Diesel particulate matter investigations in underground coal mines

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Abstract—A number of underground coal mines are using diesel-powered vehicles as the main source fuel for the transport. The primary concern with these diesel-operated vehicles is the diesel particulate matter (DPM), because it is known to be a carcinogenic agent after prolonged exposure. A well-designed ventilation system is necessary to dilute DPM, so that air quality is maintained to statutory guidelines. This paper outlines details of DPM characteristics, its health effects on miners, coal mine ventilation guidelines and some research investigations that underpin the control of DPM flow in underground coal mines.

Keywords-Coal mines; Ventilation ; DPM; Diesel vehicles;

I. INTRODUCTION

Coal has been playing a vital role since the industrial revolution. In 2015, it has been generated 41% of electricity and responsible for 70% steel production for the world with the total production of 7708 Mt [13]. Australia was 4th largest coal producer with 437 Mt of production in 2015. Of these, 33 operating underground coal mines have been produced 22 % of the total. Most of these mines have been using diesel-operated locos, utility vehicles and load haul dumpers for transportation of men and material.

Usage of diesel-powered vehicles has greater flexibility than electric vehicles because they travel longest distances and between working sections of a mine. The use of diesel vehicles is efficient, evidenced by ease of maintenance and consistency. Many nations have been depended on these vehicles because of these reasons [1].

The main issue with the diesel equipment is its exhaust fumes, which contain a mixture of diesel particulate matter (DPM) and other pollutant gasses such as Nitrogen oxides (NOx), Hydrocarbons (HC) including either total hydrocarbons (THC) or only the non-methane hydrocarbons(NMHC) and Carbon Monoxide (CO) [2].

DPM is the by-product of incomplete combustion of diesel fuel inthe diesel engine. These particles have solid core consisting of mainly elemental carbon and having very rich surface methodology, which adsorbs many other toxic substances [3]. More than 1,800 different organic compounds have been identified as adsorbed on the elemental carbon core, some of these areorganic chemicals (polycyclic aromatic hydrocarbons or PAHs), condensed liquid hydrocarbons, inorganic compounds (sulphate compounds), Nitrous oxide(N_2O), Dioxins and metal oxides.

Recent research studies show that expose of miner with high concentration DPM in mine environment causes increase the risk of lung cancer. As per coal mine regulations, adequate airflow is required to dilute DPM concentration within the statutory limits in all underground places where the diesel engine works. However, some locations like developing tunnels, gate roads, closed cut-through and other isolated workings diesel vehicles need to operate at insufficient air quantity. Enormous time may require diluting these contaminants, but mine operators may have to be exposed to these high DPM concentrations.

As underground coal mines go deeper and deeper and increase production targets, a significant increase of usage with diesel vehicles. Efficient mine ventilation network systemsneed to be developed to mitigate high DPM concentrations where the vehicle(s) work. Research investigations need to be conducted to uncover the DPM dispersion in isolated working zones and the relation between air quantity and dispersion time. Advanced strategies and guide lines need to be developed to control high concentration DPM at underground coal mine workings using innovative strategies like curtains, exhaust and/or forcing fans and scrubbers.

Various research investigations have been carried out to regulate DPM emissions using different filters and fuelswithin the vehicles.However, none of these research studies have been conducted to map and control the DPM in underground coal mines. This paper presents DPM characteristics, ventilation standards, health effects and previous DPM research investigations.

II. DPM CHARACTERISTICS AND MONITORING SYSTEM

Diesel particulate matter is a component of diesel exhaust (DE) that includes soot particles made up primarily of carbon, ash, metallic abrasion particles, sulphates and silicates. Total carbon (TC) of the particulate matter is defined as sum elemental carbon (EC) and organic corban (OC). DPM has a solid core consisting of elemental carbon, with other substances attached at the surface, including organic carbon compounds known as aromatic hydrocarbons. The effective density of agglomerated diesel particles decreases as a function of particle size [21]. The effective density of agglomerated diesel particles varies from 1.1 to 1.2 g/cm^3.

The chemical composition of DPM has not followed any trend. The chemical composition of fuel sulphur content, decrease in particulate sulphate level as fuel sulphur content decreases. Considerable differences in sulphate and hydrocarbon emission levels were observed within engine and vehicle groups [22]. Wide range of soluble organic fraction (SOF), fuel derived hydrocarbon (FHC) and lubricating oil hydrocarbon (LHC) were identified with engines operating cycles and Furthermore, wide range of polycyclic aromatic hydrocarbons (PAH) levels were observed with vehicles and engine groups.

