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Differential Pressure as a Measure of Particulate Matter Emissions from Diesel Engines

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A diesel particulate matter analyzer capable of direct, real-time measurement of engine exhaust particulate is necessary to effectively institute source control technology currently being used on diesel equipment and to ensure that the control measures are working. To investigate the potential of a differential pressure monitor to measure diesel particulate matter in undiluted exhaust, samples were collected from three different diesel engines—Kubota, Isuzu, and Deutz—running under 12 different RPM and load scenarios. These measurements were compared to elemental carbon concentrations in the sampled exhaust as determined by using the NIOSH 5040 analytical method. Elemental carbon is used as a surrogate measurement for diesel particulate matter. The results of the two data sets were then compared using a linear regression analysis. The coefficient of determination (or R^2) was calculated to be 0.98, 0.94, and 0.74 for the Kubota, Deutz, and Isuzu engines, respectively. R^2 values of this magnitude indicate that this method can be successful in estimating elemental carbon emissions in the engines tested. In addition, for replicate samples, the coefficient of variation ranged from 7.1% to 10.2% with an average of 8.5%. These data indicate that this method could prove useful to mechanics as they work to maintain engines and DPM control technologies.

Introduction

In an effort to reduce the exposure of the underground metal/nonmetal mining community to diesel particulate matter (DPM), the Mine Safety and Health Administration (MSHA) published an underground metal/nonmetal rule that reduced the allowable concentration of DPM to an interim limit of 400 μg/m^3 and eventually to a final limit of 160 μg/m^3 (*1*). Under this rule, DPM is defined as total carbon (TC), based on the National Institute for Occupational Safety and Health (NIOSH) Method 5040 analysis (*2*), or 1.3 times the elemental carbon (EC) results from the same test (DPM = TC = 1.3 × EC). Currently, MSHA is not mandating a specific course that mine operators need to follow to reach these limits, and thus operators are able to implement their own approach to achieve these concentrations.

The two main avenues available to reduce DPM concentrations in a mine environment are to either reduce the emissions of DPM at the source or reduce the ambient concentrations by increasing the ventilation rates. Because altering ventilation rates and patterns tends to be expensive and difficult, most mine officials will attempt to control DPM emissions at the source. Several options are currently available that will reduce emissions of DPM at the source, including engine design, engine derating, fuel formulations, fuel additives, diesel oxidation catalytic converters, and diesel particulate filters (*3*). The effectiveness of the source control technologies in decreasing DPM emissions has been demonstrated in mines in both Canada and the United States (*4*, *5*).

One problem discussed by these researchers is the lack of a portable, near-real time, commercially available DPM analyzer for undiluted exhaust (*5*−*7*). A method capable of quantifying engine exhaust particulate, directly from the tailpipe, is necessary in order to effectively institute source control technology and to ensure that the control measures are working. Some instruments are commercially available that can estimate DPM in diluted and undiluted exhaust. These include a tapered element oscillating microbalance (TEOM), a nephelometer, an aetholometer, a photoacoustic instrument, and a smoke meter (*6*). While each of these measurement systems has certain merit, their usefulness in a mine environment may not be practical due to the need for expensive and complicated equipment. In addition, the use of a dilution tunnel during DPM measurement studies introduces the potential for the creation of particulate matter artifacts and the coagulation of DPM particles (*8*).

In this paper the results of testing a differential pressure (ΔP) monitor developed to measure DPM in undiluted diesel exhaust are reported. Previous research on the ΔP monitor for ambient particulate sampling (*9*, *10*) demonstrated that the method was useful for measuring aerosols of uniform composition and that small mass loadings of DPM onto filters results in a rapid increase in pressure across the filter. These concepts suggested the use of the ΔP monitor for a direct diesel engine exhaust monitor. In addition, Birch and Cary (*11*) established the use of EC as a marker for exposure to DPM. Because EC constitutes a large portion of the particulate mass, it can be quantified at low levels, and its only significant source in many workplaces is the diesel engine (*11*). More recent studies in both mining and other industries have corroborated the use of EC as a surrogate for DPM (*12*−*14*), and MSHA included the use of EC in the underground metal/nonmetal DPM rule, as discussed above.

