Calibrating Low-Cost Particulate Matter Sensors with a Heated Inlet

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Abstract

Particulate Matter 2.5 (PM 2.5) is a hazardous pollutant composed of particles that are smaller than 2.5 micrometers in diameter. Due to the extremely small nature of the particles that compose this pollutant, they are more likely to pass through the nasal cavities increasing the risk of respiratory diseases (Li, et al., 2018). As PM 2.5 poses a danger to human lives, it is important to monitor the levels of this pollutant, but the reference sensors are expensive and difficult to maintain which limits their accessibility.

To help address this issue, low-cost sensors (LCS) have been created, but they are less accurate than the reference sensors. One reason for this is that many PM 2.5 particle types are hygroscopic, so they absorb the water in the air and grow when there is relative humidity (RH) exceeds ~75% (Jayaratne, Liu, Thai, Dunbabin, & Morawska, 2018). Expensive sensors regulate the RH at a lower value than 75% to prevent the PM 2.5 particles from swelling. Unlike the expensive sensors, LCS are unable to regulate the RH which causes them to overestimate the levels of PM 2.5. By researching reduce the RH of the air, LCS will become more accurate and allow for more effective ways to monitor PM 2.5.

Due to COVID-19, this project could not be completed in the lab, so this project utilized Sara Harbison's RP project: *Heated Inlet Calibration of PM Sensors*. Using her data, it is hypothesized that the addition of a heated inlet to a low-cost Plantower 3003 (PMS3003) sensor will lower the RH improving the accuracy of the LCS.

Method

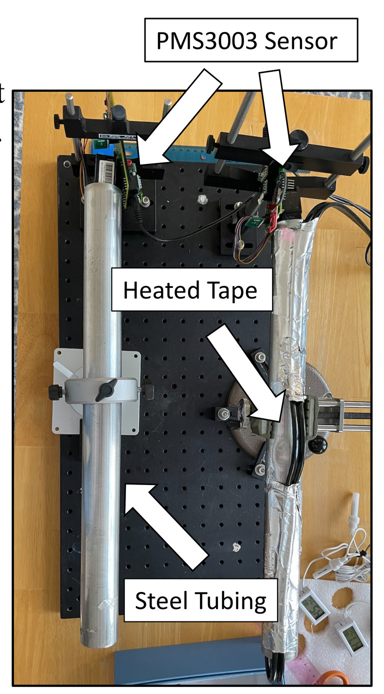
Data Analysis

Correction Equation

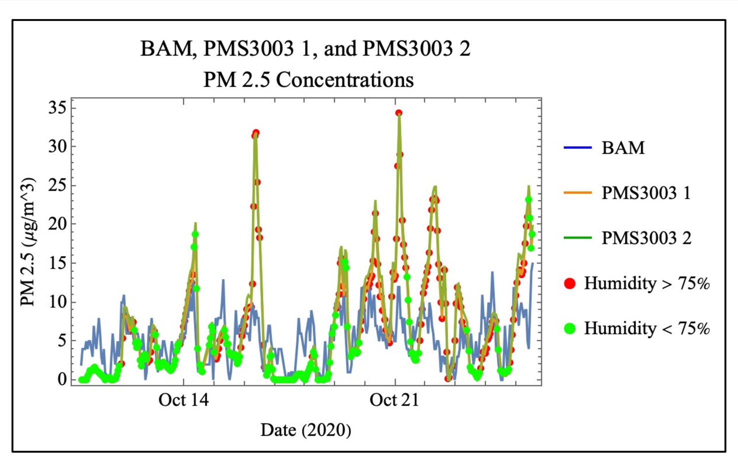
1. Receive BAM-1020 data from the Maryland Department of Environment and PMS3003 sensor data from Sara Harbison.
2. Import the data into Wolfram Mathematica.
3. Compare each PMS 3003 sensor with the BAM-1020 sensor to find the most accurate sensor and its linear equation.
4. Use the inverse of the linear equation to create the correction equation and apply it to the more accurate PMS 3003 sensors to create a slope of 1.