A. DPM size distribution

DPM is defined as sub-micron physical aerosol component of diesel and are divided into three categories with respect to size. Nanoparticles of less than 50nm diameter, ultra-fine particles of less than 100nm diameter and fine particles of less than 2.5μm diameter.

DPM is composed of numerous small particles holding very little mass, mixed with relatively few larger particles, which contain most of the total mass.Fig.1 shows a typical DPM size distribution weighted by number, surface area, and mass [4],[5]in three modes.

Initially,the nuclei mode: diameter of particles in this mode is between 3 to 30 nm and is mainly consisted of volatile organic and sulphur compounds in varying proportions as well a small amount of solid material likely to consist of carbon and metallic compounds. This mode typically contains 0.1-10 % of the particle mass and up to 90 % or more of the particle number. Secondly,the accumulation mode: diameter of the particles in this mode is between 30-500 nm and most of the mass composed primarily of carbonaceous agglomerates and adsorbed materials are found in this accumulation mode. Finally, coarse mode: it consists of particles larger than 1,000 nm and contains 5-20 % of the Diesel aerosol mass.

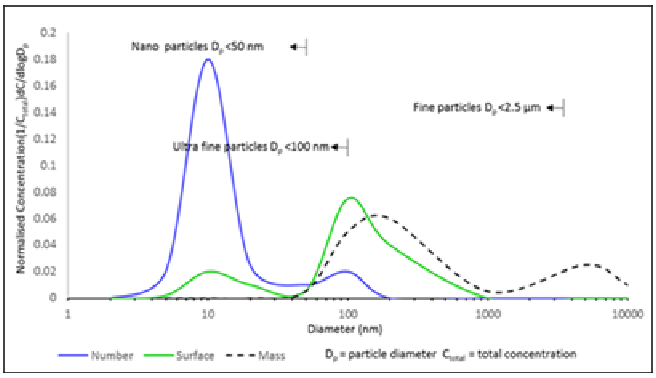


Fig.1. DPM particles size distribution [4]

B. DPM monitoring system

Different countries are following variousmethods to monitor DPM concentration in underground coal mines, NOISH analytical method 5040 is most popular method among them. In this method, laser light passed through the DPM sampling filter to continuously monitor the filter transmittancethroughthe thermal-optical analysis system. Specimen of organic and elemental carbon is accomplished with temperature and atmosphere control. The process of continuous monitoring of filter transmittance is in two stages[9].

In the first stage, organic carbon (OC) and carbonate carbon (CC) are evolved into a helium atmosphere as the temperature is stepped to about 850°C. The evolved carbon is catalytically oxidized to CO_2 in a bed of granular MnO_2, then reduced to CH_4 in a Ni/firebrick methanator. CH_4 is quantified by flame ionization detector (FID). In the second stage, the sample oven temperature is reduced, an oxygen-helium mix is introduced, and temperature is increased to 940°C. As oxygen enter the oven pyrolytic ally generated carbon is oxidized and a concurrent increase in filter transmittance occurs, the point at which the filter reaches its initial value is called split between OC and EC. Carbon evolved prior to the spilt is considered OC and after the split is called EC. If a sample contains carbonate source carbon, expose the second filter punch to HCl vapor one hour before the analysis.

III. HEALTH EFFECTS WITH DPM

Various research agencies have been conducted to investigate health effects on DPM. Initially, in 1988, NIOSH has published an experimental report about rats and mice's exposed to diesel exhaust gases, published a potential link between occupational exposure to diesel exhaust and lung cancer [1].

In 1995, Health Effects Institute (HEI) published their research report after reviewing over 30 epidemiologic studies of workers exposed to diesel emissions in occupational settings for the period 1950 through the early 1980s[1]. They concluded that weak associations between exposure of diesel exhaust to human lung cancer. Long-term exposure to diesel exhaust in a variety of occupational circumstances is associated with a 1.2 to 1.5fold increase in the relative risk of lung cancer compared with workers classified as unexposed.

Mines Safety and Health Administration (MSHA) [6] reviewed 47 epidemiological studies and determined that in 41 studies, there was some degree of association between occupational exposure to diesel particulate matter and an excess prevalence of lung cancer. MSHA concluded that exposure at a mean concentration of 0.64 mg/m^{3}DP for a period of 45 years would result in a relative risk of 2.0 for lung cancer.

