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EVALUATING PERFORMANCE OF REAL-TIME DPM MONITORS FOR QUANTIFYING AIRBORNE ELEMENTAL CARBON (EC) AND ORGANIC CARBON (OC)

K. V. Raj, CDC NIOSH, Spokane WA
D. A. Parks, CDC NIOSH, Spokane WA
M. McNinch, CDC NIOSH, Spokane WA
Ml. Wilson, CDC NIOSH, Spokane WA
A. L. Miller, CDC NIOSH, Spokane WA

ABSTRACT

Diesel particulate matter (DPM) has been shown to contribute to various adverse health effects on underground miners. In order to reduce worker exposures, it is critical to measure the levels of DPM in the active work settings and in real time. However, the 5040 method, developed by the National Institute for Occupational Safety and Health (NIOSH), which quantifies the mass of elemental carbon (EC) and organic carbon (OC) in the samples, is based on full-shift samples, and can take days or even weeks for results. Use of real-time monitors could significantly reduce the risk of DPM exposure to miners, and available monitors have been shown to quantify DPM, mainly using the EC and other surrogates. The NIOSH Spokane Mining Research Division is conducting research aimed at developing a field-portable DPM monitor that is able to quantify both EC and OC. One part of this work is to understand the effect of OC on currently available real-time DPM monitors. This paper will present the results from experiments that were designed to observe the effect of OC on real time monitors and compare the results with the NIOSH 5040 method.

BACKGROUND

Diesel engines remain ubiquitous in mining environments and, as such, are one of the primary sources of ultrafine- and nano-aerosols in the mining environment in the form of diesel particulate matter (DPM). As a result of their small size, DPM has longer residence times in a mine atmosphere than the typically larger mechanically generated dust [1]. In addition, the small size enables DPM to penetrate deeply into the respiratory system [1], and exposure to DPM has been shown to contribute to various adverse health outcomes of the pulmonary system [2] and cardiovascular system [3]. Diesel exhaust has been classified as a carcinogen to humans (Group 1) by the International Agency for Research on Cancer [4]. Due to mounting concern about adverse health outcomes, extensive efforts are being made to reduce workers' exposure to DPM, with the high exposures that often occur in underground mines being of particular concern [5].

New technologies are being developed to reduce engine emissions and thereby airborne DPM levels, including advanced engine technologies, a host of aftertreatment systems [6], and a variety of alternative fuels. The latter have been shown to markedly decrease respirable DPM and other hazardous components of diesel emissions from mining vehicles [7], yet high exposures persist, especially in underground mines [8].

In order to reduce worker exposures, it is critical to measure the levels of DPM in active work settings. In mine settings, exposures to DPM are measured by collecting air samples on filters (usually full-shift samples) and sending them to a lab for analysis using the Mine Safety and Health Administration (MSHA) P13 method, a variant of the National Institute for Occupational Safety and Health (NIOSH) 5040 method. The 5040 method is designed to quantify the mass of elemental carbon (EC) and organic carbon (OC) on the samples [9], which is then used to determine the concentration in the sampled air. MSHA has set a limit for exposure, which is based on the concentration of total carbon (TC), or the sum of both EC and OC. The allowable TC in the air (time-weighted average over the shift) is 160 $\mu g/m^3$ of TC [10].

Quantification of both EC and OC from particulate samples is commonly done using thermal-optical methods [11-13], and the 5040 method is one such method. This approach measures the mass of EC and OC fractions of the sample separately by heating a sample in an inert environment in order to evolve the organic fraction of the sample, followed by the heating of the sample in an oxidizing environment in order to evolve the elemental fraction.

Since the regulatory method requires lab analysis [10], results are often not available for days or weeks and, therefore, have limited utility for informing timely decisions aimed at reducing worker exposures. For this reason, NIOSH is researching field-portable methods for the measurement of carbon, both EC and OC.

While it has been shown that the mass concentration of EC (as determined by way of the NIOSH 5040 method) can be predicted accurately using field-portable instruments [14, 15], the quantification of OC, and thus of TC, has been elusive. Generally speaking, EC has the property of being light absorbing, while OC is significantly less so in the visible region of the electromagnetic spectrum [16]. This allows optical speciation of OC as the fraction of the aerosol which is non-light-absorbing [17]. However, there are thousands of possible compounds which can be considered OC, all of which have different properties and, therefore, react differently with their environment. Because of this, the values attained for the mass of the organic fraction of the particulate matter depend upon the process chosen to measure that mass [18, 19].

