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Real-time Diesel Particulate Matter ambient monitoring in underground mines

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Abstract A real-time Diesel Particulate Matter (DPM) monitor has been developed on the base of the successful National Institute of Occupational Health and Safety (NIOSH) designed Personal Dust Monitor (PDM) unit. The objectives of a recently completed Australian Coal Association Research Program (ACARP) study was to modify the PDM to measure the submicrometre fraction of the aerosol in a real-time monitoring underground instrument. Mine testing focused on use of the monitor in engineering evaluations of Longwall (LW) moves demonstrated how DPM concentrations from vehicles fluctuate under varying ventilation and operational conditions. The strong influence of mine ventilation systems is reviewed. Correlation between the current SKC DPM measurement system and real-time DPM monitors were conducted and results from eight mines show a correlation between elemental carbon (EC) and the new monitor DPM mass ranging from 0.45 to 0.82 with R^2>0.86 in all but two cases. This differences in 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 or interference from other submicrometre aerosol. Real-time monitoring clearly reflects the movement of individual diesel vehicles and allows pin-pointing of high exposure zones such as those encountered where various vehicles engage in intense work in areas of constrained or difficult ventilation. DPM shift average monitoring approaches do not readily allow successful engineering evaluation exercises to determine acceptability of pollution levels. Identification of high DPM concentration zones allows efficient modification of mine ventilation, operator positioning and other work practices to reduce miners' exposures without waiting for laboratory analysis results.

Keywords real-time diesel particulate matter, total carbon, elemental carbon

Introduction

Conventional mine atmosphere measurements of DPM in many mines around the world is of increasing importance and has been measured systematically by various approaches for a number of years. A real-time DPM monitor has been developed on the base of the successful PDM unit. The heart of the PDM is a miniaturized direct mass measuring sensor that measures mine dust. The PDM was originally developed by Rupprecht and Patashnick Co., Inc. (now Thermo Fischer Scientific) under contract from the Center for Disease Control and Prevention, National Institute for Occupational Safety and Health (NIOSH).

The PDM is capable of measuring in near-real-time many types of aerosols regardless of particle size, chemical composition or refractive index. Currently a size selective cyclone defines the respirable mass fraction that is of interest in the prevention of coal workers pneumoconiosis. Other size selective devices could be used to define size fractions of interest for other applications.

In collaboration with an ACARP funded project, 2005 to 2007 (Gillies and Wu, 2008) Thermo Fisher Scientific and NIOSH undertook changes to the PDM to convert it to a DPM particulate submicrometre real-time monitoring underground instrument which was named the D-PDM. NIOSH undertook calibration or verification laboratory evaluation of the new unit's performance. Their Laboratory has also designed a cyclone that cuts at 0.8 micron particulate size appropriate for a DPM monitor. The real-time DPM unit continually reports levels of mine atmosphere submicrometre aerosol. The D-PDM results have been correlated by parallel SKC system DPM evaluations. A phase of Australian robustness and engineering testing

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has been undertaken to ensure the instrument can effectively assist mine management.

Fig.1 illustrates the major components of the PDM and D-PDM.

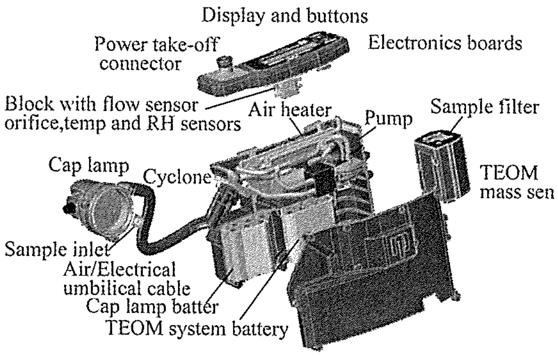

Fig.1 Major components of the PDM and D-PDM

The real-time D-PDM monitor has in the five years period since the ACARP project been used in many Australian mines and empowered and educated operators in the control of their environment. The monitoring approach has application to all forms of diesel powered mining. With its real-time atmospheric monitoring ability, the D-PDM monitor has demonstrated that it can be use as an engineering tool to pin-point high DPM exposure zones such as those encountered in LW face moves or on development faces using diesel ram cars. Isolation of high DPM concentration zones allows efficient modification of work practices to keep underground miners exposure within shift length exposure regulations.