This research evaluates the relationship between near real-time ΔP measurements and the amount of EC found on a filter collected from undiluted diesel exhaust. The use of ΔP to track EC emissions can be employed to monitor the deterioration of an engine or the diesel emission control technologies over time. The convenience and affordability of this type of instrument, consisting only of a small pump and a filter probe, would allow it to be used extensively in mines by mine mechanics to determine when servicing is necessary or if a particular engine is exceeding normal operating emission levels. With this information, these mechanics could more efficiently work to maintain the diesel engines and emission control technologies and, thus, reduce DPM emissions, resulting in lower exposure levels for the underground metal/nonmetal community. In addition, as regulations begin to appear that concern diesel emissions to the ambient air, a form of this technology could be useful to mechanics working with on-road diesel vehicles and nonmine equipment to assist them in reducing emissions from these sources.

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TABLE 1. Engine Parameters

parameter	Kubota V1200-B	Isuzu C240	Deutz 912W
combustion chamber type	spherical	swirl	swirl
turbocharging	no	no	no
engine geometry	vertical/in-line	vertical/in-line	vertical/in-line
no. of cylinders	4	4	6
injection system	direct	indirect	indirect
injection pressure	360 bar	117 bar	115 bar
rated power	14.2 bhp at 1800 rpm	56 bhp at 3000 rpm	94 bhp at 2300 rpm
rated torque	2.5 lb-ft at 1800 rpm	108 lb-ft at 2000 rpm	192 lb-ft 2200 rpm

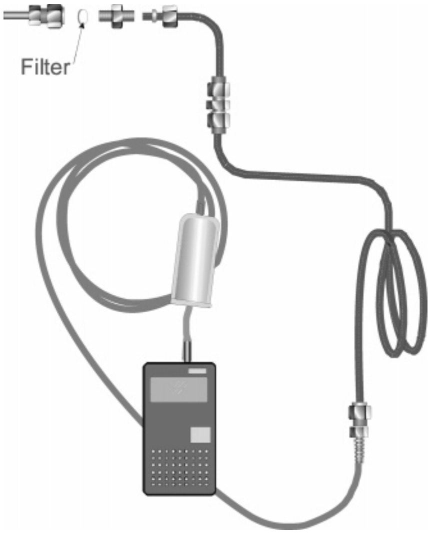

FIGURE 1. Schematic of sampling apparatus.

Experimental Section

The ΔP monitor approach is based on measuring the increase in differential pressure that develops across a glass fiber filter collecting DPM at a flow rate of 0.250 L/min. An incremental increase in DPM upon the filter should correspond to a proportional increase in the differential pressure across that filter.

Description of ΔP Monitor. The basic components of the ΔP monitor consist of (1) a 5.08 cm (2 in.) long, 0.96 cm (0.38 in.) diameter stainless steel inlet probe; (2) a 0.96 cm (0.38 in.) diameter glass fiber collection filter with a custom holder: (3) a flow-controlled sampling pump with a flow capacity of 0.250 L of air/min; (4) a pressure transducer capable of measuring to 0.1 in. of water; (5) exhaust cooling coil; and (6) a pump protective filter. Figure 1 is a schematic of this sampling apparatus. For this investigation, an SKC pocket pump with integral pressure transducer (SKC Inc., Eighty-Four, PA) was used to collect the sample onto the filter.

Sampling Procedure. The sampling procedure for the ΔP monitor was initiated by introducing the sample probe into the exhaust stream of the diesel engine. The probe tip was secured approximately 5 cm (2 in.) into the exhaust pipe by a fabricated clamp attached to the exhaust pipe. The clamp maintained the probe tip at a constant angle to ensure that the exhaust velocity pressure would not interfere with the differential pressure measurements. The diameter of the exhaust pipe must be sufficient so that the combination of exhaust velocity pressure and static pressure are less than the clean filter backpressure, which in this investigation was approximately 4 in. by water gauge.

The clamp, along with the design of the sample probe which had a 90° bend after the filter, allowed the researchers to place and hold the probe in the exhaust stream without being affected by the extremely hot exhaust stream. Keeping the filter in the hot exhaust stream avoided problems with condensation. The temperature of the exhaust stream at the sampling point reached as high as 800 °F, and was measured using a type K thermocouple. It is also important to note that, because the particles of interest were less than 1 μm in aerodynamic diameter, losses due to particle inertia are considered small; thus, isokenetic sampling was not necessary (*5*).

