Calibration of low-cost particulate matter sensors for coal dust monitoring

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Abstract

Mining-induced coal dust causes various respiratory diseases to mine workers mainly coal workers' pneumoconiosis (CWP). Currently available underground monitors are expensive and bulky. These disadvantages limit them for regulatory sample monitoring purposes. Moreover, personal exposure levels for most miners remain unknown, risking them to potential overexposures. Low-cost light scattering particulate matter (PM) sensors offer a potential solution to this problem with the capability to characterize PM concentration with high spatio-temporal resolution. However, these sensors require precise calibration before they can be deployed in mining environments. No previous study has promulgated a standard protocol to assess these sensors for coal dust monitoring. The goal of this study was to calibrate Plantower PMS5003 sensors for coal dust monitoring using linear regression models. Two other commercially available PM sensors, the Airtrek and Gaslab CM-505 multi-gas sensors, were also evaluated and calibrated. They were evaluated for factors including linearity, precision, limit of detection, upper concentration limits, and the influence of temperature and relative humidity in a laboratory wind tunnel. The PMS5003 sensors were observed to be accurate below 3.0 mg/m^3 concentration levels with R-squared values of 0.70 to 0.90 which was the best among the sensors under with an acceptable precision below 1.5 mg/m^3. Moreover, this study shows that temperature and relative humidity have minimal influence on the efficacy of low-cost PM sensors' ability to monitor coal dust. This investigation reveals the feasibility of low-cost sensors for real-time personal coal dust monitoring in underground coal mines if a robust calibration model is applied.

1 Introduction

Coal dust concentrations in underground mines can be considerably higher than surface mines due to limited ventilation to dilute the coal dust. This puts underground mine workers at a greater risk of coal dust overexposure. Overexposure to respirable coal mine dust (RCMD) has resulted in the onset of irreversible diseases, such as coal workers' pneumoconiosis (CWP), emphysema and chronic bronchitis collectively known as 'black lung" which can cause permanent disability and premature death (MSHA, 2014). Miners have also been diagnosed with silicosis due to exposure to coal dust with high silica contents (Knight et al., 2020; D. Wang et al., 2020). In recent times, there has been a resurgence of CWP among US coal miners (Blackley et al., 2016) which is of great conern to the mining industry. Contrary to common understanding that CWP is only associated with long-term coal dust exposure, recent data indicates that advanced CWP has been found in younger coal miners (MSHA, 2014).

Accurate real-time personal dust exposure monitoring is essential to alert mine workers to change behavior and apply mitigation methods to reduce their exposure when working. The Mine Safety and Health Administration (MSHA) requires the use of continuous personal dust monitors (CPDM) for measuring RCMD mass concentrations and determining compliance with the regulatory exposure limits. However, current CPDM devices are expensive and bulky (Badura et al., 2018; Barakeh et al., 2017; Kelleher et al., 2018; P. Kumar et al., 2015). For example, PDM3700 is the MSHA certified CPDM to be used in coal mines, but it costs ~\$17,000 and weighs 2.0 kg (Halterman et al., 2018). These expensive PDMs are worn only by a few miners for regulatory compliance monitoring. These are mainly miners who are exposed to the highest coal dust concentrations at their work locations and those who have already been diagnosed with pneumoconiosis (MSHA, 2014). This practice has serious drawbacks, most notably is that the exposure levels for most miners are unknown. Besides, dust control effectiveness of modified engineering control strategies is not well understood by mining engineers due to lack of sufficient monitoring data. Finally, there is a lack of sufficient exposure information to accurately correlate coal dust exposure to its related-health data in epidemiology studies.

Light scattering low-cost particulate matter (PM) sensors have the potential to accurately monitor coal dust concentration in real time. The low cost, small size, and low power requirements of these sensors offer the promise of being widely worn by all coal mine workers. These could yield accurate concentration information if properly calibrated. Even though this technology has been significantly explored by researchers for other environmental applications (Kelly et al., 2017; Li, 2019; Sousan et al., 2016; Y. Wang, Li, Jing, Zhang, Jiang, & Biswas, 2015a), it remains a new technology for monitoring coal dust (Amoah et al., 2022). Because of questionable accuracy and long-term reliability of these sensors, it is critical to adopt a systematic approach to evaluate and effectively calibrate these sensors before they can be applied for coal dust monitoring. Many low-cost PM sensor calibration studies have demonstrated promising results in comparison with

Federal Equivalent Methods (FEMs) or research-grade instruments for air quality PM monitoring (Chen et al., 2019; De Vito et al., 2008; D. Liu et al., 2017; Spinelle et al., 2013; Y. Wang, Li, Jing, Zhang, Jiang, & Biswas, 2015b). However, there are very few studies that investigate the performance and application of low-cost sensors for monitoring coal dust. Existing research by governmental agencies such as US Environmental Protection Agency (EPA) (Williams et al., 2014) and European Metrology Research Program (EURAMET) (Spinelle et al., 2013), as well as research in the literature (Y. Wang, Li, Jing, Zhang, Jiang, & Biswas, 2015a) have established standard protocols for calibrating low-cost PM sensors for environmental PM monitoring. However, there is still limited understanding of how these calibration models will perform with mining-induced coal dust.

The objective of this study was to evaluate and calibrate three types of lower cost PM sensors against a FEM reference monitor, Personal Dust Monitor (PDM) model 3700 and a research grade Aerodynamic Particle Sizer (APS) model 3321. A custom-built wind tunnel in the laboratory was used for the calibration experiments. Sensors and monitors were exposed to various levels of concentration within the tunnel to generate the linearity plots between the sensors and the reference monitors. Since several studies have established the linear relationship between light scattering low-cost PM sensors and reference monitors, univariate calibration models using linear regression were developed based on the linearity analysis to calibrate the sensors (Austin et al., 2015; Ghamari et al., 2022; Kelly et al., 2017; Liu et al., 2017; Polidori et al., 2016). The precision, limit of detection and upper concentration limits were evaluated to provide further understanding of the sensors' performance with coal dust. A 2^2 factorial design was used to determine the influence of temperature and relative humidity (RH) on the sensors' performance at low (~0.5 mg/m^3) and high (~1.5 mg/m^3) coal dust concentration levels. This method provides an understanding of the influence of each of the two levels of both temperature and RH on sensor outputs as well as the interaction of both conditions. The implementation of these sensors for coal dust monitoring will expand personal exposure monitoring in mines as every miner can wear one to detect timely overexposures to ensure timely controls are engineered to protect miners' health. On a broader scope, low-cost PM sensors can greatly supplement more expensive research grade monitors used in other occupational environments.

2 Experimental Methods

2.1 Low-Cost PM sensors and reference monitors

Three low-cost PM sensors were evaluated in this study – the Plantower PMS50003 (PMS) low-cost PM sensor, the Airtrek PM sensor, and the Gaslab CM-505 multi-gas sensor. Two units of each sensor were evaluated. The Gaslab sensor, shown in Figure 1 (a) measures PM 2.5 and PM 10 particle concentration together with oxygen, carbon dioxide and carbon monoxide concentrations. The Gaslab uses a combination of NDIR sensors, electrochemical sensors, and fluorescent sensors to measure gases and uses laser scattering technology to measure PM 2.5 and PM 10. The Airtrek sensors on the other hand, shown in Figure 1 (b) use light scattering principles like that of the Plantower PMS5003 sensor to measure PM concentrations. The Airtrek sensors measure PM in four size bins of 1.0 µm, 2.5 µm, 4.0 µm, and 10.0 µm.

The Plantower PMS5003 (shown in Figure 1(d)) was used to assemble in-house made dust monitors. They are inexpensive light scattering PM sensors that are commercially available for about $ 30. This sensor employs a fan to draw ambient air into the light scattering measuring cavity through its inlet. As illustrated in Figure 1 (c), the LED radiates laser-induced light into the sensing area to target particles within the measuring cavity. Light is scattered as it hits the particles. It is detected by the photo-diode detector, which is positioned at 180° with the LED light. The scattered light received by the photo-diode detector sends pulses of electric signal to the in-built microprocessor. The number and intensity of electrical signals detected by the microprocessor are then converted to number and mass of particles respectively based on MIE theory (Yong & Haoxin, 2016).

