Evaluation of Low-cost Particulate Matter (PM) Sensors: A Preliminary Investigation

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Evaluation of Low-cost Particulate Matter (PM) Sensors: A Preliminary Investigation

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ABSTRACT

The new generation of low cost and highly portable Particulate Matter (Williams et al.) sensors, which offer significant advantages in terms of compact size and low cost, opens an exciting opportunity for people to use such sensors for a wide range of applications. There have been an increased number of studies focusing on the evaluation and calibration of various PM sensor systems, but how these sensors actually perform in the real situation still remains unknown to the society. In this study, three low-cost PM sensors based on light scattering and two commercial high-cost PM monitoring products were tested to preliminarily investigate their performances in three realistic indoor environmental settings (incense burning, spraying air-freshener, and spraying whiteboard cleaner) to help us understand their availability, usability, and overall feasibility. Two metrics, i.e., response time and the linearity of response are selected as the evaluation indexes. A preliminary investigation of low-cost PM sensors’ potential applications with building automation system in smart buildings is presented. The conclusion suggests that low-cost sensors perform reasonably well in quick response and yield good linearities. Besides, low-cost sensors have a potential for smart building applications including building filtration control.

INTRODUCTION AND BACKGROUND

Human exposure to particulate matter (PM) has been linked to adverse health effects such as pulmonary and cardiovascular symptoms. PM diameter can be varied from a few nanometers to tens of micrometer. Existing studies (Krewski et al. 2009; Zeger et al. 2008) have shown exposure to particles, in particular, fine particles (<2.5 μm in diameter) pose a major health risk because such particles directly reach alveoli and target circulator system. In addition, exposure to ultrafine particles (<0.1 μm in diameter) has an adverse effect on cardiopulmonary function that is independent of fine particle exposure (Oberdörster et al. 2005; Sioutas et al. 2005). The awareness of the impact of airborne particles, particularly fine and ultrafine particles, on health is growing.

PM in the indoor environment may generated by the many different indoor and outdoor sources. Common indoor source of fine particles (<2.5 μm in diameter) include cooking (Wallace et al. 2004), cigarettes (Waring and Siegel 2007), vented clothes dryers (Wallace 2005), and chemical reactions. Examples of important outdoor particle sources include industry, heating plants and traffic. Particle concentration indoors could be higher than outdoors due to strong influence of indoor sources (Wallace 2006) and the penetration from outdoors into indoors through Heating, Ventilation, and Air-Conditioning (HVAC) system ventilation duct, or through cracks in windows, doors, and building exterior wall.
People spend the majority of their lives indoors, for example, the average American spends 18 hours indoors for every hour outdoors (Klepeis et al. 2001). Reducing exposure to indoor PM has big health and economic impacts as demonstrated by various literatures and studies (Brook et al. 2010; Stephens et al. 2010). ASHRAE Standard 62.1 - Ventilation for Acceptable Indoor Air Quality (ASHRAE 2002) requires that “In buildings located in an area where the national standard or guideline for PM 2.5 is exceeded, particle filters or air-cleaning devices shall be provided to clean the outdoor air at any location prior to its introduction to occupied spaces”. HVAC mechanical ventilation and air filtration systems have been used as a standard practice to reduce PM concentrations. The indoor PM can be handled to some extent if HVAC systems and/or individual filtration systems are used effectively and timely.

However, until recently, airborne PM concentrations have rarely been measured in buildings for monitoring and HVAC control purpose other than for research purpose. This is mainly due to significant high cost associated with PM measurements (Piedrahita et al. 2014). Fortunately, with most recent and modern sensing and communication technologies, the PM measurements are becoming not only more actuate, but also less expensive, the sensor devices are becoming smaller, and are much more affordable than ever before. This offers promising uses for informing occupants on Indoor Air Quality (IAQ) through real-time monitoring, and moving towards smart and adaptive controls of building systems based on the demand.