The PDM and D-PDM internally measure the true particle mass of aerosol collected on its filter. Measurements are insensitive to water spray as opposed to optically based measurement approaches. The underground mining industry has no real-time direct reading atmospheric DPM monitor at present. A phase of Australian mine robustness and engineering testing has been undertaken to ensure the instrument can effectively assist mine management. It has been shown that the D-PDM monitor can be used as a tool to evaluate the effectiveness of various currently available or under development diesel exhaust management and control systems within the underground mine environment during their normal operations and usages. Tests have been undertaken at points of expected high atmospheric DPM such as during LW face moves. The paper discusses, through use of mine examples, how the monitor has performed within the underground mine environment in evaluating DPM during the various phases of LW moves. The project has closely examined the influence of aspects of the mine ventilation system. Results have been compared to alternative industry pollutant measuring approaches. The outcomes of the project demonstrate a new tool for understanding the atmosphere in the presence of DPM.

1 Ventilation considerations in handling DPM

LW moves rely on use of high powered equipment of Shield-Chock movers (chariots) and other powerful machines that produces high levels of exhaust pollutants of gases and DPM. Many Australian mines find it a challenge to meet DPM "Target Limits" during all phases of operational moves. "Target" limits used generally follows the New South Wales Guidelines for DPM of 0.1 mg/m^3 Elemental Carbon or alternatively a limit of 0.2 mg/m^3 Submicron Particulate. Approaches adopted in Australian mines rely as a first step on both ensuring there is enough air and optimization of the ventilation system design. Issues that should be considered in optimizing the design include:

(1) Maximize air quantity where LW face equipment recovery, movement or installation occurs.

(2) Have all moving equipment (at least loaded machinery) travel in opposite direction to air flow.

(3) Ensure that air velocity is higher than machine speed to ensure a plume of exhaust does not hang over travelling equipment in situations where machinery cannot be moved against airflow.

(4) Have parallel transport roads so that movement occurs in a circuit of loaded machines travelling inbye on one road and outbye on a parallel one.

(5) Ensure that miners are working upstream of machinery and particularly machinery that is working on faces loading or unloading and positioning.

(6) Divide available air so that the majority is passing along the headings used by loaded machinery.

(7) Monitor DPM with real-time instruments so that points where "Target" limits are not being met are identified and improvements are made during the current LW move or planned for the next move.

2 Development of real-time personal diesel particulate monitor

Mine atmosphere measurements of DPM in Australian mines have been measured systematically since the early 2000s. Most initial atmospheric readings have been taken on a shift average basis using SKC sampling units. The SKC is derived from a US NIOSH design and gives readings in the surrogate Total Carbon (TC) or Elemental Carbon (EC) units after laboratory analysis procedures have been completed.

DPM=TC+Inorganics=

EC+Organic carbon (OC)+Inorganics

TC in mine testing is generally 80% of DPM (Volkwein, 2006).

Some DPM regulatory guidelines are starting to emerge in Australia and the individual states are generally moving to acknowledge DPM limits in use in the US in the early 2000's of 0.2 mg/m^3 submicrometre particulate matter, 0.16 mg/m^3 TC particulate and 0.1 mg/m^3 EC particulate. A few prescriptive mining regulations are in force internationally such as those applying to the US metalliferous mining industry from May 2008 based on a DPM limit of TC particulate.