These PMS sensors characterize PM by size into PM1, PM2.5, and PM10. The manufacturers of the PMS sensors state that PM1 is measured for particles in the size range of 0.3 µm to 1.0 µm, PM2.5 for particles in the size range of 1.0 µm to 2.5 µm and PM10 for particles in the size range of 2.5 µm to 10.0 µm. For each size category, the PMS reports two PM outputs, one without any form of correction factor, called standard PM concentration (or CF = 1) and the other with an atmospheric calibration factor, called environmental PM concentration. The manufacturers have not published any details about the calibration factor and how it was developed. Therefore, due to considerable uncertainties about manufacturer calibration, the standard PM concentrations were used for this study. Manufacturer specifications indicated high anti-interference performance using non-PM shielding technology. Previous studies have also shown that the Plantower sensors have superior performance as they have been integrated into PurpleAir air quality monitors (Sayahi et al., 2019). These characteristics justify the reason the PMS sensors were used for this study.

Together with a DHT-22 temperature and relative humidity sensor, NodeMCU ESP8266 (Systems, 2015) and a 4 line by 20-character LCD screen, the PMS5003 was integrated into a prototype monitor (low-cost PM monitor) as displayed in Figure 1 (e). This monitor was programmed with Arduino IDE to display real time concentrations of PM2.5 and PM10, temperature and relative humidity readings every 1.0 s onto the LCD screen. To protect the low-cost PM sensor and its critical components from rainfall, sunlight, and physical damage, the sensor, and its components are housed in a 10.0 cm x 4.0 cm x 1.5 cm acrylic plastic box. This also allowed the team to see the screen readings in real time through the transparent acrylic case. The side of the acrylic case is strongly fastened but left uncovered to allow for normal operation of the PMS sensor without interference to the sensors' exposure. The low-cost PM monitor is continuously powered using a 5.0 V USB cable. For data analysis, the PM monitor is interfaced with a ThingSpeak Matlab based online IOT platform which serves as a cloud where all data is transmitted through Wi-Fi.

(a) *Gaslab CM-505 multi-gas sensor*

(b) *Airtrek PM sensor*

(c) *Schematic PMS5003 sensor* (d) *Plantower PMS5003 sensor* (e) *PM monitor*

Figure 1. Low-cost PM monitor: (a) schematic diagram of the plantower PMS5003, (b) a picture of the Plantower PMS5003 sensor, (c) the in house fabricated low-cost PM monitor

The primary reference monitor used in this study is the personal dust monitor model 3700 (PDM3700). This is a real time personal coal dust monitor which operates on the principle of tapered element oscillation microbalance (TEOM). It is capable of reporting concentrations at 1-minute intervals. The PDM3700 is equipped with a respirable size inlet installed near the inlet which ensures that the cut-off diameter for coal dust going through the mass sensor is 5.0 µm. This makes it capable of monitoring respirable size coal particles. It is used by miners by mounting the sample inlet, incorporated in the universal cap lamp, on the bill of a miner’s hard hat to monitor dust within the miner’s breathing zone (Volkwein et al., 2006). The National Institute for Occupational Safety and Health (NIOSH) has validated PDM3700’s accuracy, precision, and comfortability, and Mine Safety and Health Administration (MSHA) has approved this equipment as the regulatory compliance monitoring device (Volkwein et al., 2006). This has also been designated as Federal Equivalent Method by the U.S. Environmental Protection Agency (EPA) for environmental air quality PM monitoring (US-EPA, 2012).

The APS measures PM mass and number concentration by particle aerodynamic sizes from 0.5 µm to 20.0 µm using the time-of-flight principles. To make it comparable with the PDM, PM concentration of particle size ranging from 0.00 to 4.37 µm from the APS was used for this study since it compares with the 4.37 µm D_{50} of the PDM cyclone. The APS draws ambient PM-laden air into the monitor through a nozzle at an accelerated flowrate of 5.0 liters per minute. Ideally, the APS needs to sample airflow at the same velocity as the air velocity at the sampling location. In this case, a 0.8 cm diameter nozzle was used to achieve a sampling velocity of 1.5 m/s to get as close as possible to airflow velocity in the wind tunnel. The accelerated airflow goes through the sensing zone where the PM concentrations are measured using the time-of-flight principles. Particle size distribution is then reported every 15 seconds based on the settings used for this study (TSI Inc., 2017).

2.2 **Wind tunnel**

The calibration chamber used in this study is a custom-built wind tunnel made with metal frames and acrylic glass panels (Figure 2). The wind tunnel has a U shape with cross-sectional dimension of the tunnel being 0.5 m x 0.5 m to simulate the airway bends in underground mines. The entire dimension of the U shape is 4.5 m long and 2.0 m wide.

The wind tunnel has a particle generator that is made up of a compressed air duct, dust reservoir with injector, and a concentration regulation valve installed at its inlet which dispenses dry coal dust into the wind tunnel. The injected coal dust goes through an aerosol dispersion system to ensure a homogenous distribution of coal dust particles across the cross section of the wind tunnel. The outlet of the wind tunnel is connected to a dust collector that also enables exhausting type airflow through the wind tunnel. The fan drives air through the wind tunnel at a velocity of 1.0 m/s which is the normal air velocity in underground mines (Roghanchi et al., 2016). The wind tunnel has a platform built at the monitoring location which is 25.0 cm from the top of the tunnel on which the sensors and the nozzles for the monitors are installed.