Heated Inlet

1. Receive the raw data and heated inlet data from Sara Harbison and import the data into Wolfram Mathematica.
2. Apply the previously found correction equation to the raw data and create a linear regression between the corrected data and the heated data.
3. Find the root-mean-square-error (RMSE) and mean bias error (MBE) between the raw data and corrected data and the heated data and raw data.
4. Compare the RMSE and MBE of the two calibrations.

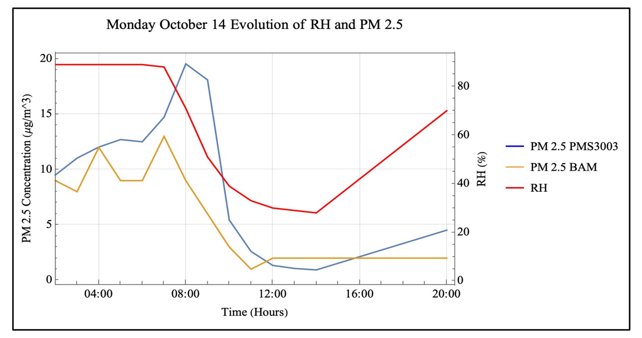


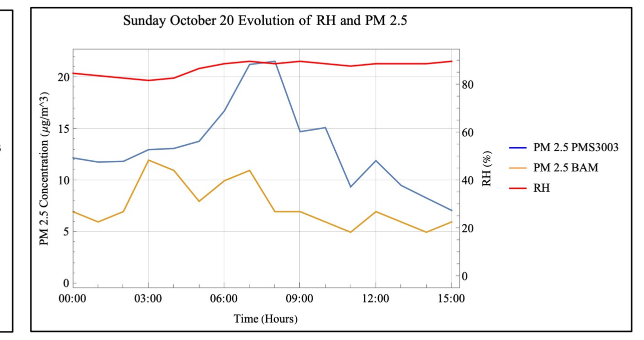
Impact of Relative Humidity



In general, the peaks in PM 2.5 concentrations recorded by the PMS3003 sensor occurred at times of RH equal to or greater than 75% represented by the red points. While the PMS3003 sensor displayed peaks in PM 2.5 concentration at times with high RH, the BAM 1020 sensor did not display a correlation between the RH and PM 2.5 peaks. While the hygroscopicity of many PM 2.5 particles impacts the PMS3003 sensor, the BAM 1020 sensor PM 2.5 measurements were not impacted by high RH. Unlike the PMS3003 sensor, the BAM sensor has an internal heating unit that warms the air and lowers the RH preventing the PM 2.5 particles from swelling.