The sampling pump was started exactly as the probe entered the exhaust stream. After 20 s, the initial ΔP measurement in inches of water was recorded. Preliminary tests demonstrated that it took approximately 20 s for the pressure increase to stabilize after the probe entered the exhaust stream. The final ΔP measurement was recorded 60 s later, and the pump was immediately stopped. The probe was quickly removed from the exhaust stream and allowed to cool. Because EC was being collected during the initial 20 s stabilization period, prior to the start of the ΔP measurement, the total sampling time was 60 s for ΔP and 80 s for EC. Once the probes had cooled sufficiently, the glass fiber filter was removed and sent to the laboratory for Method 5040 analysis. The analysis technique is described later in this section.

Because of the diameter of the exhaust pipe and physical sampling obstructions, it was necessary to sample the replicates in sequence. All replicate samples were collected one after the other within a 10-min period. The replicate samples were all collected under steady-state conditions (*15*), thus the diesel engine emission rate should have remained constant. A minimum of three ΔP measurements were collected for each test.

Test Engines. ΔP tests were completed on three different engines: (1) Kubota V1200-B, (2) Isuzu C240, and (3) Deutz 912W. A summary of engine parameters is presented in Table 1. There were no throttle controls on the Kubota engine, thus it ran under constant 1800 rpm. The constant throttle on the Kubota limited the number of modes that could be tested for this engine. Engine conditions were varied using an electric generator by placing a percentage of the rated generator power output on a resistance heater. This engine was only tested under four load scenarios.

For both the Isuzu and Deutz engines, it was possible to change the engine throttle as well as the torque, thus they were tested using the 8-Mode test protocol developed by MSHA (*15*). An eddy-current dynamometer was used to place the necessary loads on the Isuzu and Deutz engines. This system produces braking torque using the principle of eddy currents induced in a rotating magnetic disk, immersed in a magnetic field. The load on the engine was varied by increasing or decreasing the strength of the magnetic field. The operating conditions for each engine at each mode are presented in Table 2.

Elemental Carbon Analysis. NIOSH Method 5040 analyzes for organic carbon (OC) and EC in two different stages using a Sunset Laboratory, Inc. (Hillsboro, NC) carbon analyzer. In the first stage, OC is measured by ramping up the oven temperature over four different temperature steps

TABLE 2. Summary of Engine Operating Conditions

mode		Kubota V1200-B	Isuzu C240	Deutz 912W
1	rpm	1800	3000	2300
	load (%)	80	100	100
2	rpm	1800	3000	2300
	load (%)	50	75	75
3	rpm	1800	3000	2300
	load (%)	20	50	50
4	rpm	1800	3000	2300
	load (%)	no load	10	10
5	rpm		2000	1550
	load (%)		100	100
6	rpm		2000	1550
	load (%)		75	75
7	rpm		2000	1550
	load (%)		50	50
8	rpm		842	675
	load (%)		no load	no load
9	rpm			1550
	load (%)			90

that are programmed into the instrument while pure helium (He) flows over the sample. The temperature steps are approximately 200, 450, 650, and 870 °C. The evolved OC is oxidized to carbon dioxide (CO_2) and subsequently reduced to methane (CH_4), which is measured using a flame ionization detector (FID). Because no oxygen is present to oxidize the EC, it remains on the filter.

In the second stage, the oven temperature is reduced to about 600 °C and then raised to around 900 °C while a mixture of He and oxygen (O_2) flows over the sample, allowing EC to react with O_2 to evolve CO_2. The EC is then measured in the same way as the OC. A heat-treated quartz fiber filter is used as a blank, and a sugar standard is run each day as an OC reference.

Data Analysis. The ΔP results were calculated by subtracting the initial differential pressure from the final differential pressure. This yields the increase in pressure due to the filter loading that occurred in a one-minute period. For each of the replicate sets of ΔP samples, a mean, standard deviation, and upper and lower 95% confidence limits were calculated.