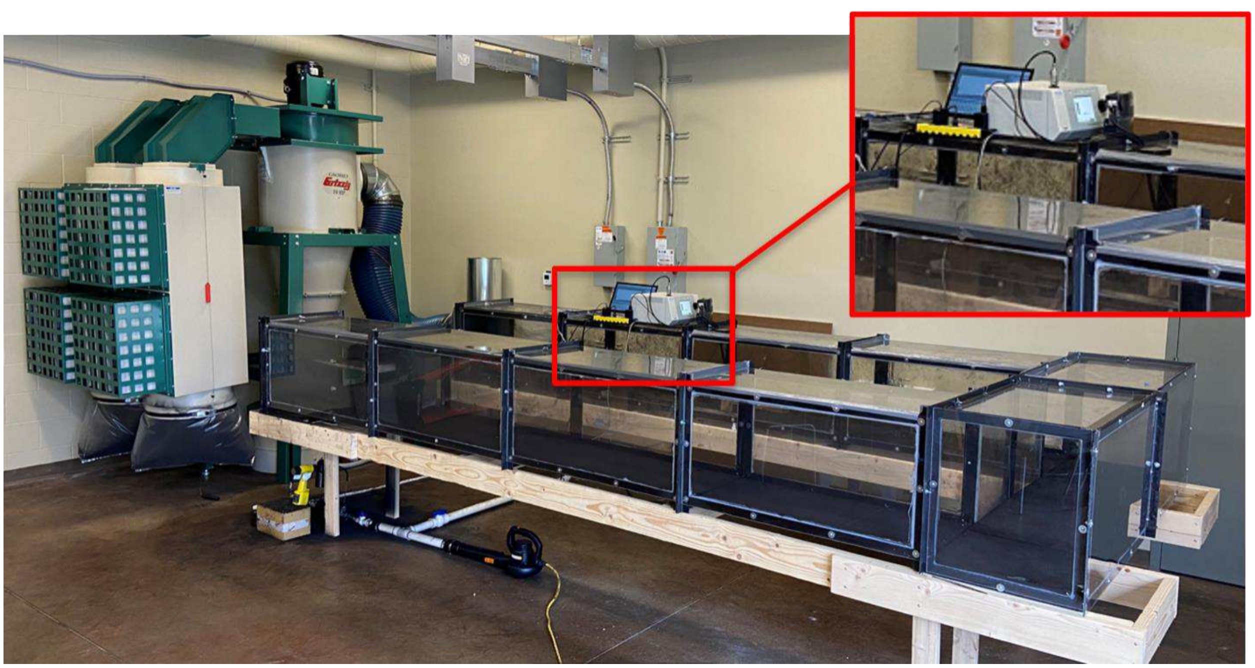


Figure 2. Calibration wind tunnel and the experimental set-up

2.3 Calibration procedure

The coal dust used for this experiment is the Keystone mineral black 325 with a density of 1,220 kg/m^3 with particle sizes in the range of 0.04 µm to 35.00 µm. Detailed characteristics and particle size distribution of this coal dust can be observed in Figure 3 (A. R. Kumar, 2018). Prior to the injection of coal dust particles, the two PMS sensors, APS, PDM, two Airtreks, and two Gaslabs were placed on the monitoring platform in the wind tunnel. The inlets to the sensors and monitors were placed very closely to one another to minimize spatial differences in particle concentration in such a way that did not cause interference with each other's exposure to airflow. Regarding the APS and PDM, the monitors were kept outside the wind tunnel and particles were sampled from the wind tunnel through nozzles which were positioned to face the flow in the tunnel. The remaining sensors and monitors were placed inside the wind tunnel with their inlets facing the flow. It was imperative to ensure that particle concentration at the sampling locations stayed within 10% variation which was observed prior to the start of the experiments using the PDM. This was ensured by performing a preliminary test measuring and comparing the concentrations across the sampling location within the wind tunnel using the PDM. The uniform concentration maintained was the precaution used to ensure that variation in dust concentration between the sensors and monitors was insignificant.

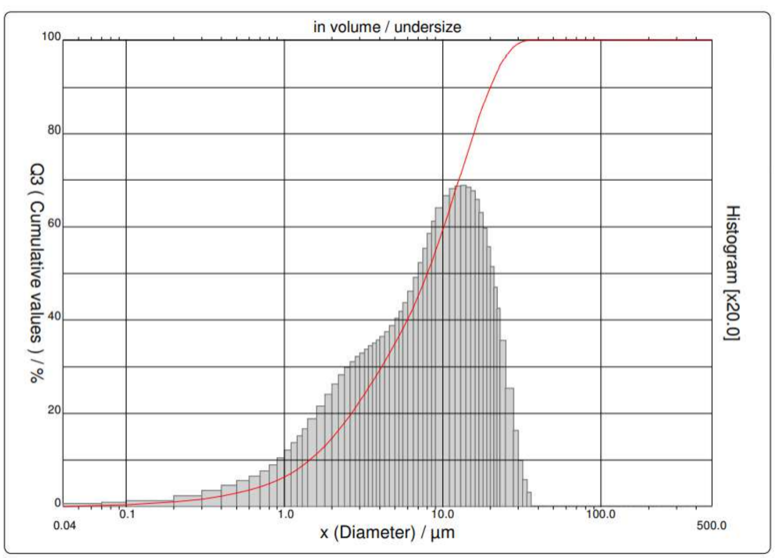


Figure 3. Particle size distribution for Keystone mineral black 325 coal dust

MSHA coal dust regulation is based on end-of-shift Time Weighted Average concentrations of 1.5 mg/m^3 (MSHA, 2014). The dust coal concentration in mines should typically fluctuate around this value, therefore we investigate the sensors' responses to different concentration levels ranging from 0 to 3.0. The coal dust injection rate was adjusted throughout the course of the experiments within that range depending on the test being performed.

The clock times on all sensors and monitors were reset to synchronize the time stamps. Although the APS and PMS sensors were programmed to record real time concentrations every 15.0 seconds, the Airtrek monitor reported concentrations every 30.0 seconds, while the Gaslab reports concentrations every 2.0 seconds. For these sensors and monitor that record their outputs multiple times within a minute, their readings were averaged to get minute-by-minute concentrations for all the sensors to be comparable with the PDM. This data is then used in the evaluation and calibration procedure. The PDM's reported time weighted average (TWA) concentration data were converted to minute-by-minute real-time concentrations using Equation 1 to be consistent with all the other sensors' data. In this equation, TWAn is the time weighted average at each time step, C_n is the real time concentration measured, T is the time interval between successive measurement and Tn is the total number minutes at time n.

$$\mathrm{C} = \frac{TWAn \times Tn}{T} - (C_1 + C_2 + C_3 \ldots . C_{n-1}) \qquad \text{Equation 1}$$

2.4 Calibration matrices

Low-cost PM monitors were evaluated and calibrated based on five calibration matrices: accuracy (linearity), precision, lower limit of detection, upper limit, and temperature and relative humidity influences. These matrices were adopted from the low-cost PM sensor evaluation protocol proposed and used by United States Environmental Protection Agency (US-EPA) (US-EPA, 2013; Williams et al., 2014) the US Air quality sensor performance evaluation center (AQ-SPEC) (Papapostolou et al., 2017; Polidori et al., 2017) and European Metrology Research Program (EURAMET) (Spinelle et al., 2013) which have proven to be comprehensive and effective for low-cost PM sensors. These matrices are elaborated in the following sections.

2.4.1 Linearity

The accuracy of PM sensors is the closeness of sensor measurements to actual concentrations. In the linearity test, sensors and reference monitors were exposed to the same concentrations and environmental conditions within the wind tunnel. During the test, the coal dust injection rate was changed every 10.0 minutes between 0 and 3.0 mg/m^3. During this test, concentrations occasionally spiked above the target 3.0 mg/m^3 for a few seconds after which valves were quickly readjusted to the correct levels. This, however, allowed us to observe the characteristics of the sensors at peak concentrations beyond 3.0 mg/m^3. The linearity of the PMS sensors and the other monitors were assessed using the correlation coefficient from linear regression by plotting the output of monitors against PDM and APS. The concentrations measured by the reference monitors were used as the independent variable, while the concentrations measured by the sensors were reported as dependent variables. Using both the PDM and APS as reference monitors, each sensor is evaluated with both the PDM and APS. The linearity of each sensor and monitor, which is an indication of a monitor's accuracy, is evaluated by the R-squared value calculated using the ordinary least square (OLS) linear regression method. The accuracy of a sensor is lower for those with lower linearity values. The linear regression models generated from this evaluation was then used to derive the calibration equation to improve the accuracy of the PMS to the accuracy of the PDM.

2.4.2 Precision

The sensors' precision was evaluated by the repeatability of the sensors. This was determined by the dispersion of the sensors' measured values at a constant concentration. This would give us the understanding of the consistency and reliability of the PMS outputs in an extended use. Five concentration levels were used for this test - 0.5 mg/m^3, 1.0 mg/m^3, 1.5 mg/m^3, 2.0 mg/m^3 and 3.0 mg/m^3. At each concentration level, conditions were kept constant in the wind tunnel and measurements were taken with sensors for 60 mins. The spread of a sensor's output was determined by the descriptive statistical parameter of interquartile range in boxplots. This measured the spread of the middle 50 % of the data points from the sensors. The interquartile range (IQR) is calculated using the equation in Equation 2 where IQR is the interquartile range, Q1 is the first quartile and Q3 is the third quartile of the data. Q1 is determined by the $((n+1)/4)^{th}$ term of the distribution while Q3 is determined by the $(3(n+1)/4)^{th}$ term of the distribution. This was repeated for the two reference monitors as well to compare the trend of spread of the sensors with the reference monitors.

$$IQR = Q3 - Q1 \qquad \text{Equation 2}$$

2.4.3 Limit of detection (LOD)

LOD describes the lowest concentration limit of sensors that significantly differentiates from sensor outputs at blank concentrations. This tells how the sensors will reliably differentiate concentration changes from instrument noise, which is the short-term deviations in measurements about the mean of a stable concentration which are not caused by changes in concentrations. Different from LOD, the lower limit of sensors was also evaluated as the average sensor output at zero coal dust concentration. The LOD for the low-cost sensors were evaluated by subjecting them to 0.0 mg/m^3 coal dust concentrations over a 60-minute period. This blank condition was be generated by filling the chamber with clean air with no particles and completely shutting off the valves to the dust injection system. For this experiment, air is considered clean when the PDM and APS reference monitors measures 0.0 mg/m^3. Based on outputs of sensors under these conditions, LOD is calculated using Equation 3 (Kaiser & Specker, 1956) where k is the slope from the fitted linear regression model, and σ_{blk} is the standard deviation. In this experiment, these parameters were calculated based on the 60 measurements taken over a testing period of 1 hour.