EPA evaluated eight field-deployed low-cost PM sensors in outdoor environment (Williams et al. 2014). The costs for those sensors were ranged from $150 to $2,050. However, challenges remain regarding the practical use of lower cost PM sensors in indoor environment for smart building applications, primarily because of a lack of information on sensor performance metrics such as sensor accuracy (i.e., precision and bias), sensor response time, data completeness, and other technical criteria relative to high quality data measured with laboratory-grade instrumentation. Furthermore, many indoor particle sources have widely varying particle size distributions, concentrations, and compositions that may influence sensor responses (Afshari et al. 2005; Buonanno et al. 2009; Rim et al. 2012; Wallace 2006). Therefore, it is crucial to test these new sensor products in realistic indoor environmental settings to truly understand their applicability in buildings. In addition, how these low-cost PM sensors work with a variety of smart building applications are unknown. There also remains a need to inform the HVAC engineering community on the availability, costs, effectiveness, usability, hardware compatibility, and overall feasibility and practicality of commercially available PM sensors for IAQ monitoring and integration into controls systems in both residential and commercial buildings, which will support the development of ASHRAE standards and guidelines.

Particle sensors offer tremendous advantages of low cost, compact size, and easy installation and thus have recently drawn increasing attention for usage as portable monitors measuring indoor PM concentrations. As usual, the commercially available particle sensors refer to those less than $1,000 in upfront costs, or a similar value that is considered economically feasible for widespread building applications. This paper aims to preliminarily investigate low-cost PM sensors’ performances in realistic indoor environmental settings to help the HVAC community further understand their availability, usability, hardware compatibility and overall feasibility of their application in buildings. In this work, an acrylic-glass-built and caulk-sealed chamber with dimension of 36 in by 36 in by 36 in placed in a conditioned chamber with room temperature and humidity controlled is customized as the testbed. Three widely used low-cost PM sensors which each cost approximately 10 dollars are tested by three realistic indoor PM sources (i.e., incense burning, whiteboard spray cleaner, and air fresher). Two existing commercially available particulate sensors with high-cost and acknowledged accuracy (i.e., Dylos DC1100 and Thermo Scientific Data RAM 4) are used as the baseline to evaluate low-cost sensors’ performances. In this preliminary study, two indicators, i.e., response time linearity of response are selected as the evaluation metrics to help us obtain a preliminary understanding of sensors’ performances.

There also remains a need to inform the HVAC engineering community on the availability, costs, effectiveness, usability, hardware compatibility, and overall feasibility and practicality of commercially available PM sensors for IAQ monitoring and integration into controls systems in both residential and commercial buildings.
METHODOLOGY

Particle sensors and reference instruments

In this study, three low-cost particle sensors were selected for evaluations; meanwhile, two commercial high-cost particulate measurement products were selected to get the performance baseline. Three low-cost particle sensors are Sharp GP2Y1010AU0F, Shinyei PPD42NS and Amphenol Advanced Sensors SM-PWM-01C. Each of these sensors is about $10. Two commercial products are Dylos DC1100 pro and Thermo Scientific Data RAM 4 Particulate Monitor. In the following sections, these three low-cost sensors are named as A, B, C correspondingly, and two commercial products are named as D and E. Their specifications including type, measurement unit, shortest time resolution, etc. are shown in Table 1. Both Sensor B and Sensor C have built-in thermal resistors, which would generate the heat to create an updraft flow that brings the air and the PM mixture through the light scattering region. The Sensor A doesn’t equip any self-aspirated module, instead, it relies on a through-hole on the sensor body that allows the air mixture to pass the detecting zone. Both Sensor D and Sensor E have built-in ventilation units which are expected to improve the diffusion of PMs.

Compared to commercial products (e.g., Sensors D and E) that have a built-in data acquisition system with a dedicated data collection and visualization software, most of the low-cost sensors (e.g., Sensors A, B, and C) only contain the sensor itself. To record and trend the data from these three sensors, it is necessary to build a data acquisition system. Microprocessors (i.e., Arduino UNO in this study) are used in this project, as shown in Figure 1(a). The microprocessor helps to covert the lo-pulse output signal from the sensor to the digital signal, which will be read by the computer through the established USB communication. The system cost with the proposed data acquisition system is about $40 for all three sensors. Sensors D and E communicate with the computer through serial communication port (RS-232).