Over the last two decades, various efforts have been made to develop field-portable methods for measuring DPM [14, 20-23]. Researchers have evaluated various DPM measurement instruments, including EcoChem Analytics PAS 200, TSI DustTrak DRX 8533, Thermo Scientific PDM 3600, FLIR Airtec, Magee Scientific Aethalometer® AE33, and Pinssar AAMS in underground mine environments to assess their performance [24, 25], but to date no portable (hand-held or belt-worn) methods have been shown to accurately measure both EC and OC.

Most of the existing field-portable methods are based on one of two technologies: light scattering or relative light attenuation (sometimes referred to as light extinction). While light scattering has shown some promise [14], it has limitations related to the inefficient scattering of light from DPM due to DPM's small size, and can be adversely affected by humidity. Light attenuation methods have shown good potential for quantitating EC in mine atmospheres [26], but this approach, which uses EC as a surrogate for DPM/TC can fall short if the ratio of EC to OC varies.

While it has been shown that the air in some mines has a consistent EC/OC ratio, that is not always the case [25, 27] since the ratio can vary due to four issues: 1) in most mines, a variety of diesel-powered equipment is used, and each piece of equipment has a different engine, which have different emission profiles (EC/OC ratios), even when the same fuel is being used, 2) engine load and fuel types are variable, 3) the use of aftertreatment methods, and 4) the presence of cigarette smoke, oil mist, paint spray, or blast fumes may elevate the OC. All of these factors lead to a variability of EC/OC ratios in the air, in both time and space, making it difficult to compare real-time indications of EC with time-weighted average (TWA) measurements of DPM/TC over a work shift, which is how the levels of DPM are measured for regulatory purposes.

With the known shortcomings of light-scattering and attenuation methods, and the goal of advancing real-time DPM measurements through a field-portable device, researchers at NIOSH are working on a project that endeavors to develop a new approach that allows quantification of both EC and OC. As a first step in that work, researchers are evaluating the accuracy and reliability of current real-time total carbon (TC) measurement technologies, in particular when the EC/OC ratio varies. To this end, an evaluation of four different field-portable devices was undertaken, and this paper presents the results of those measurements, as compared against the analysis of side-by-side samples analyzed using the NIOSH 5040 method.

RESEARCH METHODS

The objective of this study is to evaluate to what degree existing field-portable methods for DPM measurement respond to variability in the EC/OC ratio of airborne DPM. More specifically, the study was designed to shed light on what research might be needed to achieve a field-portable method capable of accurately speciating EC and OC in mine air, i.e. to mimic the NIOSH 5040 method.

The research approach involved generating diluted raw engine exhaust and directing it into a quiescence chamber. The aerosol in the chamber was then sampled using four different real-time monitors, while simultaneously collecting filter samples for lab analysis. Multiple tests were conducted, using various engine conditions, each having a unique EC/OC ratio.

For each test, the real-time data were logged with each instrument, and TWA were calculated for the test duration. The collected filter samples for each test were analyzed using the NIOSH 5040 method, as well as a Fourier Transform Infrared spectroscopy (FTIR) method under investigation at NIOSH [28]. The resulting EC and OC data were then compared to the TWA of the real time devices to see how well the results correlated to the EC, OC, and TC from the NIOSH 5040 method.

INSTRUMENT SELECTION

To investigate the most common real-time DPM monitors available, two instruments which relied on light scattering and two which relied on light attenuation were tested. For light scattering, the Pinssar Ambient Air Monitoring System (AAMS) and PDR1500 from Thermo Scientific™ were tested; and for light attenuation, the FLIR Airtec diesel particulate monitor and mircoAeth® MA200 black carbon (BC) monitor from AethLabs were tested. In addition, a method now under investigation by NIOSH, namely FTIR was tested. While this approach has not yet been fully vetted, preliminary data suggest it may hold merit, and therefore it was included in this study. As a reference method for the study, NIOSH 5040 method was utilized; this is the regulatory method used by MSHA for U.S. mines, and it was performed using a Sunset Laboratory Model 5L Carbon Aerosol Analyzer.