$$\text{LOD} = \frac{3\sigma_{blk}}{k} \qquad \text{Equation 3}$$

2.4.4 Upper concentration limits

The upper concentration limit is the concentration at which a 10 unit increase in reference monitors' measurements is unproportionally characterized by a 0.2 unit or an exponential increase in the outputs of low-cost sensors. This concentration serves as the maximum concentration that a sensor is capable of measuring with an acceptable degree of accuracy. Upper limits vary significantly among the various low-cost PM sensors. Even though manufacturers report certain values as the upper limits, usually 1.0 mg/m^3, it is important to evaluate the upper limit to determine if these limits differ for coal dust particles. The results from the linearity test described in section 2.4.1 was analyzed to determine the operational range for the sensors and to determine the upper limits for each sensor. The inflection point of their response curves (also known as the knee of the curve) was determined as a sensor's upper limit using Equation 4. The maximum k value on the curve determines the inflection point at which the linearity of the sensor ends.

$$k(x) = \frac{|f''(x)|}{\left[1 + (f'(x))^2\right]^{3/2}} \qquad \text{Equation 4}$$

2.4.5 Influence of temperature and relative humidity

A 2^2 factorial design was used to determine if the temperature and relative humidity changes have a significant impact on dust monitors' readings at low and high coal dust concentration levels. The temperature and relative humidity factors each had two levels, high (+) and low (-). For these tests, low temperatures ranged from 20 to 24ºC whereas high temperatures ranged from 26 to 40ºC which represents typical underground conditions as the temperature in most mines range from 15 and 35ºC. Low RH ranged from 20 to 30% while high RH ranged from 35 to 45%. Even though RH in mines can exceed 45%, the challenge of simulating higher RH in the lab limited testing at higher RH values. At each concentration level, four tests were performed at different levels of temperature and relative humidity as shown in Table 1. The order of tests was randomized within each concentration. Each test lasted for 60 minutes. with at least of 5 minutes. stabilization time between tests when the conditions are changed. All 0.5 mg/m^3 concentration tests were performed on 4/18/2022, and the 1.5 mg/m^3 concentration tests were performed on 4/19/2022. A 2 factorial ANOVA analysis of variance was used to evaluate the effect of temperature and relative humidity on the performance of the low-cost PM sensors.

The low temperature and relative humidity conditions were achieved using the lab ambient temperature and humidity regulated by the building HVAC system. The high temperature and humidity were achieved by operating a Honeywell heater and a Honeywell cool moisture humidifier, which are displayed in Figure 4 installed at the inlet of the wind tunnel.

Figure 4. (a) the Honeywell turbo force power heater and (b) the Honeywell infrared cool moisture humidifier

Table 1. Experimental design for 0.5 and 15 mg/mg concentration at different temperature and humidity levels

Test Name	Temperature	Humidity
TLHL0.5	-	-
THHL0.5	+	-
TLHH0.5	-	+
THHH0.5	+	+
TLHL1.5	-	-
THHL1.5	+	-
TLHH1.5	-	+
THHH1.5	+	+

3 Results

3.1 **Linearity**

Prior to the evaluation of the sensors, the two reference monitors were compared beforehand to determine their accuracy of and to determine if any reference monitors had any errors which would eventually affect the sensors' calibration models. Figure 5 shows the correlation obtained from comparing the respirable particle size concentrations from the PDM with the APS. The PDM uses the BGI HD cyclone with precise D_{50} cut off point of 4.37 µm which has a proven significantly low bias relative to the International Standards Organization (ISO) respirable size selection curve. Since it is practically impossible for the APS to emulate the performance and behavior of the theoretical respirable particle size selection curve, the concentration of particles within the 4.37 µm size bin is used in this analysis (Belle, 2017) . When the data from PDM and APS were compared, a remarkably high linearity was observed between them. The R-squared value of 0.92 indicates a high correlation between them. In PM monitoring studies, an R-squared above 0.80 is generally considered as highly correlated, with R-squared values from 0.60 to 0.80 representing moderately correlated monitors, while a measure of R-squared below 0.60 is considered to have low correlation (Kelly et al., 2017; Sayahi et al., 2019). A statistical test performed on these results gave a P-value of 0.00 indicating strong statistical significance of these results. It is apparent that despite the two monitors operating on different PM measurement principles, the difference in technologies had no significant impact on their correlation. Both monitors were seen to be highly accurate and appear to be equally responsive to coal dust particles. This explains why both monitors are recognized for their high accuracies. As much as the APS is not recognized as a coal dust monitor, it has shown a high level of accuracy to be used as reference monitor for coal dust monitoring.

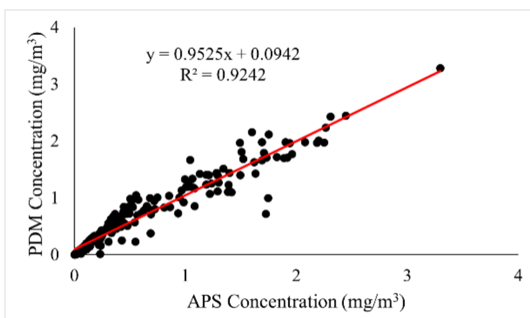


Figure 5. Correlation between PDM reference monitor and the APS reference monitor

To calibrate the low-cost PM sensors, we evaluated the linearity of each sensor by analyzing the relationship of the output of the PDM and APS against each sensor. Figure 6 displays the statistical plots for the pairwise correlation between the sensors and reference monitors. Prior to the evaluation, the boxplot algorithm for outlier detection was used to filter out data points which were flagged as outliers. The PMS low-cost PM sensors had the best linear correlation among all the sensors under evaluation while the Airtreks and Gaslab monitors had progressively lower performance, respectively.