Sensor A detects the concentration of PMs, while Sensor B and Sensor C count the particle numbers in a unit volume. However, Sensor B measures only one size of PMs (pcs/m$^3$ for the particle size greater than 1 µm), while Sensor C is capable to detect PMs in two different size range (pcs/m$^3$ for the particle size between 1 to 2 µm and between 3 to 10 µm, respectively). For the reference products, sensor D has two output readings, representing the particle count in two different size range (pcs/m$^3$ for the particle size greater than 0.5µm and 2.5 µm, respectively). And sensor E measures the concentration of PMs (in mg/m$^3$). The detection sensitivities and units of outputs from all sensors are listed in Table 1. In this study, the sampling frequencies of all the PM sensors are set to one reading per minute.

<table>
<thead>
<tr>
<th>Table 1. Specifications of the tested PM sensors and monitors</th>
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<td>Symbol</td>
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<td>A</td>
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<td>Total Cost (approx.)</td>
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<td>Detectable Range</td>
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<td>Time Resolution</td>
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<td>Outputs</td>
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Chamber for the test
The controlled laboratory tests were conducted in an existing custom built acrylic glass chamber with a dimension of 36 in by 36 in by 36 in, as shown in Figure 1a. The walls, ceiling, and floor of the chamber consist of panes of acrylic glass mounted in metal frames. The main reason for using such material is to minimize sink effects and to ensure insignificant emission of particles from the inner surfaces of the chamber. The edges of the chamber were sealed with caulk. A sealable utility port with a uniform diameter of 3 in was drilled on the one vertical side of the chamber to allow for sampling and passing electrical circuits. During the experiments, the unused part of the port will be snugly plugged. An operable door of 24 in by 24 in allows placing particle sensors and PM source easily. This chamber is placed in a conditioned chamber as shown in Figure 1b.

![Figure 1](image1.png) (a) PM sensors with microcontroller; (b) The test chamber setup; (c) The test chamber location.

### Testing setup

<table>
<thead>
<tr>
<th>Relaxation</th>
<th>Incense Burning</th>
<th>Relaxation</th>
<th>Whiteboard cleaner</th>
<th>Relaxation</th>
<th>Air-freshener</th>
<th>Relaxation</th>
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![Figure 2](image2.png) The timeline of the PM test.

PM in the indoor environment may generate by the many different indoor and outdoor sources. In this study, three types of particle sources are adopted to mimic the realistic PM level. All the sensors are tested under the same circumstances. The particle sources were placed between the sensors with an equal distance (15 in / 0.381 m approximately). Figure 2 illustrates the testing procedures. Before the test is started, a 10-minute relaxation time allows the test rig to go into a relatively steady state prior to the test. The individual test for each particle source is conducted in the sealed chamber for 10 minutes, followed by a 15-minute relaxation time which will allow the in-chamber environment back to a normal/steady state. During the relaxation period, the chamber door is fully opened, which allows the in-chamber environment back to a steady condition expeditiously. These PM sources are:

**Incense Burning:** One direct-burning incense stick was burned constantly in the sealed test chamber for 10 minutes.

**Whiteboard Cleaner Spray:** The whiteboard cleaner was pumped for 3 times in one second in the test chamber, and then the chamber was sealed for 10 minutes of the testing period. Ingredients for this whiteboard cleaner include: water, sorbitan oleate, isobutane, propane, fragrance, propylene glycol, sodium phosphate, and steartrimonium chloride.

**Air-Freshener Aerosol Spray:** The aerosol spray of air-freshener lasted for approximately one second in the test chamber, and then the chamber was sealed for 10 minutes of the testing period. Ingredients for this aerosol spray include: water, corn-based ethanol, glycol ether DPnB, and cleaning agents.
Assessment Metrics

After the raw data was collected, a comprehensive data analysis was conducted to evaluate the performance of each test particle sensor. Two metrics, i.e., the response time and the linearity of response were included in this preliminary study. The detailed descriptions of each metric are as follows:

Response Time: The sensor response time refers to the amount of time required for a sensor to respond to a change in concentration. The response time of testing low-cost sensors and high-grade sensors were qualitatively evaluated based on the testing results.

The linearity of Response: The linearity of response was assessed using the least square regression and Reduced Major Axis (RMA) regression after plotting the outputs of the sensors against the reference measurements. Linear correlation, with R$^2$ values via the RMA regression analysis will be conducted using the software from Bohonak and Linde (Bohonak and van der Linde 2004). In this study, the dependent variables will be test sensor outputs, and the independent variables would be the measurements from two high-cost sensors, i.e., Sensor D and Sensor E.