3 Monitoring of diesel particulate matter

3.1 Mine A

Mine A testing found it was straight forward to analyse results for arrival and departure times of diesel machines at the face and see whether these matched the arrival of the vehicle exhaust plume. Fig.2 examines one three hour period record of real-time DPM readings as compared to heading air velocity and Shield carrier speed. Close examination of results from No.108 monitoring the DPM downstream of the main gate (MG) and back road showed that when the shield carriers travel in that in three cases they arrived at the tail gate (TG) end of the face in advance of the peak level of the DPM cloud. This indicated that the carriers were generally travelling at higher average speed than the air velocity.

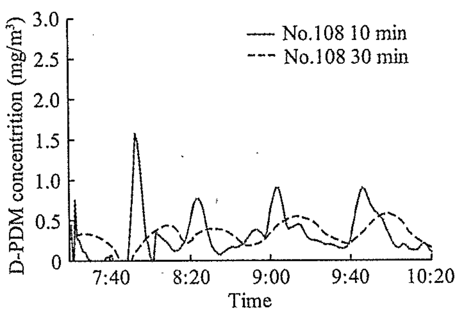

Fig.2 Observations of shield-chock carrier DPM over a three hour period

However carrier No.1112 arrived slightly later indicating slower machine travel speed than air velocity. The time difference and the peak concentration depend on the air velocity and Shield carriers' travel speeds. Put simply if the shield carrier travels at the same speed as air velocity peak concentration will be extremely high and the carrier will arrive at the same time as the peak. Note that the DPM data has a lag time because it is presented as a rolling average concentration over the previous 10 min or 30 min.

3.2 Mine B

Mine B monitored a highwall mine with no underground mains headings. It was found over a number of tests that 62% of DPM within the panel was generated by Carriers hauling Shields in the gateroads and 38% generated by vehicle movement along the LW face. Air passing down the segregated belt gateroad reached the face clean and could have been used to better effect on the face where operators were installing newly arrived shields. When planning LW moves mines should evaluate and review alternatives for ventilating shield travel roads to the face. The DPM plots in Fig.3 show variability with the Dozer working as four shields were installed. The difference between LW Maingate (MG) and Tailgate (TG) plots clearly shows contributions of the face Dozer.

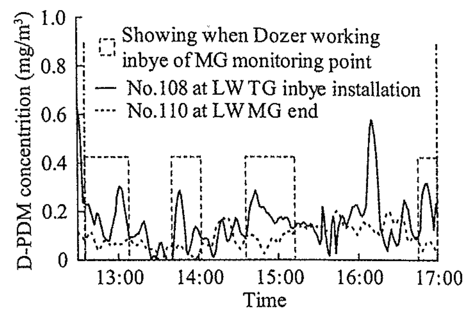

Fig.3 DPM in Mine B LW installation face outbye/inbye the face working dozer

3.3 Mine C

Fig.4 shows the influence of DPM make from diesel activities at a LW face with outbye monitored levels subtracted. The close match between time the chariots and loader were operating in the face and monitored pollution levels inbye is clearly seen.

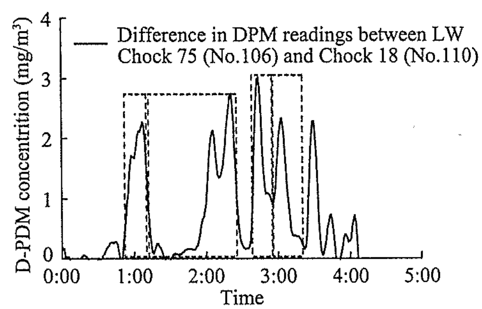

Fig.4 DPM and diesel equipment activities in Mine C LW installation face

An audit was completed on sources of DPM within the LW installation panel by strategic placement of the DPM monitors. It was found that 25% was contributed from outbye diesel activities in mains, 25% from diesel activities in panel the Travel Road, and 50% from diesel activities within face areas. A good initiative in this mine has been to limit the number of vehicles in the panel by the use of a Tag Board and Traffic controller at the panel travel road entrance. The diesel Tag Board design should consider the diesel loading from outbye mains diesel activities which account for up to 25% of the total diesel LW panel loading. Summary of DPM levels from each shift at points monitored throughout the panel showed increasing levels from influence of additional equipment in series in the ventilation circuit.