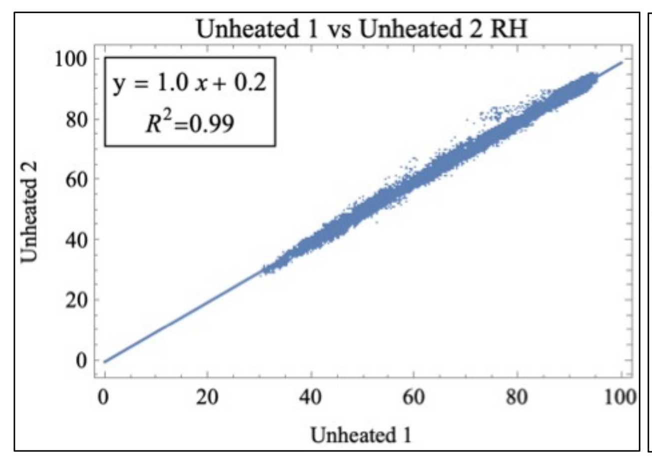
RH and PM 2.5 Relationship

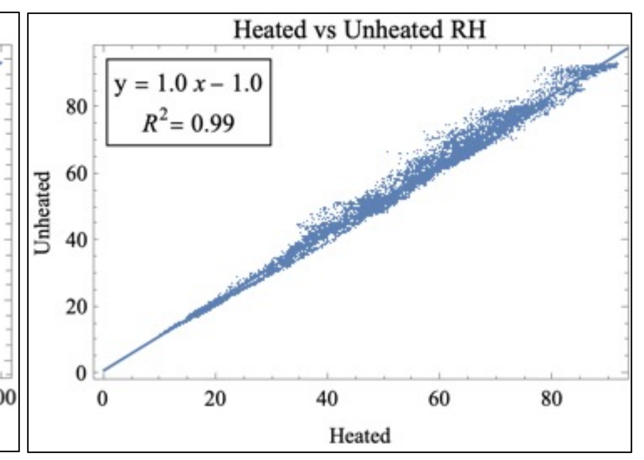




The two graphs above display the evolution of RH and PM 2.5 concentrations over time for two different days days in October. The graph to the left shows that the PM 2.5 concentrations recorded by the PMS3003 sensor peaked right after the RH was above 75% and they went down sharply after the RH reached a low percentage. This graph is a representation of what was expected to happen with high RH. The graph on the right is a less expected representation of what usually happens with high RH. Even though the RH was above 75% for the whole time period, the PMS3003 PM 2.5 measurements rose and then lowered during the period. This shows that there are other environmental factors that can impact the PMS3003 PM 2.5 measurements.

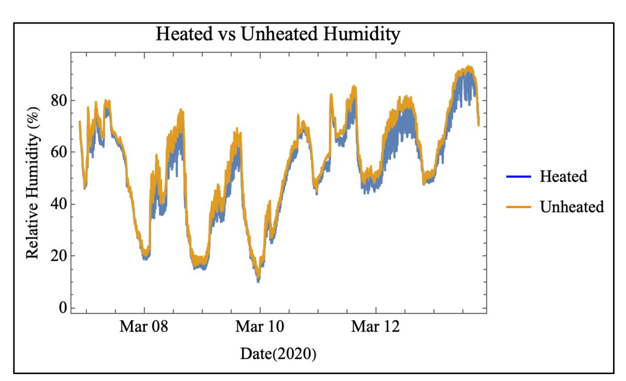
RH Linear Regressions

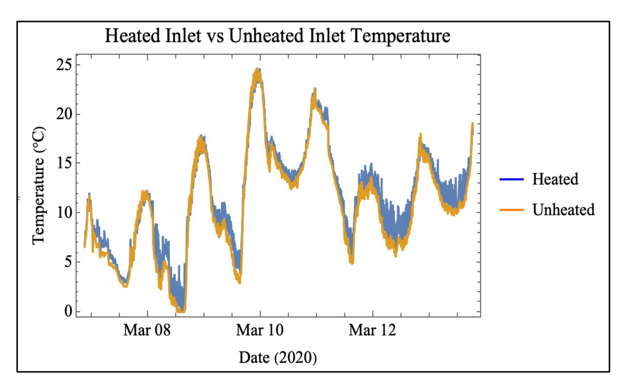




The R^2 values for RH of the two unheated sensors and the unheated sensor and heated sensor were the same with the value of 0.99 shown in the figures above. The heated inlet was expected to lower the RH greatly but the R^2 value shows that the RH did not create a significant change when the heated inlet was added. If the heated inlet created a change, the fit of the data for the heated inlet and unheated inlet would have been less accurate than that of the two unheated sensors.