Light Scattering

The Pinssar AAMS is a nephelometer and as such measures particulate concentrations by way of light scattered in the sample. The instrument was designed to be a trending monitor for submicron DPM and therefore uses a micro cyclone to exclude all particles larger than 800 nm. The data is available in real-time (and archived) with a variable measurement interval. For this study, measurements were taken every 2 minutes (data is presented as the average value in µg/m³ for a 24-second sampling period). The manufacturer suggests that users calibrate the unit to predict DPM concentrations by using the results from their NIOSH 5040 method monitoring program, taking side-by-side measurements and using the results to readjust the Pinssar's calibration coefficient to match the aerosol in the workplace.

Another light-scattering nephelometer used for the study was the Thermo Scientific PDR1500. These monitors are rugged, portable (belt-worn), self-contained instruments with a built-in data logging capability, and many auxiliary sensors including temperature, humidity, and pressure. The instrument is able to log data at intervals from one second to an hour and has a dynamic range of 0.001 to 400 mg/m^3 [29]. These instruments are typically used for measuring respirable dust, smoke, fumes, and mists in different environments and are factory calibrated using respirable dust aerosols. The PDR1500 also has the option to attach a cyclone pre-selector for sampling a different cut size of particles.

Light Attenuation

The light attenuation method utilizes the principle of an aethalometer, an instrument which exploits the fact that equivalent BC is strongly absorbing in the optical region of the electromagnetic spectrum. An aethalometer collects an aerosol sample on a filter and measures the optical attenuation of light through a filter (due to absorption, scattering and refraction) using one or more light sources and optical detectors. The rate of change of optical attenuation on the filter is proportional to the rate of change of mass concentration of black carbon (BC) particles on the filter. Aethalometer data has been shown to correlate with DPM measurements in mines [30] but requires specific calibration before being used to measure DPM concentrations in occupational settings.

The FLIR Airtec is essentially a single wavelength, single sample spot aethalometer. It has a portable (belt-wearable) rugged form factor and built-in data logger. The Airtec utilizes light absorption at 650 nm, has Teflon filters with variable flow rates of 1.7 and 0.85 liters per minute (lpm), and possesses a dynamic range of 50–600 µg/m^3 (8-hr TWA EC) [26]. Likewise, the microAeth® MA200 is a self-contained, portable (wearable) aethalometer, which measures the mass concentration of light-absorbing carbonaceous particles in a sampled aerosol. The instrument has five analytical channels, each operating at a different wavelength (880 nm, 625 nm, 528 nm, 470 nm, 375 nm) and features the patented DualSpot loading compensation method that measures and compensates for differing optical properties of aerosols. In the MA200, measurement at 880 nm (near infrared regime IR) is interpreted as concentration of BC. Measurement, at 375 nm, is interpreted as Ultraviolet Particulate Matter (UVPM), indicative of organic sources such as wood smoke, tobacco, and biomass burning. The five-wavelength optical engine enables discrimination between organic and elemental particles, which can be helpful in source identification when measuring different aerosols.

Fourier Transform Infrared Spectroscopy

NIOSH researchers are also investigating Fourier transform infrared spectroscopy (FTIR) as a potential method for quantifying EC and OC. While slightly less portable than prism, slit, or grating type spectrometers, the FTIR method has advantages that include better signal-to-noise ratio, throughput, and precise wavenumber measurement [31]. It has been shown that a mid-infrared FTIR method correlates well with the NIOSH 5040 method for EC and OC over a wide range of OC-to-EC ratios [28]. The concentration in the aerosol was measured by collecting it on a quartz filter and then measuring the transflection mode spectrum of the loaded filter.

NIOSH 5040 Method

The NIOSH 5040 method (chosen as the reference in this work) is a thermal-optical technique for which instruments have been developed by Sunset Laboratories Inc. to analyze the samples, which are aerosol type and size independent [13, 32, 33]. The first step in the NIOSH 5040 process is to deposit the DPM onto quartz fiber filters. This is typically done on standard 37-mm SKC quartz fiber filters with 0.8-µm impactors. The loaded filter is then punched to 1 cm^2 (or 1.5 cm^2) and placed in the instrument's oven. The sample is then heated first in a helium (non-oxidizing) environment and then in an oxidizing environment. In both cases, the evolved carbon is oxidized to CO_2, reduced to CH_4, and then detected via a flame ionization detector (FID). The non-oxidizing cycle defines OC aliquot, while the oxidizing cycle defines EC aliquot. By continuous monitoring of the optical transmittance of the sample during analysis, this method aims to make corrections for the pyrolytic conversion of organics into elemental carbon during the non-oxidizing cycle.