TEST RESULTS AND ANALYSIS

This section presents and discusses the experimental results using the two metrics (i.e., response time and linearity of response). In this study, a total of three low-cost PM sensors were tested against two commercial PM sensors with high cost and acknowledged accuracy. Considering that the measurement units of these five devices are not identical, they are organized into two groups according to their measurement units, and the results are analyzed independently for each group. Specifically, three devices (i.e., B, C, and D) which count the number of the PM are organized in the first group, and the other two devices (i.e., A and E) measuring the mass concentration of the PM are organized in the second group. The results are presented in Figure 3. The X-axis lists each time-step during the test, while the left Y-axis represents the PM count in the unit of counts per liter, and the right Y-axis shows the mass concentration in the units of micrograms per cubic meter.

![Figure 3 Testing results of PM count and mass concentration from different sensors. (Note, results from Sensor A is not included)](image)

It's obvious from Figure 3 that the stimulations introducing by different PM sources significantly influence the PM count and mass concentration of the internal environment in the test chamber. At the time step of the 10th minute, the 35th minute, and the 60th minute, when the PM sources of incense burning, aerosol whiteboard cleaner, and aerosol air-freshener were respectively generated inside the chamber, significant changes in PM count/concentrations can be observed. In addition, the influence on the in-chamber environment from selected PM sources is different. Comparing
to the incense burning and aerosol sprays of whiteboard cleaner, the aerosol sprays of air-refresher would maintain a higher PM mass concentration and PM amount for a relatively longer period. In addition, the influence from incense burning is significantly less than the other two particle sources during the test.

It’s worthy to mention that a drastic fluctuation in measurement results among all sensors are observed in the first 35 minutes. This is assumedly due to the fact that the measurement sensitivities of Sensors B, C, and D are lower in the range of low PM counts. The measurement results from Sensor A is not presented in this paper because these results are far away from those measurements of other sensors. One possible reason is that the lack of a self-aspirated module (i.e., the heat resistor inside the B and C) in Sensor A makes it harder to detect the change in PM concentration. A further investigation is underway to understand more of Sensor A behaviors.

Response time

The response time of PM sensors can be easily observed from Figure 3. The time lag among different curves represents the difference on the response time, and the height of the curve indicates the response amplitude. Figure 3 shows that these sensors have different responses to the PM changes in the chamber environment. Comparing to Sensor D, Sensors B and C react to PM count changes as soon as the particle sources began to generate in the chamber, while Sensor D suffers from an obvious time lag of approximate two minutes. The result from Sensor E indicates incense burning and whiteboard cleaner spray have a 3-minute and a 2-minute response time delay, while air-refresher spray has the response immediately. In other words, the response time was getting shorter as the experiment continued.

There are three possible reasons for these phenomena. Firstly, the intrinsic characteristics of these sensors such as the underlying working principles are different. Secondly, the motion of the particle may play a critical role during the test. Lastly, although sensors were placed at an equal distance to the particle sources and most sensors have a self-aspirated module, since the PM-air mixture is not well mixed at the beginning of each test, these test sensors are not measuring the exact same samples until the PM and chamber air is well mixed and evenly fulfilled the chamber. In addition, the ingredients of PM sources are different. Limited to the current experiment condition (e.g., without a well-mixed PM-air mixture at the beginning of each test), the time lag of the response time inevitably tends to occur. A ventilation device (e.g. a fan) may help reduce such time lag. A quantitative evaluation of the response time will be one focus in the further research.

Linearity of response

As it has been mentioned earlier that the measurement result of Sensor A is hardly satisfactory possibly because of its lack of any self-aspirated module, only the linearity responses of the Sensors B and C are investigated in this study at this moment. Three groups of the response linearity analysis are presented. This includes the linearity responses of Sensor B and Sensor C with three different ranges of the particle size. Figure 4 illustrates the outputs from the sensors against the reference Sensor D.

