor (μg/m^3)

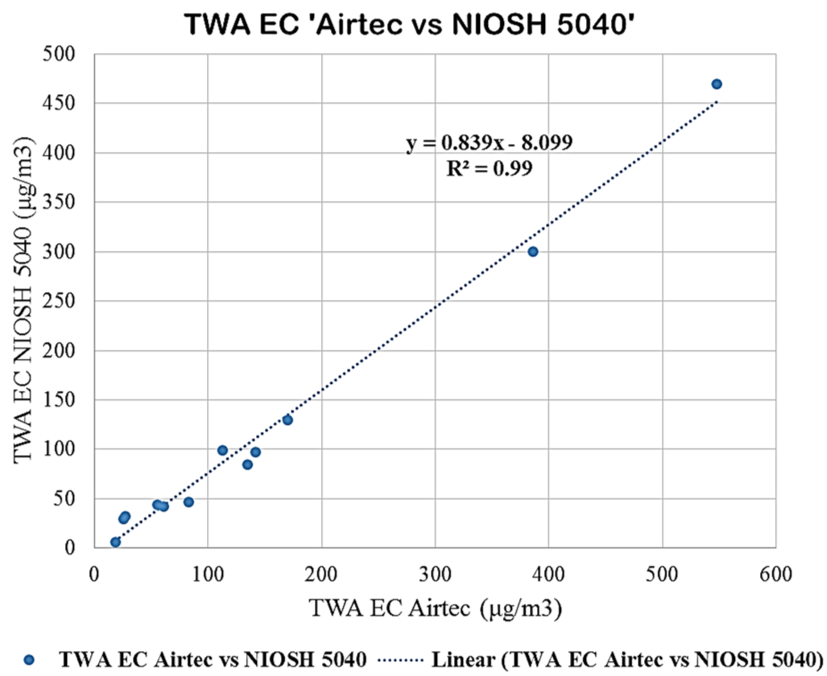

Fig 6. Correlation between shift average EC by Airtec and NIOSH 5040 method

4. Summary and Conclusions

Real-time monitoring of mine air pollutants is becoming popular in the mining industry as it allows the efficient implementation of dust and DPM control strategies. Real-time monitoring often highlights mine situations where the concentration of pollutants is relatively high for short but significant time periods. Relatively new and emerging real-time techniques were used for the determination of dust and DPM concentrations in metal and nonmetal mines in USA.

Higher dust concentrations were observed in a nonmetal mine as compared to the metal mines and belt conveyor was identified as the main source of dust in a nonmetal mine. The results of this study indicated 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 was developed between shift average EC content measured by both, real-time and NIOSH 5040 methods. The established relationship could assist in the estimation of NIOSH 5040 EC content by using shift averaged EC concentration obtained from the Airtec monitor. The equation (I) could be used as a tool for determining the miners' DPM overexposures in metal and nonmetal mines, and it will also help in implementing the DPM control measures right at the time of high DPM concentrations in underground mine atmospheres. The correlation equation (I) may not be applicable to the coal mines because of environmental interferences.

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