Prior to comparing the ΔP data between each test, it was first necessary to apply a temperature correction. A temperature correction was necessary because the sample flow was being controlled at the sample pump. Since the temperature of the sampled air at the pump was near ambient while the air temperature at the sampling point was at exhaust gas temperature—which ranged between 100 and 800 °F depending on the engine operating condition—the 250 mL/min flow rate at the pump would be proportionally greater at the higher temperatures occurring at the filter. A higher volumetric flow rate through the filter would thus result in a proportional increase in differential pressure across the filter. The proportional increase in air volume was calculated using a form of Charles law shown below:

$$V_2 = \frac{V_1 T_2}{T_1} \tag{1}$$

The percentage increase in air volume was then used to standardize the differential pressure increase measured during each engine scenario. The use of Charles law to standardize the pressure differential is appropriate in this application because the sample probe is open to the atmosphere; thus, the pressure in front of the filter should remain constant.

The EC results were obtained from the Method 5040 laboratory analysis in the units of μg of EC/cm^2 of filter. These data were used to calculate the EC concentration (mg/m^3) of the exhaust stream for each sample by dividing the EC mass (μg) on the filter by the sample volume (m^3) collected over the 80 s sampling period and then correcting for units (μg to mg). For each of the replicate sets of samples, a mean, standard deviation, and upper and lower 95% confidence limits were calculated.

To evaluate the relationship between ΔP and EC, a linear regression analysis was used where EC was the dependent variable and ΔP was the independent variable. The coefficient of determination (or R^2) was computed for each engine type. R^2 is a summary measure of the goodness-of-fit of the model or the proportion of variation in the dependent variable (EC) that can be explained by the independent variable (ΔP). This relationship was also evaluated graphically using an *XY* scatterplot with EC concentration (in mg/m^3) on the *Y*-axis and ΔP on the *X*-axis.

An analysis of variance was used to evaluate the fit of the regression line by using the *F* statistic. The *F* statistic is the ratio of the deviation between the predicted values for elemental carbon and the mean to the deviations about the regression line. If the *F* statistic results in a *p* value of less

TABLE 3. Statistical Summary of Results with Isuzu Engine

	ΔP (in. of water/min)				
test	mean	SD	lower 95% CI	upper 95% CI	coeff of variation (%)
low idle/no load	0.69	0.14	0.35	1.03	19.9
intermediate speed (2000 rpm)/50% torque (20 hp)	2.72	0.47	1.56	3.88	17.2
intermediate speed (2000 rpm)/75% torque (29.7 hp)	4.25	0.17	3.83	4.66	3.9
rated speed (3000 rpm)/10% torque (5.7 hp)	1.88	0.04	1.78	1.99	2.1
rated speed (3000 rpm)/50% torque (25.4 hp)	2.76	0.13	2.43	3.09	4.8
rated speed (3000 rpm)/75% torque (38.4 hp)	3.94	0.27	3.27	4.61	6.8
rated speed (3000 rpm)/100% torque (50.6 hp)	4.58	0.08	3.88	5.27	1.7

	EC concentration (mg/m^3)				
test	mean	SD	lower 95% CI	upper 95% CI	coeff of variation (%)
low idle/no load	6.42	0.61	4.87	7.94	9.6
intermediate speed (2000 rpm)/50% torque (20 hp)	16.77	1.69	12.56	20.98	10.1
intermediate speed (2000 rpm)/75% torque (29.7 hp)	41.02	2.19	35.57	46.47	5.3
rated speed (3000 rpm)/10% torque (5.7 hp)	9.72	1.05	7.10	12.33	10.8
rated speed (3000 rpm)/50% torque (25.4 hp)	15.07	1.50	11.33	18.80	10.0
rated speed (3000 rpm)/75% torque (38.4 hp)	19.79	0.18	19.34	20.24	0.9
rated speed (3000 rpm)/100% torque (50.6 hp)	33.16	2.28	12.64	53.69	6.6

TABLE 4. Statistical Summary of Results with Kubota Engine

	ΔP (in. of water/min)				
test	mean	SD	lower 95% CI	upper 95% CI	coeff of variation (%)
20% load	1.50	0.09	1.36	1.65	6.0
50% load	3.35	0.14	3.12	3.57	4.2
80% load	5.67	0.45	4.95	6.39	8.0
no load	0.95	0.10	0.79	1.11	10.4

	EC concentration (mg/m^3)				
test	mean	SD	lower 95% CI	upper 95% CI	coeff of variation (%)
20% load	32.91	2.78	28.47	37.34	8.5
50% load	54.64	3.84	48.53	60.74	7.0
80% load	92.55	3.45	87.06	98.04	3.7
no load	19.71	0.93	18.24	21.19	4.7

than 0.05, then this indicates that the linear model is appropriate for describing the relationship between ΔP and EC.