The United States Environmental Protection Agency (US EPA) conducted a health assessment for diesel engine exhaust [7]. They concluded that acute effects with respect to health, such as eye, throat and bronchial irritation, light headache, nausea, cough and phlegm were evident. With respect to chronic non-cancer respiratory effects they suggested, from animal studies, the potential for chronic respiratory disease in humans. The US EPA also concluded that lung cancer was evident in occupationally exposed groups but could not define sufficient dose response data to produce a quantitative risk assessment.

In United States, National Cancer Institute (NCI) was conducted a case study in a cohort of 12315 workers in eight non-metal mines, which included 198 lung cancers deaths and 562 incidence density-sampled control objects. For each case, subject selected up to four control subjects, individually matched on mining facility, sex, race and birth year, from all workers who were alive before the day the case subject died. They have estimated diesel exhaust exposure represented by respirable elemental carbon (REC), job and year based on an extensive retrospective exposure assessment at each mine. They conducted both categorical and continuous regression analyses adjusted for cigarettes and other potential confounding variables [8]. Researchers observed that statistically significant increase trend in lung cancer risk with increasing cumulative REC and average REC intensity. Cumulative REC, lagged 15 years, yielded a statistically significant positive gradient in lung cancer risk overall heavily exposed workers, risk approximately three times greater than that among workers in the lowest quartile of exposure. Chances of getting lung cancer for smokers is higher than non-smokers.

Based on research interpretation of the toxicological and epidemiological data, regulatory authorities in USA, Europe and Canada have concluded that sufficient evidence exists to indicate that diesel particulate presence an increased risk of lung cancer, although the absolute quantification of potency remains unclear.

IV. COAL MINE REGULATIONS TO DPM

As per Australian and Indian coal mines regulations [2], The recommended maximum workplace exposure (mine atmosphere) for diesel particulate in the elemental carbon (EC) fraction when expelled from a diesel engine is 0.1 mg/m^3. Which is approximately equal to 0.16mg/m^3 Total Carbon(TC) or 0.2mg/m^3 Diesel Particulate(DP).

The minimum ventilation quantity in the mine where the diesel engine is operating shall be the maximum of the ventilation required to dilute gaseous emissions, Particulate emissions and heat stress. The minimum ventilation quantity should also have considered the total number and power of diesel engines operating in the same ventilation current at any one same time. For a newly developed mine, good practice is to provide 0.1m^3/s/kW of diesel engine power to overcome, diesel emissions (gaseous and particulate) and heat stress.

For gaseous emissions, the minimum ventilation quantity in each place where a diesel engine operates shall be such that ventilation current of not less than:

- 0.06 m^3/s/kW of maximum capacity of the engine, or
- 3.5 m^3/s

Whichever is the greater is directed along the airway in which the engine is operating. If more than one diesel engine is being operated in the same ventilation current, the diesel engine rated kW shall be added.

As per US MSHA 2008 [23], A miner's personal exposure to diesel particulate matter in an underground mine must not exceed an average eight–hour equivalent full shift airborne concentration of 160 microns of total carbon per cubic meter of air.

As per MSHA, the minimum ventilation air quantity requirement is based up on the name plate air quantities for the equipment engines. These nameplate quantities are determined by laboratory testing using MSHA test procedures, which designed to approximate the duty cycles of the engines. The ventilation rates are based upon the exhaust contaminants measured at different engine speeds and loading factors. The projected time weighted average(TWA) is calculated by

$$TWA_{projected} = \frac{Q_{measured}}{Q_{requested}} TWA_{measured} \quad (1)$$

In Canada, to approve the diesel engine in coal mines, the minimum raw exhaust DPM concentration should not exceed 150 mg/m^3 gassy and non-gassy coal mines. To dilute diesel engine exhaust contaminates in underground mines, each state and provinces follow their own regulations, most of them are require 0.06 m^3/s/kW of air quantity.

The minimum ventilation quantity in each place where a diesel engine operates shall not less than 0.067 m^3/s/kW in China and shall not be less than 0.063 m^3/s/kW in South Africa.

V. FIELD INVESTIGATIONS

A. NOISH field study

The first DPM experimental study was conducted by metal/non-metal diesel partnership formed by National Institute of Occupational Health and safety (NOISH), the National Mining Association (NMA), the National Stone Sand and Gravel Association (NSSGA), the United Steel Workers of America(USWA) and the MARG Diesel Coalition [10].

This study was conducted in 533m isolated zone located at 52E ramp of Stillwater Mining Company's Nye Mine in in two phases. The first phase was to establish the effectiveness of the selected technologies in reducing diesel emissions by using an isolated zone methodology. The second phase was to assess the diesel particulate filters in controlling the exposure of underground miners in actual production scenarios. The average width and height of the opening are 3.6m and 2.7m respectively and the ramp has 9% rise towards the downstream end.