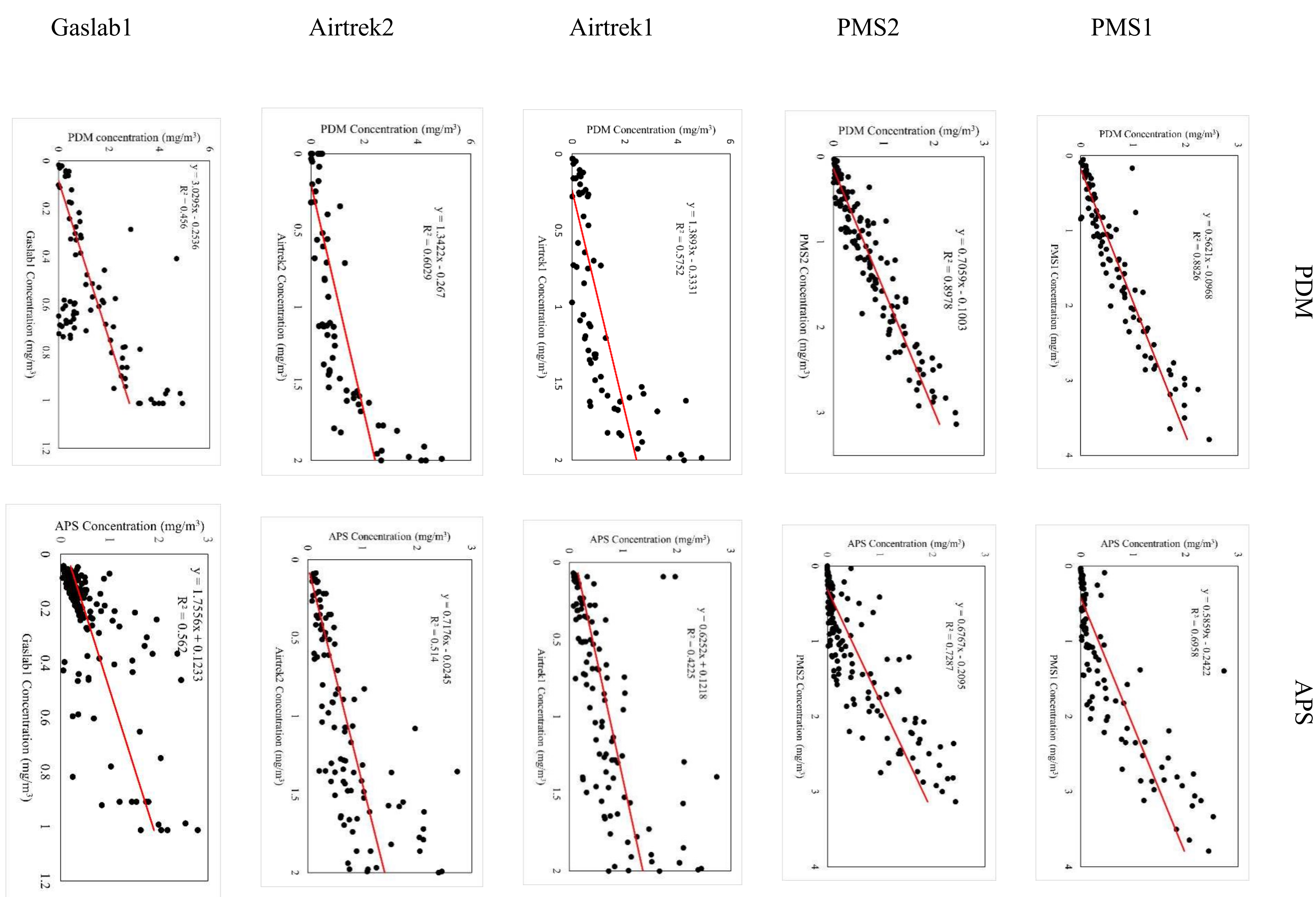
As can be seen from the plots, a considerably high linearity was recorded for both PMS sensors against both reference monitors. High R-squared values of 0.88 and 0.90 was recorded for PMS1 and PMS2 respectively with the PDM at P values of 0.00 for both sensors. These results agree with several previous studies which have obtained similar high linearity values for the PMS sensors (Sayahi et al., 2019; Y. Wang et al., 2015) . However, relatively lower R-squared values were observed for the same sensors using the APS as reference monitor with R-squared values of 0.70 and 0.73 for PMS1 and PMS2 respectively. P-values generated for this statistical analysis were 0.01 and 0.02 for PMS1 and PMS2 respectively highlighting the statistical significance of the outputs. It should be noted that these results are only true for testing concentrations below 3.0 mg/m^3. While other studies have recorded relatively higher R-squared values for the same sensors, this was only achieved when NaCl or Arizona road dust are used for the testing. Coal dust on the other hand, has particle characteristics which are different from these particles and so the sensors could react to them.

The intra-model correlation between the two PMS sensors was found to be 0.97 with a P-value of 0.00 which makes them exceptionally agreeable with each other and can be calibrated using the same calibration model. The PMS can confidently measure coal dust concentrations provided the concentrations stay below 3.0 mg/m^3.

Although these results point to an acceptable level of accuracy for the PMS sensors, a striking characteristic was observed during the test when concentrations went above 3.0 mg/m^3. Beyond this concentration, the PMS sensors reported excessively high outputs which were unrealistic and disproportional with the actual concentration level. For example, the sensor concentrations reached as high as 60.0 mg/m^3 when concentration levels within the wind tunnel was below 5.0 mg/m^3 as indicated by the APS. These data points, as well as all other outliers for the other sensors' data were therefore eliminated from the statistical analysis as outliers using boxplot algorithms as keeping them on the plots would make the plots unreadable. This characteristic of the PMS sensors has not been observed in previous studies due to generally low testing concentrations used. In those studies, PMS testing concentrations ranged between 0 and 1 mg/m^3.

Airtrek sensors had slightly lower linearity values as compared with the PMS sensors. As can be seen from the plots displayed in Figure 6, at concentrations below 2.0 mg/m^3 when the Airtrek sensors reported 1.5 mg/m^3, both Airtrek 1 and Airtrek 2 appeared to have a higher linear correlation with the reference monitors. This fairly agrees with manufacturer's datasheet stating that the Airtrek has a measurement range of up to 1.0 mg/m^3 even though it can report concentrations to 2.0 mg/m^3. However, when concentrations within the wind tunnel exceeded 2.0 mg/m^3 when the Airtrek sensors reported 1.5 mg/m^3, their outputs began to steeply approach 2.0 mg/m^3 giving the overall Airtrek response an exponential look. This was because the Airtrek sensors would still report concentrations beyond 1.5 mg/m^3 but with less accuracy, and report 2.0 mg/m^3 for all concentrations which are sensed by the sensors to be beyond 2.0 mg/m^3. A linear regression statistical analysis to determine the accuracy of the The Airtreks resulted in R-squared values of 0.58 and 0.60 for Airtrek1 and Airtrek2 respectively using the PDM as reference monitor. P-values generated from the statistical analysis were both 0.00 against the PDM emphasizing on its statistical significance. It was also found that Airtrek1 and Airtrek2 had R-squared values of 0.42 and 0.51 respectively using the APS as reference and P-values of 0.00 for each sensor. It can be seen from these results that these sensors can be reliable for concentrations below 1.0 mg/m^3. Between these sensors, there is an apparent high intra-model linearity with an R-squared of 0.73 with a P-value of 0.01. With a robust calibration model, individual calibration models are not required since a single calibration model can fit these sensors to achieve improved performance.

The Gaslab sensors had the lowest linearity among the three sensor models under evaluation. Gaslab1 reported R-squared values of 0.46 and 0.56 for PDM and APS respectively with P-values 0.00 each, whereas Gaslab2 reported linearity values of 0.66 and 0.52 for PDM and APS respectively with P-values of 0.00. The two Gaslab sensors recorded the lowest intra-model correlation of 0.23 among all the sensors while generating a P-value of 0.02. Much of the non-linearity between these sensors and the reference monitors was due to the limited range of the gaslab sensors which makes them report their maximum limit of 1.0 mg/m^3 even when the concentration exceeded that. As seen in Figure 6, it can be observed that these sensors reported no output beyond 1.0 mg/m^3 even when concentrations within the wind tunnel exceeded 1 mg/m^3. These results confirm the specifications of the Gaslab monitors by the manufacturers having a measurement range of 0.0 to 1.0 mg/m^3. These sensors may provide reliable monitoring information for environments with lower PM concentrations like indoor offices and home spaces.



Gaslab1
Airtrek2
Airtrek1
PMS2
PMS1
PDM
APS
PDM concentration (mg/m3)
PDM Concentration (mg/m3)
APS Concentration (mg/m3)
Gaslab1 Concentration (mg/m3)
Airtrek2 Concentration (mg/m3)
Airtrek1 Concentration (mg/m3)
PMS2 Concentration (mg/m3)
PMS1 Concentration (mg/m3)
y = 3.0295x - 0.2536
R² = 0.456
y = 1.3422x - 0.267
R² = 0.6029
y = 1.3893x - 0.3331
R² = 0.5752
y = 0.7059x - 0.1003
R² = 0.8978
y = 0.5621x - 0.0968
R² = 0.8826
y = 1.7556x + 0.1233
R² = 0.562
y = 0.7176x - 0.0245
R² = 0.514
y = 0.6252x + 0.1218
R² = 0.4225
y = 0.6767x - 0.2095
R² = 0.7287
y = 0.5859x - 0.2422
R² = 0.6958