DPM GENERATION AND SAMPLING

The goal was to create DPM aerosols that were similar to the ambient aerosol derived in a mine environment after the exhaust exits the tailpipe and to use various engine loads to create DPM with a range of EC/OC ratios. The aerosols were generated using a lab-based system, specifically designed for collecting tailpipe exhaust on samples from diesel engines. The system consisted of a heated and insulated sampling tube, a dilutor, a quiescence chamber, and a multi-port sampling manifold [28]. The samples used for this study were generated using a 6-kW genset powered by a Robin DY42 diesel engine. A variable resistive load bank was used to modify the load on the engine and thereby the EC/OC ratio of the lab samples.

The hot diesel exhaust was drawn through the heated and insulated sampling tube via the suction provided by an ejector-style dilutor (Figure 1), where it was instantly diluted with dry, cool air. The sampling tube was heated to within approximately 10°C of the tailpipe temperature to prevent premature condensation of volatile DPM aerosols. The dilutor was configured to provide a dilution ratio of approximately 10:1, and the secondary airflow exiting the dilutor was directed under slight pressure into a quiescence chamber, where pressure was regulated to around 50 Pa by a separate fan and louvre control that jettisoned some filtered air to the ambient atmosphere.

The quiescence chamber was designed to produce laminar, well-mixed flow. The incoming aerosol comes in at one end near the top and moves slowly downward to the 13 sampling ports that are located in one side of the chamber (Figure 1). Five of the ports were connected to a vacuum manifold, which was fitted with 1.7 liter/min critical orifices. The vacuum supplied to the manifold was maintained at 70 kPa to ensure critical flow through the orifices, using a Gast vacuum pump. Standard 37-mm “DPM cassettes” made by SKC (with quartz fiber filters and 0.8 µm impactors) were used to collect the DPM from five ports. The remaining ports were dedicated to other instruments as outlined in Table 1.

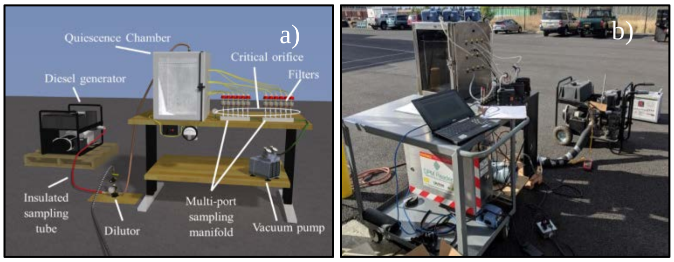

Figure 1. a) Artist sketch of test setup, b) Photo of setup to sample emissions from an operating (loaded) engine.

Table 1. Port setup for different instruments and sampling cassettes.

Instrument	Port #				
SKC Cassette (5040 analysis)	3	6	7	11	12
FLIR Airtec	2	8	9		
PDR 1500	4	5	10		
MA200	1				
Pinssar	13				

Before each test, the diesel engine was warmed up at the predesignated engine load. The real-time instruments (all synchronized to the same clock time) were then turned on and set to log data. The vacuum pump was then started, and the start time recorded. The duration of each test varied depending on the DPM concentration in the chamber. One of the main goals of the sampling procedure was to load the filter samples with adequate mass, as might be collected in the field, but to not overload them. Thus the target mass was ~50–150 µg per filter. Filter loading was estimated by monitoring the FLIR Airtec reading and multiplying by 1.7 LPM and collection time to get the estimated mass on filters. When the estimated mass was approximately 75 µg the vacuum pump was turned off, and the stop time was recorded. The real-time data were downloaded and a TWA value was calculated using the exact time period for which the filter sample was loaded. The filter samples were analyzed by NIOSH 5040 method, and the TWA values for EC and OC were recorded.

Instrument Calibrations

The ports were randomly selected for different instruments and SKC cassettes, and an equal distribution of DPM inside the chamber was assumed. The diesel generator was turned on and allowed to warm up for 5 minutes after which the load bank was switched on at the prescribed load for experiments. The loading at which the experiments were performed were 3,000, 4,000 and 5,000 Watts.

In the first set of three experiments, all the instruments were run at each of the three load settings. This set of experiments was done to properly modify the calibration factor of the instruments, since all the instruments come with a factory calibration setting. The tests entailed generating data from all instruments, while simultaneously taking samples for 5040 analysis. That data set was then used to modify the calibration factor based on the NIOSH 5040 analysis. This was done by comparing TWA data from the 5040 method with TWA data from the logged data stream and calculating a calibration factor that would make the instrument data match the 5040 data.