3.4 Mine D

Mine D tests on the recovery face were in a well ventilated situation with gateroad belt heading air diluting adequately DPM pollution from the gateroad travel heading. An electric tracked "mule" moved Shields along the face and did not add DPM pollution. Fig.5 shows influence of DPM make at the installation face with outbye monitored levels subtracted.

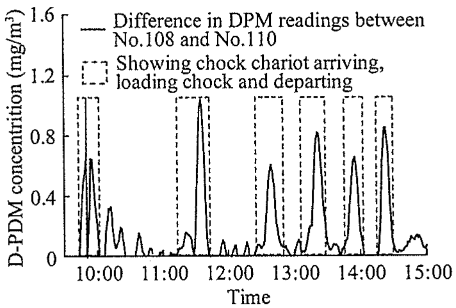

Fig.5 Difference in outbye and inbye DPM in Mine D LW installation face

3.5 Mine E

Mine E examined one 2.5 hour period as a 37 tonne Dozer was brought in to pull the first shield on recovery a LW face as shown in Fig.6. About 51 m^3/s of air was measured on the LW recovery face. Between 14:45 and 15:32, the Dozer attempted to pull out the first shield but was unsuccessful. It worked hard much of the time at maximum engine power. Between 15:32 and 16:00 a Shield Carrier Chariot was chained to the Dozer and together they successfully pulled the first Shield while working hard. A general observation on LW moves was that some high submicrometre aerosol readings were recorded due to the large numbers of diesel activities in working sections of the mine. This was contributed to by frequent vehicle movements or traffic jams. Miners should not be placed working inbye heavy vehicles working very hard such as the dozer when pulling shields. For the LW move routes it is best if vehicle travels against airflow direction.

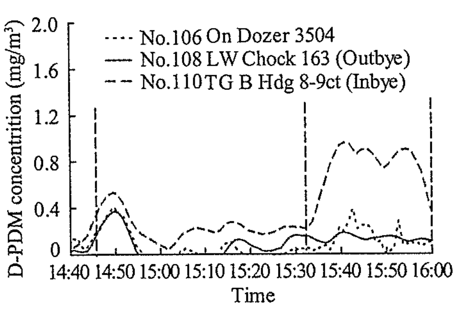

Fig.6 Submicrometre DPM in LW recovery face pulling shield

3.6 Mine F

Mine F monitored a highwall mine with no underground Mains headings. Ventilation quantity was high and air entered the panel in a clean state.

The main diesel activities at LW installation face and within the panel are an EIMCO delivering Shields into face from MG side of face and a Shield Chariot transporting units from portal to MG side of the installation face. A total of seven Shields were installed during the survey period as shown in Fig.7. For the seven peaks or higher levels of DPM, cycle time and DPM make were identified and calculated. The DPM makes varied from 7.6 to 14.8 g/cycle with cycle time ranging from 25 to 54 minutes. This compared well with other mines' data. For example LW move from one neighbouring mine shows DPM makes ranging from 3.0 to 22.4 g/cycle and cycle times from 16 to 29 minutes for operations of Shield Chariots (arrived, unloaded shields and departed) and EMICO 936 (into face, repositioned Shields and out of face). The short cycle times in the other mine were due to the Chariots only needing to travel half the length of the LW panel.