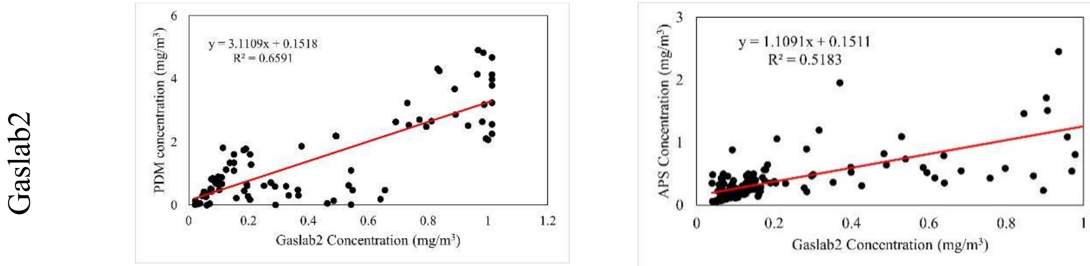
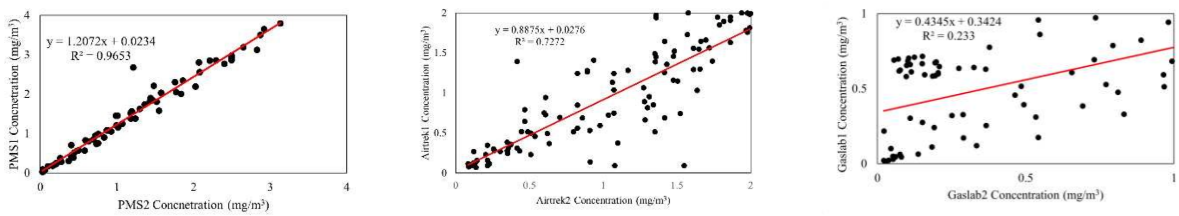


Figure 6. Pairwise correlation between the two PMS sensors, two Gaslab sensors and the two Airtrek sensors each against the two reference monitors PDM and APS



(a) *(b)* *(c)*

Figure 7. Intra-mode correlation between the two models of each sensor type (a) PMS5003 sensors (b) Airtrek sensors (c) Gaslab sensors

3.2 **Precision**

The results of the tests for precision are displayed in Figure 9. The boxplots of sensor concentrations are shown against true concentrations measured by the PDM using their raw data from the test without removing any outliers. At a constant concentration, the higher the interquartile range of a sensor's distribution shown in the boxplots, the lower the precision of the sensor. The results of the sensors are compared with that of the reference monitors. It can be seen from the PDM and APS results in Figure 8 that even though the concentrations were not perfectly constant, the true concentration range at each concentration level remained constant, indicating their precision and consistence with changes in concentrations. However, in general, there is an increase in the spread of data as concentrations increase, making these sensors unreliable at higher concentrations. It can be seen from the figure that these sensors begin to show imprecision at concentrations 1.5 mg/m^3 and above. The spread of the sensors' data is progressively higher than the spread of the reference monitors' data at elevated concentrations.

In the case of the PMS1 and PMS2 sensors, the spread of the measurements at concentrations below 1.5 mg/m^3 was determined by the interquartile range set at 1.1 mg/m^3 and 0.5 mg/m^3 respectively. As can be seen from Figure 9, the level of precision for both sensors began to noticeably increase as concentrations increased relative to the results from the two reference monitors. At the highest level of concentration where the precision was the worst, the spread of the sensor concentration had increased considerably to 13.3 mg/m^3 and 17.8 mg/m^3 respectively when the concentration reached 3.0 mg/m^3. This indicates the PMS sensors' inability to reproduce accurate readings at higher concentrations. Therefore, the PMS sensors could be used for mine coal dust monitoring where concentrations are generally low such as inside operators' cabs and on miners underground as personal monitors. It should be noted, however, that the average concentration of coal dust in underground coal mines is 0.55 mg/m^3 (Doney et al., 2019). Therefore, the limitation of imprecision at higher concentrations makes them capable of accurately measuring concentrations within an underground mine under normal operations.

Similar to the PMS sensors, the Airtrek sensors showed the highest precision values at concentrations below 1.0 mg/m^3, which marginally increased while concentrations increased. The spread of concentration outputs for Airtrek1 and Airtrek2 at 0.5 mg/m^3 were 0.38 mg/m^3 and 0.35 mg/m^3 respectively which increased progressively to 1.91 mg/m^3 and 1.86 mg/m^3 respectively at 3.0 mg/m^3 relative to the reference monitors. A review of the manufacturers' datasheet for the Airtrek sensors reveal that the recommended upper limit for PM monitoring is 1.0 mg/m^3. Even though the sensors can measure and report concentrations higher than its recommended upper limit, these results indicate that those readings could be imprecise. Deploying these sensors for higher coal dust concentration environment can create misleading results to users.

The trend of decreased precision with increasing concentration appeared to be slightly different with the Gaslab sensors. While they showed high precision performance at lower concentrations and lower precision at higher concentrations, their limited upper concentration limits of 2.0 mg/m^3 indicated high precision performances at those concentrations. This was due to the Gaslab sensors consistently reporting 2.0 mg/m^3 when the concentrations went beyond 2.0 mg/m^3. The results from our precision tests confirm that even though these low-cost PM sensors can measure and report concentrations beyond their recommended upper limits, they begin to be imprecise and could report misleading results at higher concentrations. Nevertheless, if the imprecise readings from the sensors at higher concentrations appear to be consistent, a more robust calibration algorithm can correct this phenomenon. However, a quantitative number of repetitions of this experiment will have to be performed to determine a consistent trend if one exists.

The EPA uses a slightly different method to evaluate sensor precision where the variation about the mean of a sensor output at a constant concentration is determined to be its precision. However, the dynamic testing environment used in this study made it impossible to compare the results to EPA standards which uses a static environment in its testing chamber. Using EPA method of evaluation in this case would result in excessively high variations which would be due to fluctuations in concentrations and not the imprecision of the sensors.

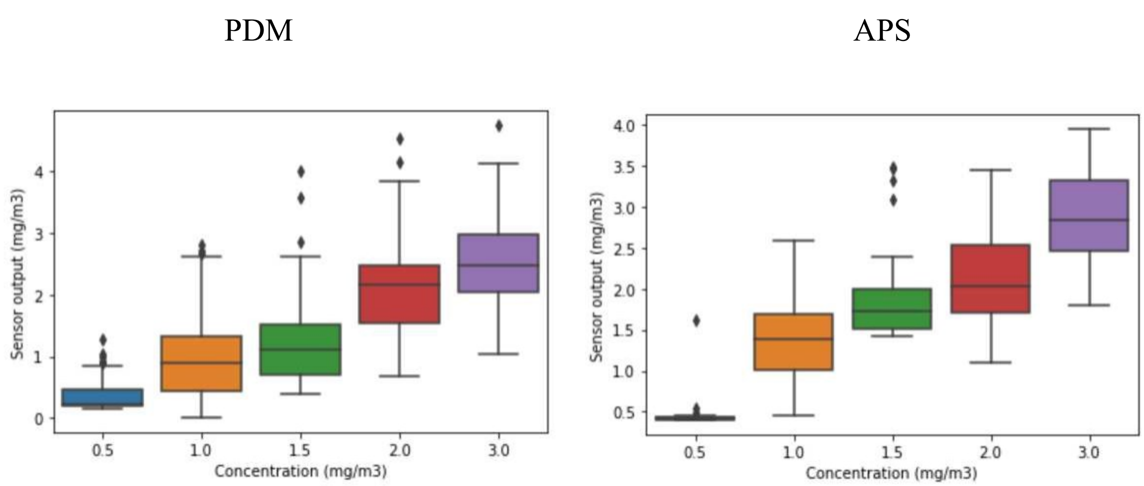
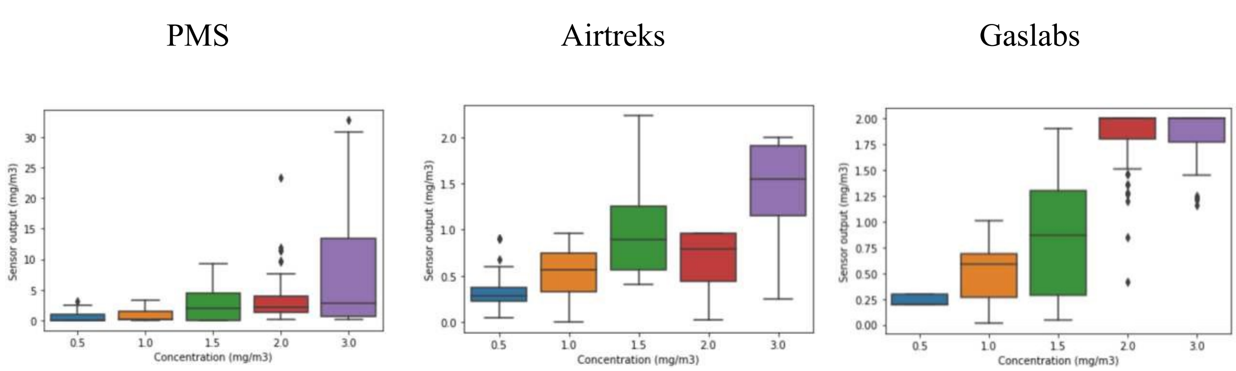