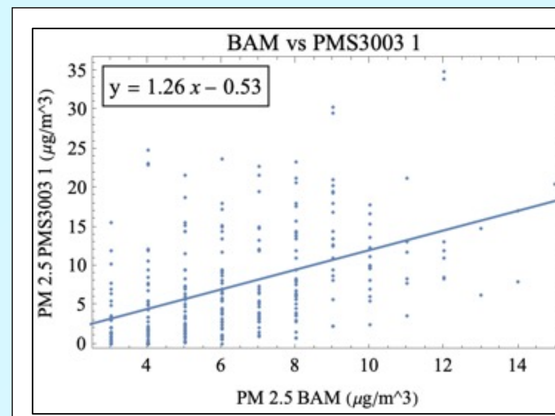
Impact of the Heated Inlet

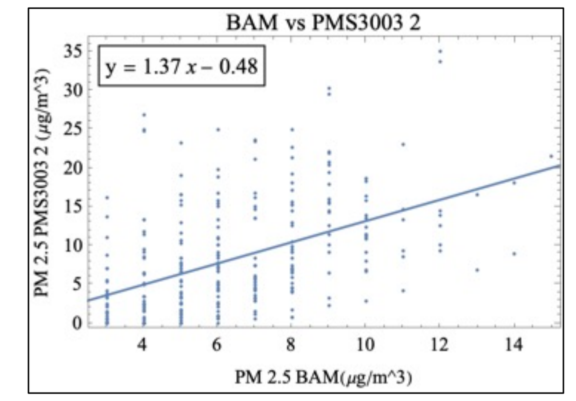


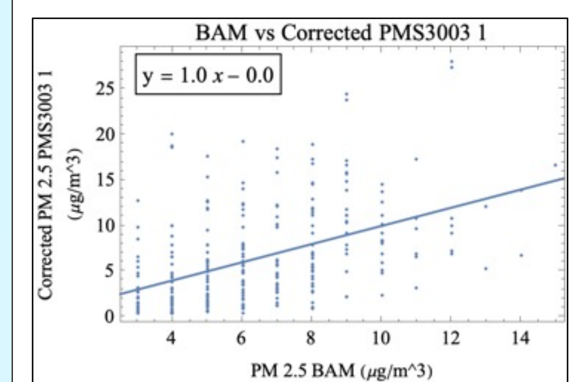


The heated inlet's purpose was to heat up the air entering the sensor in order to lower the RH using a heated tape. These graphs show that the air was heated, and the RH was lowered but these changes were not significant. The temperature was raised a maximum of three degrees Celsius. When air is warm, it is able to hold more water vapor which causes the RH to lower. For the heated inlet to make the sensor more accurate, it must warm the air entering the sensor enough for RH to be consistently stay under 75%.

Correction Equation

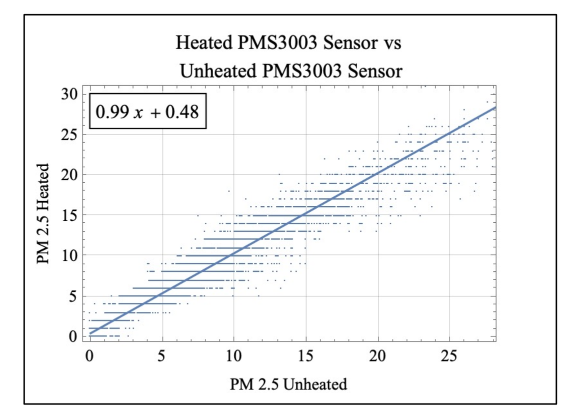


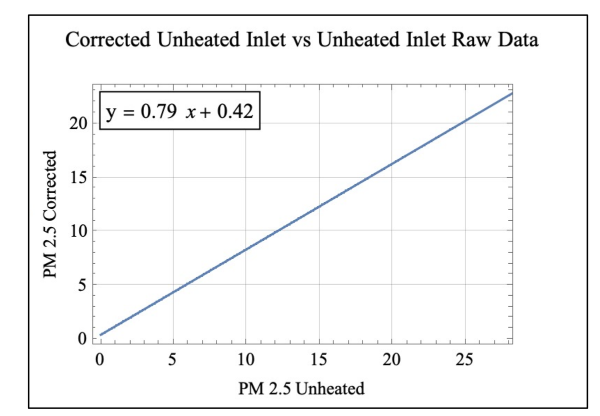




The two PMS3003 sensors were tested without adjustments and compared with the BAM 1020 sensor through linear regressions to find the more accurate PMS3003 sensor. The measurements from PMS3003 sensor number one were more accurate, so the inverse of the linear equation from this sensor was used to create the correction equation. The correction equation y = (x+0.53)/1.26 was then applied to the PMS3003 sensor number one so a linear regression with the BAM 1020 data and the corrected data could be created. The slope of about 1 demonstrates that the correction equation created agreement between the BAM 1020 sensor and the PMS 3003 number one sensor.