For light-scattering instruments, the TWA for TC was used since the instrument is designed to estimate mass based on the number and size of particles (available surface area) using a selected dust source. For the light extinction instruments, the TWA for EC was used since that type of instrument is typically calibrated using a source of black carbon or soot. The MA200 did not have the option to change the calibration factor internal to the instrument, thus all calibration was applied in post processing.

RESULTS

Table 2 shows the averaged EC and OC values of the five samples from NIOSH 5040 method and TWA values from all the instruments for the first set of three tests. It can be seen from the table that TC has increased with the increase in loading as does the EC-to-OC ratio.

Table 2. Averaged EC and OC from NIOSH 5040 method and other instruments before calibration.

Loading (kW)	NIOSH 5040 EC (µg/m^3)	NIOSH 5040 OC (µg/m^3)	EC/OC	NIOSH 5040 TC (µg/m^3)	MA200 BC-IR (µg/m^3)	FLIR (µg/m^3)	PDR (µg/m^3)	Pinssar (µg/m^3)
3	345	701	0.49	1,046	547	604	268	544
4	785	818	0.96	1,603	1,103	941	415	770
5	1,486	1,078	1.38	2,564	1,928	1,750	693	1,370

TWA data from the Airtec, MA200, Pinssar monitor, and PDR for the first three tests were plotted against NIOSH 5040 data. Figures 3 and 4 show the plots of instrument data versus NIOSH 5040 data. For the light-scattering instruments (Pinssar and PDR), the TWA values of the three experiments were plotted against the TC values from 5040 analyses, whereas for the Airtec and MA200 (IR channel), the TWA were plotted against the EC values only, since these devices are mainly sensitive to pure carbon species.

The calibration factor of each instrument was changed by multiplying the slope of the linear regression equation by the factory calibration factor. The calibration factors obtained after modification are presented in Table 3. Note that for the MA200, since the calibration factor could not be programmed into the device, the subsequent raw data were multiplied by that factor for comparison of the data in Table 4.

After the recalibration process, three additional tests were conducted to demonstrate the real-time behavior of the instruments after recalibration and to provide data for comparison of the various methods. This was conducted for three cases with varying EC/OC ratios. Table 4 shows the averaged EC and OC values of the five samples from NIOSH 5040 method along with the TWA values from other instruments after modification of factory calibration factors.

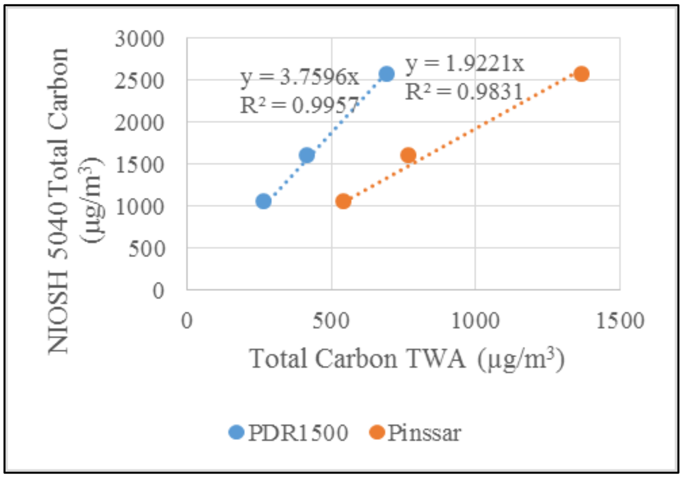

Figure 3. TWA of PDR1500 and Pinssar data versus NIOSH Total Carbon.

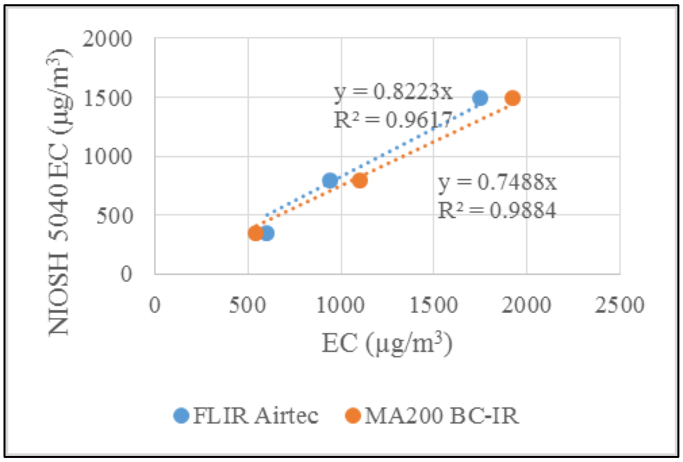

Figure 4. TWA of FLIR Airtec and MA200 BC-IR data versus Elemental Carbon.