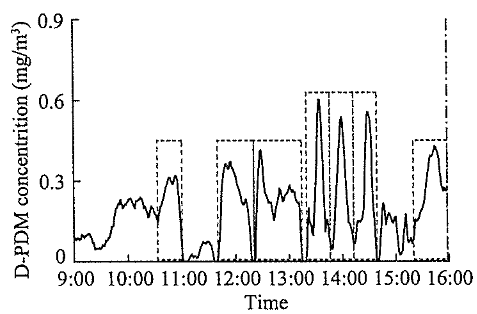

Fig.7 Submicrometre DPM of a chariot transporting shield to installation face

3.7 Mine G

During the LW Move real-time DPM surveys at Mine G, one of the D-PDM units was placed on board the Chock Chariots to identify the DPM exposure levels of chariot operators. Significant DPM levels were recorded especially when the chariot was travelling in new LW panel TG B Hdg with chock loaded. The high DPM level exposure of the chariot operator in B Hdg is contributed by the following causes: (1) Chariot was working under load thus more exhaust generated. (2) Chariot was travelling in the same direction as the ventilation air flow thus reducing the effective air velocity over the engine exhaust. (3) Chariot was blocking much of the cross-sectional area of the B Hdg thus increasing airway resistance and forcing more air flow through A Hdg and as a consequence leaving less air available to dilute the exhaust from the Chariot.

A simplified Ventsim model was created to demonstrate the last point with chariot travelling in TG B Hdg. Fig.8 shows the effect of the Chariot in B Hdg on the ventilation air split between A and B Hdgs.

A total of 60 m^3/s was available in the TG between A and B Hdgs and it was assumed that air split evenly between A and B Hdgs initially near Mains. A restriction of 67% of the cross-sectional area in the B Hdg by the Chariot loaded with a Shield was assumed. This restriction has reduced the airflow in B Hdg from 30 m^3/s down to 14.5 m^3/s and air velocity decreased from 2.0 m/s to 1.0 m/s. It should be noted that actual air split between A and B Hdg near the installation face was measured at 28 and 32 m^3/s for A and B Hdgs during the surveys.

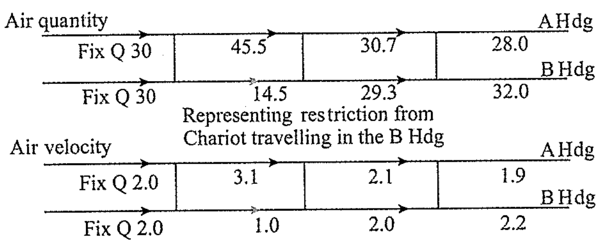

Fig.8 Simplified ventsim model showing the effects of Chariot travel on air split

A chariot took one hour to travel from B Heading near the Recovery Face to the installation face which is about 3.0 km (thus at an average speed of 0.83 m/s). Therefore, a relative velocity of 0.17 m/s (about 2.5 m^3/s with 14.5 m^2 area) across the Chariot's engine exhaust can be calculated. This small amount of air available it had caused the built up of DPM around the Chariot while it was travelling inbye in B Heading with a shield which is evidenced by the high exposure level measured by the D-PDM unit on board it.

3.8 Mine H

Mine H completed an audit on sources of DPM within a LW installation panel by strategically placing the real-time DPM monitors at points as shown in Table 1. DPM make values account for DPM monitored value in air (mg/m^3) and air quantity diluting the exhaust (m^3/s). These values (mg/s) give a value that can be compared for different equipment under varying ventilation and other mine conditions.

Table 1 Sources of DPM identified in the installation LW panel in Mine H

Location	Sources (μg/s)	Concentration (%)	Comments
MG C & D Hdgs	3.03	18.6	Mains air at MG entrance
Borehole	0	0	Back of LW panel, fresh air
LW Face	4.77	29.2	Shunting Mule or LHDs
TG D Hdg	6.96	42.6	Shield carriers travel way
TG C Hdg	0	0	No diesel activity
Leakages	1.57	9.6	Mains air; coffin seal & double doors
Measured total	16.32	100	

4 Comparison of DPM results from parallel SKC and D-PDM tests

It is appropriate to compare field results from the real-time DPM monitor with another available measuring instrument, the NIOSH developed SKC impactor system. The SKC system delivers laboratory analysed shift average results and not real-time results. During investigations parallel underground SKC were taken for comparison with the real-time DPM monitored results. These samples came from the same mine atmosphere through careful use of a system of gaining a discrete mine atmospheric sample with outlets for real-time DPM and SKC monitors. Under the SKC system the sample submicrometre fraction is deposited on a filter after first passing through a respirable cyclone sampler and a 0.8 micrometre impactor that removes most of the mineral fraction of the sample. The sample filter is laboratory analysed.