Figure 8. Precision results for reference monitors



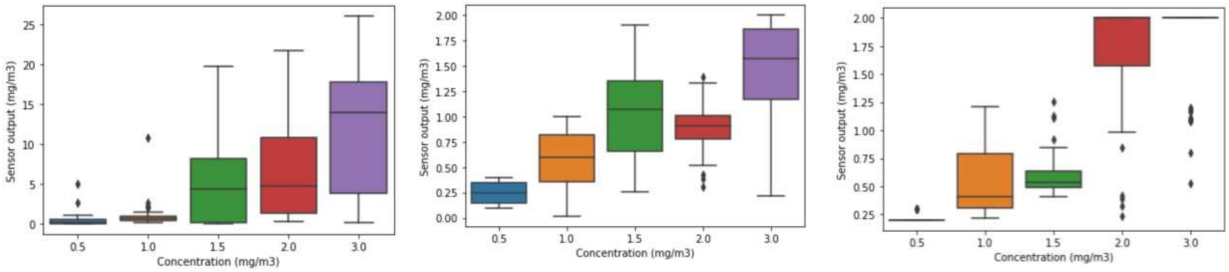


Figure 9. Precision plots for all sensors at concentrations from 0.5 mg/m3 to 3 mg/m3

3.3 **Limit of detection**

The results from this analysis are presented in Table 2. At 0.0 mg/m^3 dust injection concentration, the PDM recorded 0.00 mg/m^3 whereas the APS recorded 0.02 mg/m^3. Each of the PMS sensors recorded an average concentration of 0.01 mg/m^3 and LOD values of 0.02 mg/m^3 each which was the lowest among the sensors being evaluated. The Airtrek sensors had slightly higher LOD values where they recorded 0.02 mg/m^3 and 0.89 mg/m^3 respectively. However, these Airtrek sensors had the best response to zero concentration giving an average concentration of 0.0 mg/m^3. With such accurate outputs at zero concentrations, these sensors would have had a significantly lower LOD if the linearity test obtained a high linearity for the airtrek sensors. The Gaslab sensors had the lowest lower limit values with an average concentration of 0.02 mg/m^3 at zero concentration and LOD values of 0.81 mg/m^3 and 0.94 mg/m^3. It should be noted that due to the absence of standard calibration curves for these sensors, the calibration curves generated using linear regression methods in section 3.1 were used for this analysis.

Table 2. Lower limits of PMS, Airtrek and Gaslab sensors and their limit of detection

	PMS1	PMS2	Gaslab1	Gaslab2	Airtrek1	Airtrek2
Lower limit (mg/m^3)	0.01	0.01	0.02	0.02	0.00	0.00
LOD (mg/m^3)	0.02	0.02	0.81	0.94	0.02	0.89

3.4 Upper concentration limit

In general, the low-cost PM sensors showed significantly lower upper limits as compared with the PDM and APS. This was expected since the APS and PDM are built with more advanced technology to operate in higher concentrations. By plotting the response of the reference monitors against the sensors in section 3.1, the nature of their response were observed and the concentration at which a sensor achieves its maximum value is determined to be the upper limit using Equation 4. The results of this analysis are shown in Table 3. The two PMS sensors both demonstrated characteristics of their upper limits at 3.0 mg/m^3 of coal dust. Beyond 3 mg/m^3, a 10 unit increase in true concentration resulted in a corresponding sensor output of more than 200 % of the true concentration at which point the linearity of the sensor was discontinued. In principle, at higher concentrations when there are many particles within the sensing volume at the same time, these sensors suffer from coincidence errors. The multiple particles present in the sensing volume at the same time are recognized by the sensor as larger and heavier particles in which case the mass is overestimated resulting in such a high concentration compared with the reference monitors.

The airtrek sensors showed a slightly lower upper concentration limit of 1.5 mg/m^3 and 1.6 mg/m^3 for Airtrek1 and Airtrek2 respectively. It was observed in the linearity plots of the reference monitors against the Airtrek sensors in section 3.1 that the change in slope from lower concentration to higher concentrations gave the response an exponential curve where the knee of that curve was calculated to be the upper concentration limits. Similar to the Airtrek sensors, the Gaslab sensors were characterized by an exponential curve even though they had a more linear relationship at lower concentrations. The two Gaslab sensors had upper concentration limits of 0.9 mg/m^3 which was the lowest among the three sensors and close enough to manufacturers specified upper limits. Considering the generally low upper limits of these low-cost PM sensors it is worthwhile to only apply them for lower concentration environments for optimum performances.

Table 3. Upper concentration limits

Sensor	PMS1	PMS2	Airtrek1	Airtrek2	Gaslab1	Gaslab2
Upper limit (mg/m^3)	3	3	1.5	1.6	0.9	0.9

3.5 Temperature and RH influence

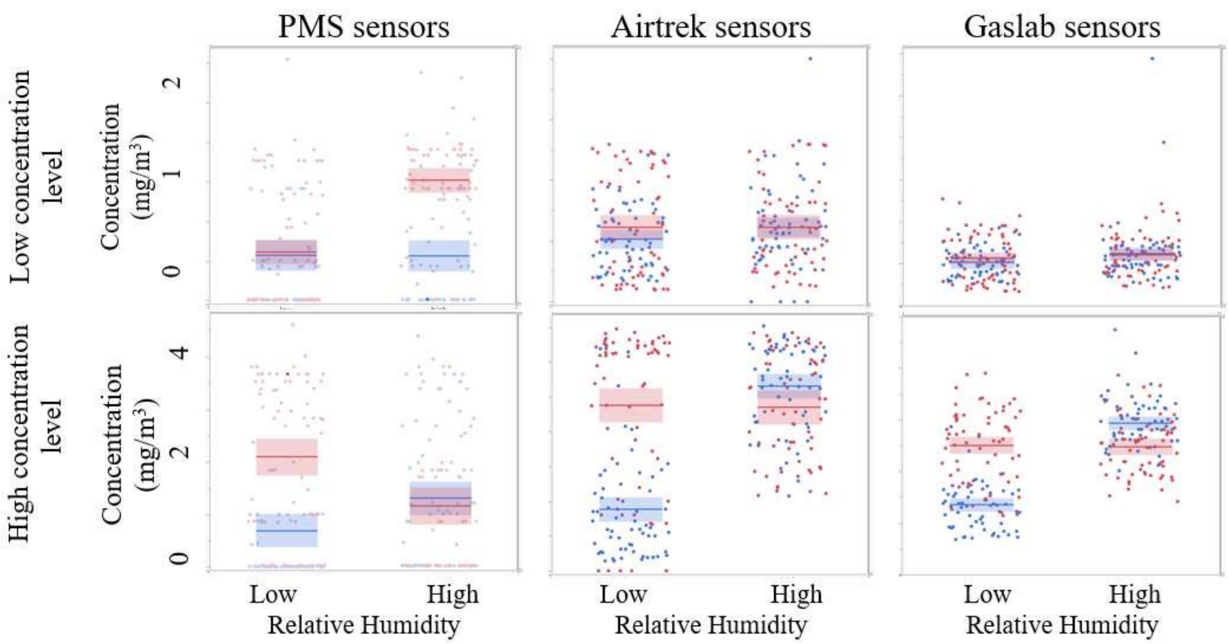


Figure 10. Concentrations reported by PMS, Airtrek and Gaslab sensors under different temperature and relative humidity conditions. Results are further elaborated with boxplots.