The slope and intercept of the regression line were also calculated as an additional comparison between the data sets. The slope represents the rate of vertical change versus the rate of horizontal change along the regression line.

The 95% confidence limit for the population mean for each of the tests was calculated to indicate the precision in the method. The equation used to calculate the confidence limits is

$$\text{sample mean} \pm t_{n-1,0.975}(S/\sqrt{n}) \qquad (2)$$

where t is the student's t distribution, S is the standard deviation, and n is the sample size.

Results and Discussion

Summary statistics of the results for each engine are presented in Tables 3–5. The results from the linear regression analysis of the ΔP and EC data sets are presented in Table 6. Figures 2–4 present this relationship graphically for the Kubota, Isuzu, and Deutz engines, respectively.

The emission concentrations at intermediate speed with 100% load for both the Deutz and Isuzu engines resulted in the pump pressure limits being exceeded during sample collection. As a result, both the ΔP and EC measurements were compromised, resulting in these samples being voided and removed from the data set. For the Deutz engine, a sample was collected at the engine setting of intermediate speed and 90% load to replace the voided samples. Results for this test are included in the data set.

The R^2 values computed using the ΔP data and the EC data indicate the degree to which ΔP can be used to estimate EC in undiluted diesel exhaust. The R^2 values computed for the Kubota, Deutz, and Isuzu engines were 0.98, 0.94, and 0.74, respectively, and are statistically significant at $p < 0.0001$. The coefficient of variation of the ΔP data was 7.1%, 10.2%, and 8.1% for the Kubota, Deutz, and Isuzu engines, respectively.

The F statistic and the resulting p values for each regression model are presented in Table 6. The resulting p values are all highly statistically significant ($p < 0.0001$), indicating that the linear model is appropriate for describing the relationship between ΔP and EC.

The Isuzu engine R^2 value was 0.74, which is lower than those for the other two engines. Also the slope of the data for this engine is flatter than the other two engines tested. There are several possible explanations for the cause of these differences. The Isuzu engine was new and had less than 50 h of running time prior to these emissions tests. It is usually recommended by engine manufacturers to allow 100 h of runtime prior to emissions testing. Both the Kubota and the Deutz had over 100 h of running time prior to these tests. In addition, the sampling setup for the Isuzu engine was different from the other two engines in that there was a muffler installed on the exhaust pipe, and the exhaust pipe was positioned vertically. Neither the Kubota nor the Deutz engines had a muffler installed on the exhaust pipe, and both exhaust pipes were horizontal.

The data from these tests indicate a statistically significant linear relationship between the ΔP reading and the amount of EC depositing on the collection filter. This relationship identifies a potential method to achieve a relative measure of engine EC emissions. A possible scenario for using the ΔP method would be for a mine mechanic to take a baseline ΔP measurement on a well-maintained engine. This vehicle

TABLE 5. Statistical Summary of Results with Deutz Engine

	ΔP (in. of water/min)				
test	mean	SD	lower 95% CI	upper 95% CI	coeff of variation (%)
rated speed (2300 rpm), 100% load (82 hp)	4.89	0.20	4.40	5.39	4.1
rated speed (2300 rpm), 75% load (62 hp)	2.42	0.14	2.06	2.77	5.9
rated speed (2300 rpm), 50% load (42 hp)	1.84	0.06	1.69	1.98	3.1
rated speed (2300), 10% load (8 hp)	0.95	0.10	0.06	1.84	10.4
intermediate speed (1550 rpm), 75% load (47 hp)	3.00	0.25	2.39	3.62	8.2
intermediate speed (1550 rpm), 50% load (32 hp)	1.49	0.20	1	2	13.5
low idle (675)/no load	0.25	0.09	0.04	0.46	33.6
intermediate speed (1550 rpm), 90% load (57 hp)	5.31	0.48	4.12	6.49	9.0