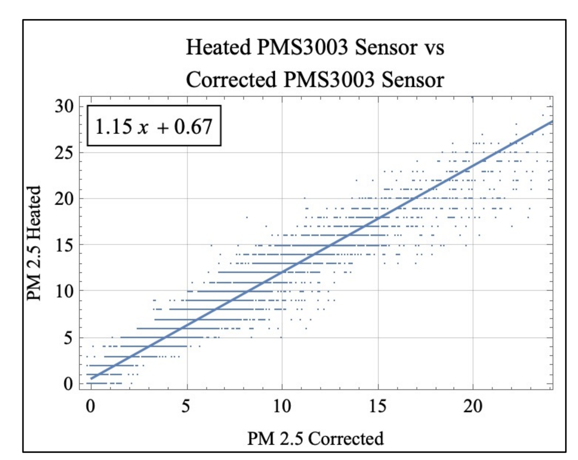
Correction and Heated Inlet





Once the heated inlet was added to the PMS3003 sensor, the data were used to create a linear regression with the heated inlet sensor measurements and the unheated sensor measurements or raw data. The correction equation that was previously created was applied to the raw unheated PMS3003 sensor data and this was compared to the raw data though a linear regression to see the impact of the correction equation.

Comparing Calibrations



RMSE and MBE Summary

	Root Mean Square Error	Mean Bias Error
Heated Data vs. Raw Data	1.62	0.42
Corrected Data vs. Raw Data	1.97	-1.13

A linear regression was created between the corrected raw PMS3003 data and the heated inlet PMS3003 data to compare the calibrations. Additionally, the root mean square error (RMSE) and mean bias error (MBE) were found for the raw and corrected data and the raw and heated data because there was no reference data. The RMSE for the raw data compared to the corrected data was 1.97 and the MBE was -1.13. The RMSE for the raw data compared to the heated data was 1.62 and the MBE was 0.42.

Summary and Discussion

To improve the accuracy of low-cost PM 2.5 sensor, Sara Harbison's heated inlet was added to a PMS3003 sensor. This sensor was tested for a one-week period and compared to raw PMS3003 data corrected with a correction equation derived from a three-week trial with two PMS 3003 sensors, and a BAM 1020 sensor. The RMSE values found had a difference of 0.35 and the corrected MBE was negative while the heated MBE was positive. As the RMSE values were not the same, the MBE values did not have the same sign, and the R^2 values for the RH were the same, the null hypothesis was rejected. The heated inlet was engineered to lower the RH of the air entering the sensor by warming the temperature, but it only raised the temperature by a maximum of 3 degrees Celsius. Since the temperature was not raised significantly, the RH was not significantly lowered. The difference in RH between the heated and unheated sensor was the same as the difference in RH between two unheated sensors displaying that a more significant impact on the RH was necessary. This means that the heated inlet was not able to improve the RH measurements therefore, it did not create a more accurate low-cost sensor.

Implications

Through more research to create an effective heated inlet or correction equation, improvements can be made to low-cost PM 2.5 sensors and PM 2.5 monitoring. An implication of this study is the heated inlet design that can be used as a reference to engineer a heated inlet that creates a more significant impact on the temperature. The creation and testing of these inlets will show if an effective heated inlet can improve low-cost sensors' accuracy. One addition to the sensor could be a small fan to increase the air circulation. This should help the heated air enter the sensor. Future studies can assess the accuracy of the correction equation used in this study to see if the correction equations are a reliable method of calibrating low-cost sensors. Future research can also study multiple types of low-cost PM 2.5 sensors with the heated inlet or correction equation as newer low-cost sensors are engineered. The improvement of these sensors and their calibration will allow for a more extensive monitoring range and allow for availability to citizen scientists. The increased accessibility and range of PM 2.5 sensors will allow for a better understanding of PM 2.5, therefore a safer environment.

References

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