Two trucks and three Load Haul Dumpers (LHDs) were used for this experiment. The major alterations on vehicles are removal of oxidation catalytic convertors of the purpose of establishing engine baseline emissions and installation of Diesel particulate filter (DPF) systems. In these study, different DPF systems, were evaluated, which includes Enlarged DPX, DCL MineX, Clean Air System, Blue Sky, Mac's Mining Repair/Donaldson, ECS Cattrap and Bio diesel.

The duty cycle for trucks consist of trucks started at the cycle at the upstream dumping point by hauling a full box of ore up the ramp to the loading point. At the loadingpoint, the operator simulated a loading cycle by repositioning the trucks for loading by an imaginary LHD. Tramming down the ramp toward the dumping point followed the loading cycle. At the dumping point the operator simulated unloading the box by engaging the hydraulics and loading the engine at which time a new cycle would start.

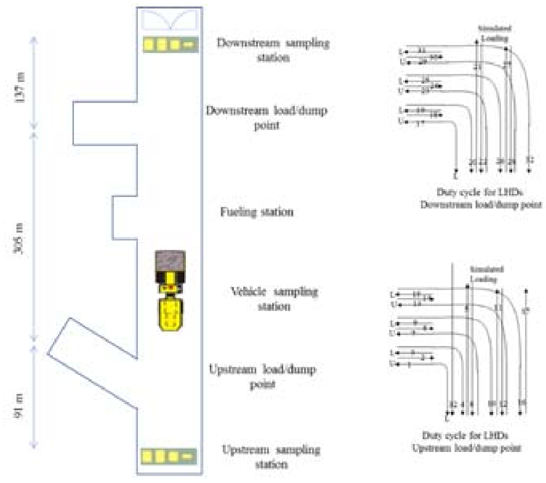


Fig.2. The isolated zone and duty cycle for LHDs [10]

The duty cycle for LHDs starts at the upstreamload/dump point with a bucketloaded with ore, Fig.2. The operator would take the vehicle into the upstream stope and unload the bucket, retreat for the length of the vehicle then advanced and loads the bucket again. The next step was to back the vehicle out of the stope and advance for two lengths of the vehicle up to the ramp. The operator engages the hydraulics to simulate loading of an imaginary truck and then backs the vehicle to the string point. These loading operations would be repeated three times. After the third execution, the loaded LHD would tram up to the ramp to the downstream load/dump point. The LHDs would execute three load/dump tasks similar to that performed at the upstream location. At the end of the load/dump session at the downstream point, the vehicle would tram loaded down the ramp to the upstream starting point to complete the cycle. Table 1 shows the results of NOISH field experiment results showthat elemental carbon concentration rapidly decreased with diesel particulate filter systems at various ventilation flow conditions.

Table.1. Elemental carbon results normalized with respect to ventilation rates [10]

DPF System	Vehicle Number	MSHA vent rate (m^3/s)	Elemental Carbon ($\mu g/m^3$)	
			Base Line	with DPF
Enlarged DPX	Haul Truck 92128	5.66	1182	51
Clean Air system/CDT	Haul Truck 92133	5.66	1038	15
Bio Diesel B20	LHD 92526	4.71	1328	1015
Biodiesel B50/ PTX	LHD 92526	4.71	1328	703
DCL MineX	LHD 99942	7.07	1112	149

B. DEEP field study

Diesel Emissions Evolution Program (DEEP) was conducted to assess the effectiveness of the DPF systems on concentrations of DPM and gasses at an isolated zone in Narannda's Brunswick Mine in Bathurst by Burnswick mine personal with the coalition of Natural Resources Canada, Canada Center for Mineral and Energy Technology (CANMET), National Institute of Occupational Safety and Health (NOISH), Andreas Mayer of VERT and diesel particulate filter (DPF) systems suppliers. In this filed study,four LHDs of 242 kW capacity and two haulage trucks of 278 kW capacity were used. The tested DPF systems were ECS Catalyzed Filter, ECS Octel Filter, DCL Catalyzed/Electric Filter and Ober land Mangold OctelFilter [11].