	EC concentration (mg/m^3)				
test	mean	SD	lower 95% CI	upper 95% CI	coeff of variation (%)
rated speed (2300 rpm), 100% load (82 hp)	99.43	5.73	85.19	113.66	5.8
rated speed (2300 rpm), 75% load (62 hp)	34.46	2.12	29.19	39.74	6.2
rated speed (2300 rpm), 50% load (42 hp)	24.34	0.74	22.51	26.17	3.0
rated speed (2300 rpm), 10% load (8 hp)	18.32	0.14	17.05	19.59	0.8
intermediate speed (1550 rpm), 75% load (47 hp)	50.12	11.77	20.88	79.36	23.5
intermediate speed (1550 rpm), 50% load (32 hp)	29.42	0.65	27.80	31.05	2.2
low idle (675 rpm)/no load	3.68	0.07	3.52	3.85	1.8
intermediate speed (1550 rpm), 90% load (57 hp)	115.52	3.27	107.41	123.64	2.8

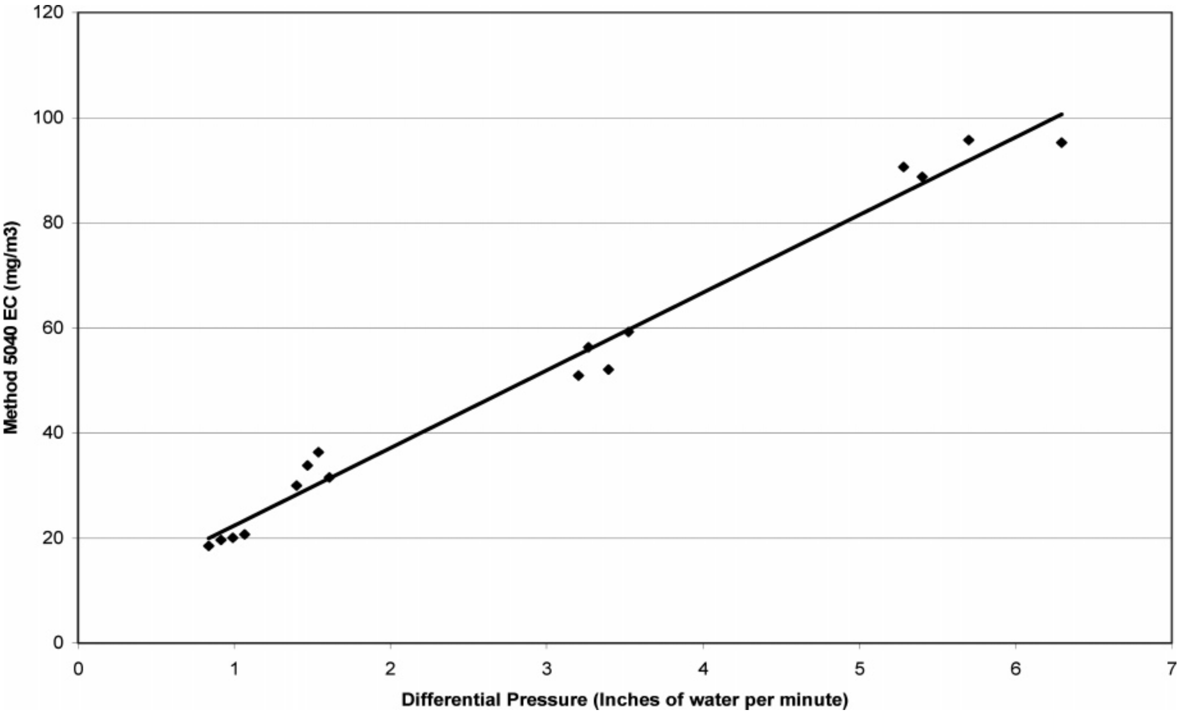

FIGURE 2. Scatterplot of differential pressure vs EC data sets for the Kubota engine.