Fig.9 shows a related set of results, namely those with a total 81 parallel (taken by SKC and D-PDM methods) samples taken from Mines A to HLW moves.

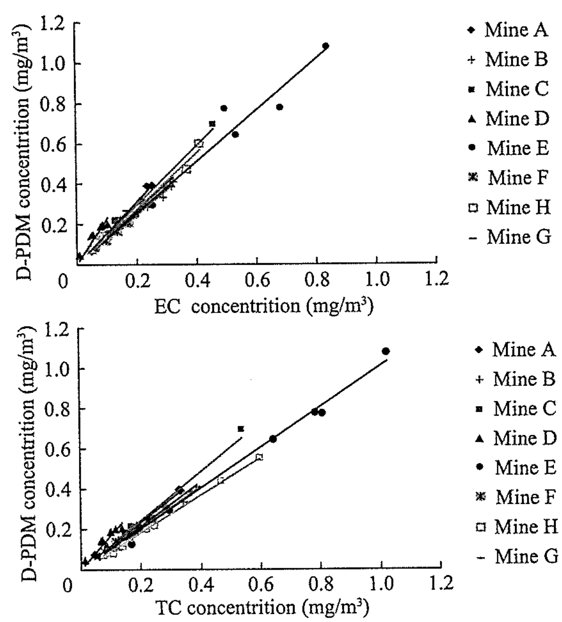

Fig.9 Mine individual relationships between EC, TC and Submicrometre DPM

Real-time DPM results (designated as D-PDM) are compared with shift average SKC impactor determinations of EC and TC particulate. Close correlations were found in all cases (R^2 ≥0.94) for TC versus DPM. All EC versus DPM correlations were good (R^2 ≥0.75). Results also demonstrate that relationships (the slopes of the individual mine relationships) vary between mines. This difference is suspected to be due to variations between mines in for instance atmospheric contamination, vehicle fleet variations, fuel type, engine maintenance, engine combustion efficiency, engine behaviour, or interference from other submicrometre aerosol. Mine H has had separate real-time DPM surveys undertaken on three occasions during LW moves in 2007, 2010 and 2011. At each yearly survey parallel samples were taken with SKC cassettes and EC and

TC NIOSH 5040 analysis determined. Fig.10 shows this mine's individual relationships between EC or TC and Submicrometre DPM from this survey data. Mine H data exhibits excellent correlations between EC and submicrometre DPM results for all three surveys undertaken as shown in Fig.10(a). Comparisons similarly between TC and submicrometre DPM relationships shown in Fig.10(b) also show that all three of the relationships fit very closely.

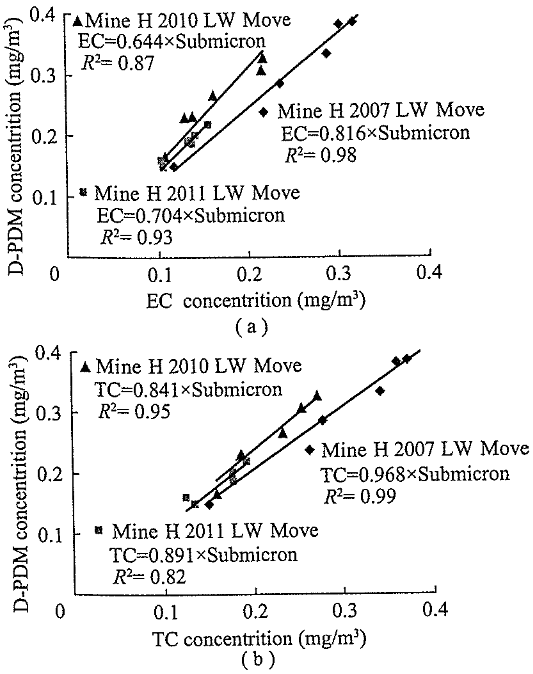

Fig.10 Mine H individual survey relationships between EC, TC and submicrometre DPM

Fig.11 shows combined relationships from averaging data from three surveys between EC and TC and Submicrometre DPM for Mine H. Fig.12 shows combined DPM results from all the mine test series (mines A to H) compared with SKC impactor collection determinations of EC and TC particulate shift average results taken in the particular mine at the same time. Combined mines' relationships are close with R^2= 0.95 for EC compared with submicron DPM. Similar combined mines' relationships are also close with R^2= 0.96 for TC.