The vehicles were operated inside the 400m isolated tested zone, Fig.3. The LHD operating cycle starts fromthe intake side, for 15 seconds the engine was run at fulltorque, and hydraulics stalled. Later the engine run atfull throttle in neutral and no load for 15 seconds. Two conditions were repeated four times later, the vehicle trammed for 400m long drift toward the return side. The return air dump cycle was 30 s run at the full throttle with transmission in neutral and no load ofthe engine. Finally, the vehicle returns to intake side. Each vehicle operates over a period thanfour hours repeating the 8- minimum full cycle.

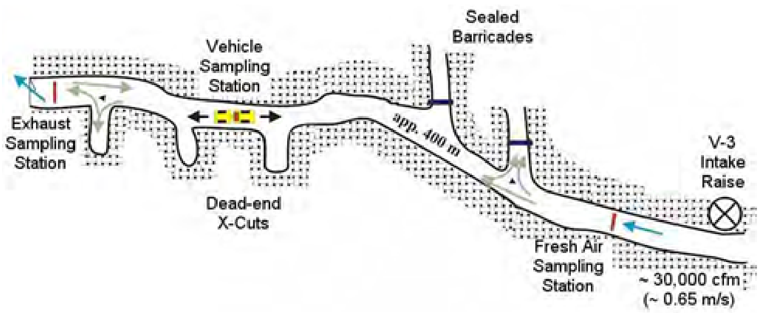
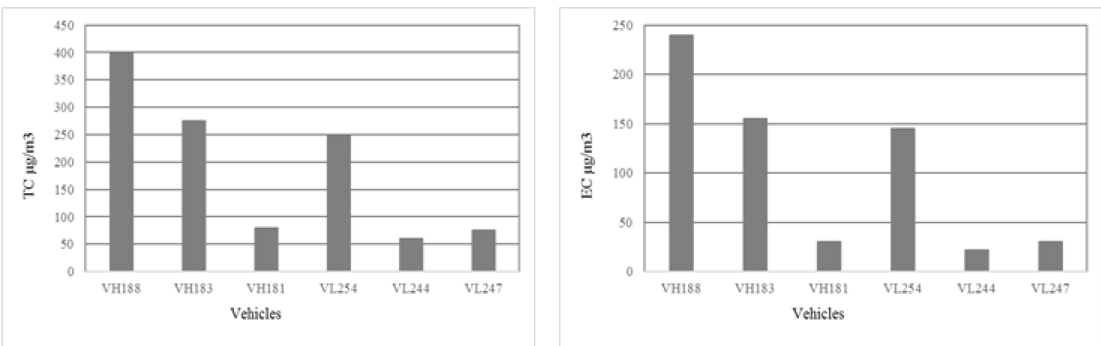


Fig.3. Isolated zone of DEEP Field study [11]

For this study, air quantity of 14.15 m^3/s was supplied. To monitor DPM, three sample stations were established at intake side, operator cabin and return side. Five samples were tested for Total Carbon (TC) from each of stations. Researchers concluded that DPM concentration in the fresh air sample station is very low and slightly higher TC concentration at exhaust sampling station than at the vehicle. Fig.4 shows the measured results of TC and EC at the return side of the sampling station.



(a) Total Carbon concentration (b) Elemental Carbon Concentration

Fig.4. TC and EC concentrations for different test vehicles [11]

C. ACARP field studies

The Australian Coal Industry Research Program (ACARP) has been conducted various research investigations to control the DPM concentrations in vehicle. Researchers have designed underground coal mine usage vehicle standards, statutory implications [14] and vehicle management strategies [15].

Similarly, commendable research investigations have been carried by ACRAP to regulate and monitor diesel-powered equipment exhaust gasses and DPM by using alternative diesel fuels [16], ultrasonic transducers with electrostatic perspiration filter [17], cooled exhaust and scrubber [18], optimizing engine, exhaust system and exhaust gas monitoring systems [19].

All these investigations are based on DPM control strategies within vehicle. None of the research investigations carried out to develop DPM control strategies in underground environment, particularly in air flow restricted zones. For these effective mapping and flow pattern of DPM is underground in underground coal mines.

Recently, to map DPM concentrations in metal/non-metal underground mine environment, a base- case computational fluid dynamics (CFD) simulation studies were conducted [12], [20].

VI. CONCLUSIONS

Diesel operated vehicles are more useful to improve production and performance of underground coal mines. Putting aside the use of diesel-powered vehicles, the use of the inefficient ventilation system will lead to serious health issues to miners because of DPM. In the process of outlining various gaps and inefficiencies are identified will require further investigations to map flow patterns of DPM in underground coal mines at various operating conditions to develop effective control strategies and to design standard ventilation policies and procedures.

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