Table 3. Modified calibration factors of the instruments.

Instrument	Factory Calibration Factor	Modified Calibration Factor
PDR	1.0	3.76
Pinssar	0.263	0.505
Airtec	217	178
MA200	1.0	0.74

Table 4. Averaged EC and OC from NIOSH 5040 method and other instruments after modification of factory calibration.

Loading (kW)	NIOSH 5040 EC (µg/m^3)	NIOSH 5040 OC (µg/m^3)	EC/OC	NIOSH 5040 TC (µg/m^3)	MA200 BC-IR (µg/m^3)	FLIR (µg/m^3)	PDR (µg/m^3)	Pinssar (µg/m^3)
3	221	502	0.44	723	280	360	1,100	1,043
4	587	660	0.89	1,247	698	683	1,363	1,336
5	1,173	879	1.33	2,052	1,308	1,206	2,350	2,293

DISCUSSION

The experiments with the factory calibration resulted in the Airtec TWA being higher than the NIOSH 5040 EC values (Table 2); however, the Airtec TWA improved with increasing EC/OC ratio (Table 4). After recalibration of the Airtec, there was significant improvement in Airtec versus EC data. In short, the Airtec performs quite well when EC is higher in concentration as compared to OC. Plausible causes of OC's apparent effect on optical attenuation could include:

- The standard method (5040) classifies some elemental carbon as organic. This has been insinuated in the past [18] when comparing the NIOSH 5040 and the IMPROVE methods (both thermal optical).
- Organic carbon contributes to the absorption at 650 nm. This seems unlikely to account for the magnitude of the discrepancy given the attenuation coefficient of OC is more than an order of magnitude less than that of EC [16] and diesel particulate; moreover "black carbon" within diesel exhaust is said to have a chemical composition close to true elemental carbon [19]. On the other hand, worn piston rings and the presence of significant quantities of unburned oil cannot be ruled out under the experimental conditions, and thus the two previous arguments may not be applicable. The attenuation of OC decreases with increasing wavelength, so the relative performance of the Airtec and the MA200 are consistent with this conjecture.
- Volatile organic carbon (VOC) contributes more significantly to the real-time measurement than to the 5040 measurement. Some VOCs have been observed (by the authors) to evaporate from the quartz fiber filter in significant quantities in less than an hour at standard temperature and pressure.

The MA200 instrument likewise showed significant improvement in matching the 5040 EC data after the data were corrected by multiplying the TWA IR-BC by the calibration factor developed in the first set of tests. After that adjustment, the MA200 data were very close to the NIOSH 5040 EC values (Table 4).

The TWA of both the PDR and Pinssar instruments were originally lower than the 5040 TC (Table 2). This shows that the factory settings were too low for this experiment. This is not surprising given that factory calibrations are done with dust that is much larger than DPM. After the calibration factor was updated, both the instruments showed improvement in predicting TC concentration, although both slightly over-predicted for these tests (Table 4). It was also found that the EC-to-OC ratio plays an important role in the accuracy of the TC predictions. Note that for high OC concentrations, predictions were quite high for both scattering devices (Table 4). Again, this could be consistent with previous findings [18].

In addition to the 5040 analysis done on all the filter samples, a tandem analysis was done using the FTIR method described in [28]. This method was developed entirely to mimic the 5040 method without concern as to whether or not the 5040 method accurately speciates OC and EC. The fact that FTIR provides a spectrum of absorption with spectral bands caused by particular chemical functional groups of organic molecules is in effect an unfair advantage when trying to replicate a thermal optical method such as 5040. Further, the ability to place a quartz fiber filter into the spectrometer and then immediately place the same filter into the 5040 instrument is also very advantageous to this approach.

As a result, one may observe that when using a calibration factor developed from several samples [28], the FTIR prediction of EC and OC for each of the tests in the current study (using the average of the five filter samples) compares well with the averaged values from 5040 (Figures 5 and 6).