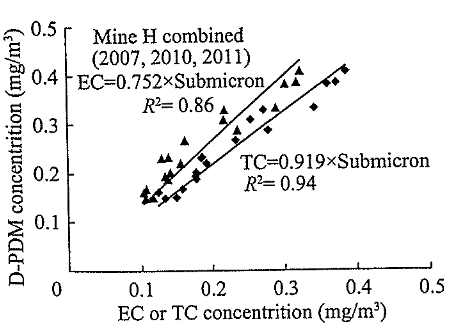

Fig.11 Mine H combined relationships between EC and TC against Submicrometre DPM

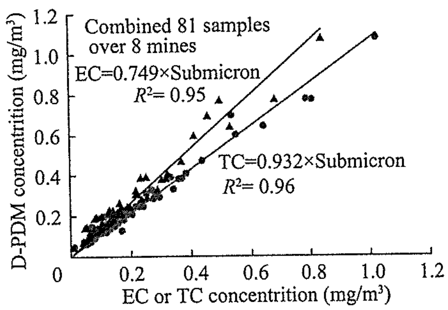

Fig.12 Combined relationships for Eight mines, EC and TC against and submicron DPM

Table 2 gives data from the eight mines including number of parallel sample and D-PDM and NIOSH 5040 impactor EC and TC relationship determinations. All EC versus DPM correlations were good ($R^2 \geq 0.86$) except for data from two mines. Close correlations were found for all cases ($R^2 \geq 0.94$) for TC versus DPM. The results also demonstrate that relationships (the slopes of the individual mine relationships) vary between mines. These differences, as stated previously, are suspected due to variations between mines in air contaminates, vehicle fleets, fuel type, engine maintenance, engine combustion efficiency and behaviour, or interference from other submicrometre aerosol.

There is international debate on the monitoring question of whether submicrometre DPM, TC or EC should be evaluated. The real-time DPM monitor under discussion is the only one measuring the full submicrometre matter. NIOSH recently has developed an EC monitor that operates in real-time using a photodector system. Various studies show that in the normal mine atmosphere (with moderate loadings of respirable dust below statutory limits) the differences and the potential levels of error between the three approaches for monitoring DPM are relatively minor (Birch and Cary, 1996; Birch and Noll, 2004; Dabill, 2005).

Table 2 Summary of individual mine and combined relationships between EC or TC and Submicron DPM

Mine	No. of samples	EC/Submicron factor	R^2	TC/Submicron factor	R^2
A	6	0.645	0.97	0.865	0.99
B	6	0.816	0.98	0.968	0.99
C	7	0.684	0.98	0.827	0.97
D	7	0.450	0.75	0.885	0.98
E	22	0.783	0.98	1.012	0.99
F	6	0.778	0.79	0.954	0.94
G	9	0.724	0.99	0.919	0.94
H	18	0.752	0.86	0.919	0.99
Combined	81	0.749	0.95	0.932	0.96

5 Conclusions

The outcome of a DPM real-time monitoring exercise is that objective testing over different mines and comparisons with SKC impactor shift average monitoring leads to the conclusion that the real-time DPM unit provides useful results. The importance of ventilation has been discussed. The principal industrial application of the unit is to give greater understanding in real-time on DPM levels in mine environments and particularly in engineering evaluation exercises. The paper has discussed how the monitor has performed within the underground mine environment in evaluations of LW moves and has closely examined the influence of aspects of the mine ventilation system on underground DPM pollution.

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