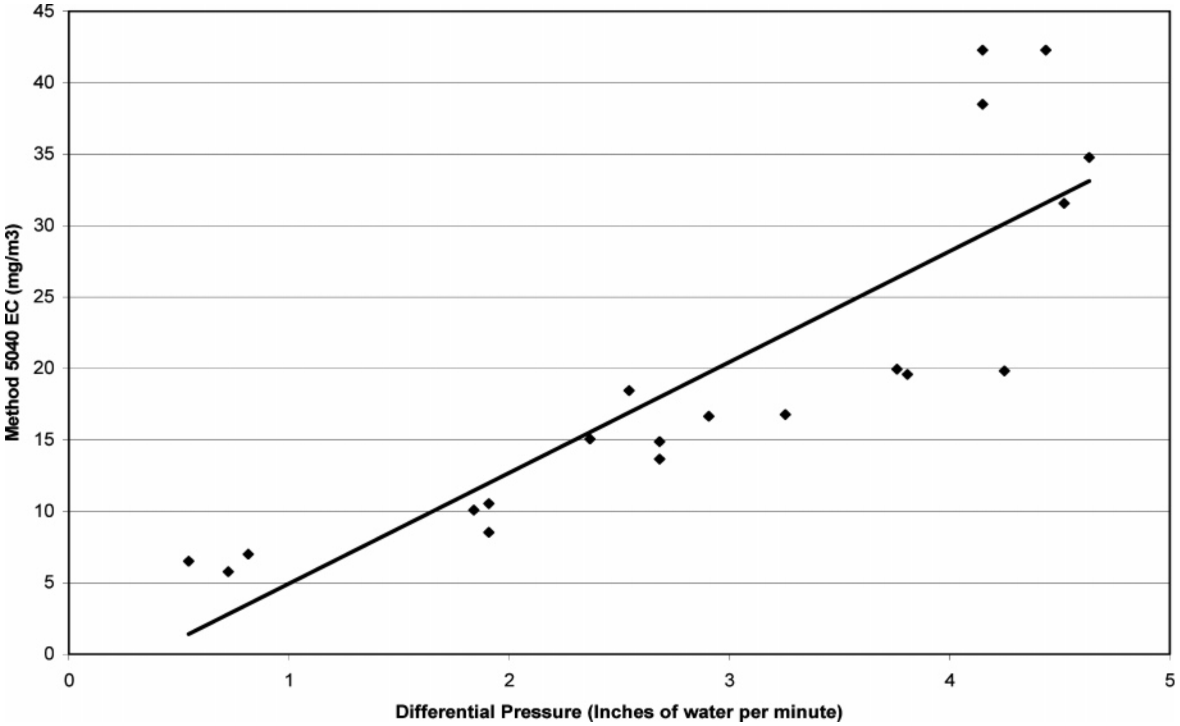

FIGURE 3. Scatterplot of differential pressure vs EC data sets for the Isuzu engine.

could then be tested routinely and once ΔP exceeded a preset number, identified through emission tests, the vehicle would be sent back to the shop for maintenance. Currently, routine testing of gaseous emissions from diesel engines is common in mines. The ΔP test could be added to this set of tests to help ensure that the equipment is properly maintained and that the DPM emissions are controlled. In the same way, the ΔP method could be used to ensure the efficiency of DPM emission control devices, such as diesel particulate filters (DPFs). When DPFs are new, the DPM emissions will be negligible and will not be detected by the ΔP method.

TABLE 6. Correlation of ΔP and EC Data

statistic	Kubota V1200−B	Isuzu C240	Deutz 912W
R^2	0.98	0.74	0.94
slope	14.8	7.7	21.6
y intercept	7.5	−2.8	−7.6
n	16	20	23
F statistic	876.64	50.66	328.93
df	1, 14	1,18	1, 21
F statistic *p* value	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$