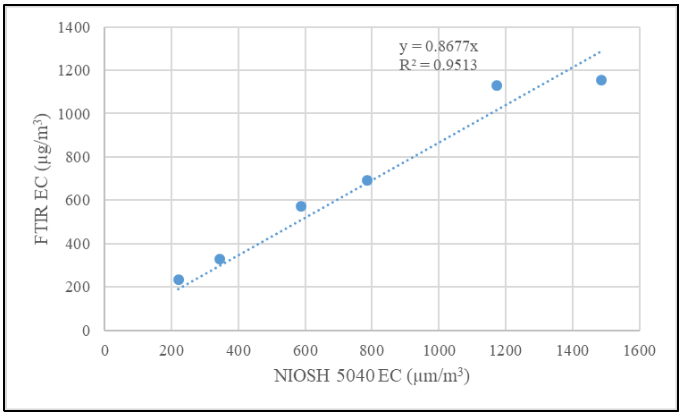

Figure 5. NIOSH 5040 EC versus FTIR Estimated EC.

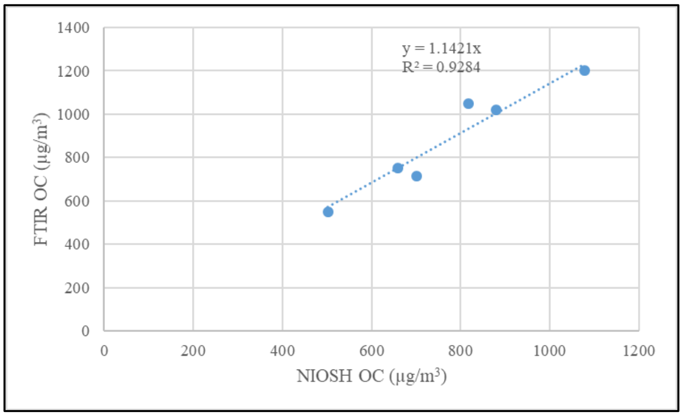

Figure 6. NIOSH 5040 OC versus FTIR Estimated OC.

CONCLUSIONS

The prevailing standard for measuring airborne DPM is the NIOSH 5040 method. This is the process used by MSHA and, therefore, the target for regulatory compliance. To date, there are limited options for a mine seeking to obtain real-time data regarding airborne DPM concentrations. As a field-portable solution would be of enormous benefit to any site looking to improve worker health while following MSHA regulations, this study provides performance data on some available options.

The Pinnsar, which takes advantage of light scattering to determine particle concentration, offers an acceptable level of accuracy provided it is calibrated to a specific environment. Problems may arise, however, in circumstances where DPM is not the only source of submicron TC, such as when pollutants are generated from additional sources; welding, cigarette smoke, oil mist, etc. Additionally, any environment in which the EC/OC ratio is not fixed will likely cause some degree of error in the results. In cases where this is not an interfering factor or calibration does not prove too onerous, the Pinssar will provide satisfactory data. Similar to the Pinssar, the PDR1500 also uses light scattering to determine DPM, and so will have similar limitations. Should a mine find calibration reasonable, and the limitations are well understood, this instrument could also prove capable of estimating TC in mine air in order to help in meeting MSHA standards. The main trade-offs in comparing the two instruments are that the PDR is more portable and has shorter time-resolution, while the Pinssar has enhanced capabilities such as wireless data transmission and the capability to log data for months (which requires automated re-calibration of the optics).

The FLIR Airtec, which is based on the principle of light attenuation, performed well after the calibration factor was modified, but slightly less so when OC levels were high. Measurements with the MA200 instrument were very close to the NIOSH 5040 EC concentration for all the three experiments after adjusting the TWA using the derived calibration factor. In general, both instruments provided fairly accurate estimates of EC and would be useful in mines where the EC/OC ratio is well defined and stable. However, one drawback of MA200 is that it does not have a built-in real-time display. The main trade-offs in comparing the two instruments are that the Airtec has a digital user interface, while the MA200 has shorter time resolution and multi-channel capability.

This study has shown that while field-portable methods based on both light scattering and light attenuation are potentially useful for estimating airborne DPM, both have some limitations, especially when potential interfering pollutants are present or the EC/OC ratio varies significantly. The FTIR method under investigation by NIOSH researchers shows promise for quantifying both EC and OC, and future research efforts will focus on developing a field-portable real-time monitor based on that technology.

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DISCLAIMER

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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