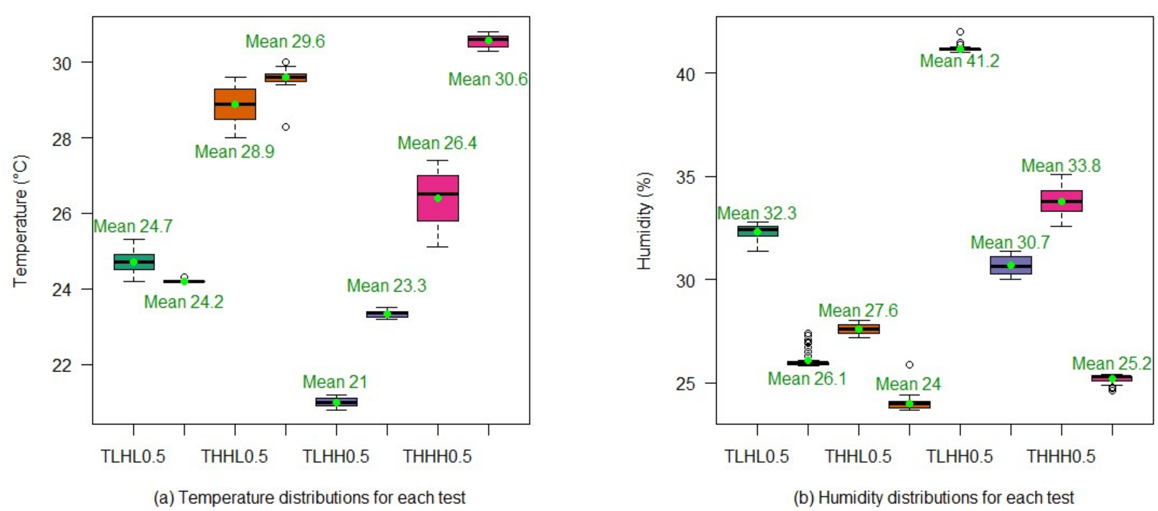


Figure 11. temperature and relative humidity distribution for the tests

Several studies have found that relative humidity results in a significant bias on the performance of low-cost PM sensors while others have also suggested no influence. It has been proven that the water droplets in the atmosphere can absorb infrared radiation which is emitted into the measuring cavity of the sensors (Y. Wang et al., 2015). Water vapor can also condense on aerosol particles, causing hygroscopic growth of particles making them seem as though they are larger particles and eventually causing overestimation of particle size and concentrations (Jayaratne et al., 2018). The influence of relative humidity on low-cost PM sensors is highly dependent on the surface properties and composition of the particles. This is the reason why many studies have found a significant influence of relative humidity on these sensors while many others have found little to no influence at all. In this study, both temperature and RH conditions had no significant effect on the performance of the low-cost PM sensors based on the 2k factorial ANOVA analysis of variance. The results of the temperature and RH conditions measured in the wind tunnel is displayed in Figure 11. The temperature achieved within the wind tunnel ranged from 20 degrees Celsius to 31 degrees Celsius while RH was measured to be from 24 % to 44 %. While a wider range of temperature and RH conditions was targeted, it was challenging controlling and maintaining these conditions within the wind tunnel throughout the experiments. Therefore, the results from this test are only valid for the temperature and RH range obtained in this test.

Using the ANOVA analysis, all sensors under all conditions of temperature and RH generated F ratios of more than 5.0 % in their respective models. This indicated no significant impact of temperature an RH on the sensors under these temperature and RH factor changes as shown in Figure 11. However, a more in-depth statistical analysis revealed that RH had marginal impact on the performance of the sensors as can be seen from Figure 10. Figure 10 shows boxplots integrated with dot plots of concentrations plotted against relative humidity while overlaying temperature conditions. Red plots represent elevated temperature and blue plots represent low temperature. These results suggest that high RH marginally overestimated the outputs of the Airtrek and Gaslab sensors at higher concentrations of 1.5 mg/m^3 especially at lower temperatures. However, this effect was not substantial enough to attribute it to the changes in RH conditions. Other factors such as a concentration fluctuation within the tunnel cause this phenomenon. If RH had significant impact on these sensors, a more robust calibration model would be applied to comprehensively calibrate the sensors to account for the influence of RH on the sensors. To fully understand why RH had no influence on these sensors measuring coal dust, further research is needed to study the surface properties and composition of coal dust particles in detail to substantiate why coal particles are unaffected by atmospheric RH.

Temperature, on the other hand, had no impact on the performance on the PMS, Airtrek and Gaslab sensors. Figure 10 shows that there was influence of the temperature rise and fall had on the sensor outputs. These results are consistent with several studies, many of which have established that there is no theoretical dependency of the light scattering principle on temperature. However, some low-cost PM sensors are affected by temperature due to the use of thermal resistors in their operation. In that case, the temperature difference between the outside environment and the thermal resistor could affect the intake flowrate and sensor outputs. In this study, none of the sensors evaluated have that technology. The reference monitors had no impact from the temperature changes since they have temperature and RH control technology in-built. It should be noted that the challenge of difficulty in controlling and maintaining temperature and RH conditions within the wind tunnel could have impacted the findings of this study.

4 Conclusion

Accurate personal monitoring is essential to detect overexposures of the miners working underground in coal mines. This is also critical for recommendations of suitable controls. However, the high cost and size limitations of the PDM limits its usage to only a few miners risking most miners to unknown overexposures. Low-cost PM sensors can measure personal exposure levels for all miners in real time due to their low cost, small size, and light weight. Prior studies have established the potentials for low-cost PM sensors to be used as PM monitors. However, their application for mining-induced PM and underground conditions remained unexplored. Therefore, this study developed a coal dust monitor using the Plantower PMS5003 sensors, evaluated their performance in laboratory experiments together with Airtrek and Gaslab sensors, and calibrated them using linear regression calibration algorithms.

It was found that all three sensors under evaluation had different degrees of linearity with the APS and PDM. The PMS sensors had the best linearity with both PDM and APS among all the other sensors under evaluation, with R^2 values ranging from 0.70 to 0.90 and an excellent intra-model linearity of 0.97 for concentrations levels below 3.0 mg/m^3. The Airtrek sensors had slightly lower linearity between 0.0 and 2.0 mg/m^3, but had lost its linearity at concentration beyond 2.0 mg/m^3 giving them an exponential response with the reference monitors. The Gaslab sensors had the least linearity among the sensors with R^2 values ranging from 0.40 to 0.52. All three sensors had precision levels identical to that of the reference monitors at concentration levels below 1.5

mg/m^3. It was found that beyond 1.5 mg/m^3, the sensors experienced a decrease in precision with increasing concentration. PMS sensors demonstrated the highest measurement range with the lowest lower limit of 0.0 mg/m^3 and highest upper limits of 3.0 mg/m^3. Airtreks generated a closer range of 2.0 mg/m^3 while the gaslabs had a range of 1.0 mg/m^3. Statistical tests gave P-values of less than 0.05 for all linearity results indicating that these results are reliable beyond the testing results. At concentrations above these limits, the sensors all show challenges reading those concentrations which would potentially give misleading outputs. However, since the upper limit for the PMS sensors are above the PEL for coal dust, the wearer would already be notified. It was also observed that temperature and relative humidity had no significant influence on the performance of these sensors even though an observation of the results show minimal overestimation of sensors' performance at higher RH. The concentration change, however, was not significant enough to attribute it to RH changes.

These results provide compelling evidence that the PMS5003 low-cost PM sensor has the potential to monitor coal dust concentrations up to 3.0 mg/m^3. Underground coal miners could widely wear this to ensure early overexposure detection and timely control to protect the health of miners. This will eliminate the high expenditure incurred by mines and the federal government associated with treatment of CWP, as well as compensations. This technology is also expected to facilitate improved underground structure and ventilation designs and provide high quality "big data" to facilitates the health studies related to respiratory diseases caused by PM. However, it will be worthwhile to note some limitations that still need to be investigated. During the tests, the research team had the limitation of achieving RH conditions higher than 45%. While RH conditions in underground mines could reach as high as 70%, future studies will need to consider testing at RH of 45% to ~70%. Although the study revealed that the influence of temperature and RH were minimal, these factors should be accounted for in a calibration model in a multiple variable algorithm to make the performance more robust. Future studies should therefore apply models such as multiple linear regression and machine learning algorithms to cover temperature and RH in the calibration models.

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