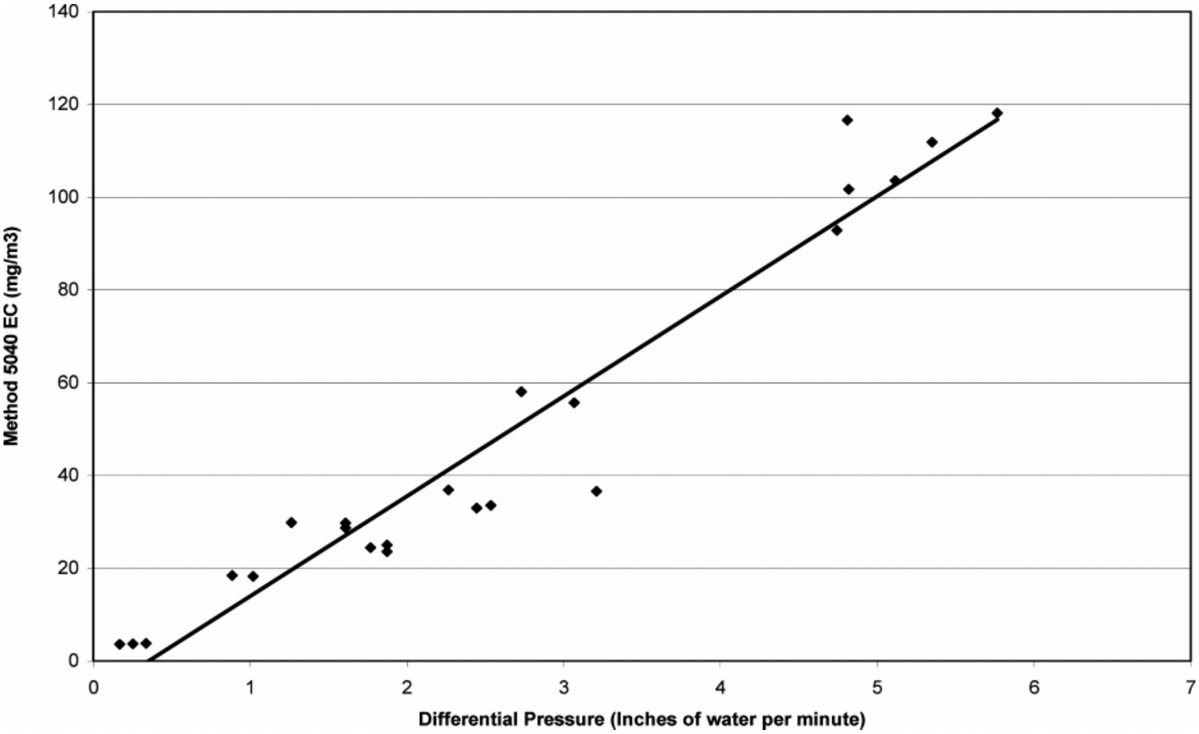

FIGURE 4. Scatterplot of differential pressure vs EC data sets for the Deutz engine.

However, as the DPFs age, leaks can occur. Once a leak occurs, the DPM emissions will increase, and this increase will be detected during a routine test using the ΔP method, allowing the DPFs to be exchanged when necessary. The effect of better maintenance of engines and control technology will be a decrease in both the emissions of DPM from the diesel equipment and the ambient concentrations of DPM in the underground metal/nonmetal mine environment. In addition, further work on this method, involving measurements on a larger number and variety of diesel engines, will refine this technique and enable it to be applicable for DPM emission measurements on a wide range of nonmining diesel vehicles and equipment. The need to perform these measurements will be important as regulations for diesel emissions to ambient air become more stringent. The convenience, ease of use, affordability, and almost real-time nature of the data indicate that the ΔP method could prove useful to mine operators and mechanics as they work to maintain engines and DPM control technologies.

There is not sufficient data presented here to develop a calibration curve for using the ΔP method to calculate an EC concentration in the exhaust plume. The development of these calibration curves need to be addressed in future work if an EC concentration measurement is desired. During this future work it will be necessary to establish guidelines for engine operating conditions during the ΔP method tests, such as running the engine at a torque/stall or a high idle condition. Changes in these operating conditions create differences in the characteristics of the emitted DPM, such as increasing or decreasing the amount of organic carbon absorbed to the EC. A change in the absorbed organic carbon could affect the filter backpressure characteristics (*16*) and the resulting ΔP measurement. Characteristics of the emitted DPM also change depending on the engine type. These engine differences will also need to be addressed if a single calibration curve is to be established.

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