Figure 4 also shows that the R² values of the three groups of data (the output from Sensor B versus the 0.5 µm output of Sensor D, the small particle output from Sensor C versus the difference value of the two outputs from Sensor D, and the large particle output from the Sensor C versus the 2.5 µm output from Sensor D) are 0.665, 0.659 and 0.631 respectively. These R² values indicate a good linear response between the low-cost sensors and the reference sensor. Additionally, the R² square values all exceed 0.83 if a 95% confidence interval was taken, which indicates both sensors perform well in terms of the linear response. It is noted that the measurement range of these sensors are not identical, which may influence the results of linearity. In this preliminary study, the linearity of response was investigated to visualize the performance difference between the low-cost sensors and a commercial product with high-cost and acknowledged accuracy. In addition, the linearity of response indicates that further improvement on accuracies and precisions can be achieved by calibrating these low-cost sensors with reference instruments.
SMART BUILDING APPLICATIONS ASSESSMENT

The low-cost PM sensors are also being evaluated for smart building applications. The possible smart building application includes:

- Monitor personal exposure to indoor PM and indoor air quality monitoring
- Occupancy detection
- Ventilation and filtration control
- Prognostics health monitoring of associated HVAC equipment

All PM sensors should be evaluated in terms of data output formats and demonstrated the ability to interface with building automation system. There is a need to test whether the sensor outputs can be accepted by a typical HVAC controller and whether test sensors can be integrated with the existing Building Energy Management System (BEMS) through the commonly used building network communication protocols (e.g., BACnet (ASHRAE 2016)). Theoretically speaking, as long as the sensor outputs are in the format of voltage (0-10 V), current (0-20mA) or pulse, the local controller should be able to take the sensor signals and use them for control purpose, as shown in Figure 5.
information can also be helpful to understand the status of filtration systems for proactive health maintenance of HVAC equipment.

As the first step of the preliminary assessment, this paper only covers the evaluation of output signals from the low-cost sensors, as listed in Table 1.

CONCLUSIONS AND FUTURE WORK

Conclusions

In this work, three low-cost PM sensors were selected and evaluated in a realistic indoor environmental setting with two commercial available PM monitors with high cost and acknowledged accuracy as the reference instruments. The on-site test was conducted in an acrylic-glass chamber. Three particle sources were generated inside the chamber to test sensors’ response time and linearity of response using a reference PM monitor. The initial evaluation of utilizing low-cost PM sensors for small building applications was briefly discussed.

According to the results, Sensors B and C which have a built-in self-aspirated module perform significantly better than the Sensor A which relies on the natural convection. In reality, the performance of Sensor A could be limited in specific circumstance since it does not have a self-aspirated module and may require an external device (e.g., fan) to help circulate the PM through the sensor.

In general, it is concluded that intrinsic characteristics, the motion of the particles in the chamber, and ingredients of PM sources have impacts on the response time, and the quantitative relationships are not clear at this moment. In addition, Sensors B and C yield good linearities with the reference measurements from Sensor D, which means that a more accurate measurement can be achieved by the calibrating them with high-grade reference instruments.

Future Work

Limited by the experimental equipment and setting (e.g. only one sensor of each type was tested, lack of ventilation and/or in-chamber air-particle mixing devices, etc.), there are some problems remaining to be addressed in the future work. Some ongoing and remaining future work as listed as follows:

- More low-cost PM sensors will be included into study.
- More metrics will be used for the evaluation, e.g., the precision of the measurement, the limit of detection, etc.
- More sources of PM (e.g., ASHRAE test dust #1), will be used in the test environment.
- A high-grade laboratory particle sizer with a high resolution will be added into the reference measurements.
- A mechanical fan will be deployed in the test chamber to mix the internal air and create a uniform test environment.
- The low-cost PM sensors will be further tested for smart building applications using a Hardware-in-the-loop (HIL) testbed. HIL is widely used in automotive and aerospace industries to verify control system hardware. HIL allows verifying control requirements using a real controller with an emulated plant. For example, sensors will be connected to a typical HVAC controller (e.g., zone VAV box controller) to test whether the sensor outputs can be accepted by a typical HVAC controller and whether test sensors can be integrated with the existing BEMS through the BACnet protocol.
- A campus wide low-cost PM sensor network for real-time personal exposure monitoring is being investigated.
REFERENCES


