Atmospheric Environment 171 (2017) 82–90

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Development of an environmental chamber for evaluating the performance of low-cost air quality sensors under controlled conditions

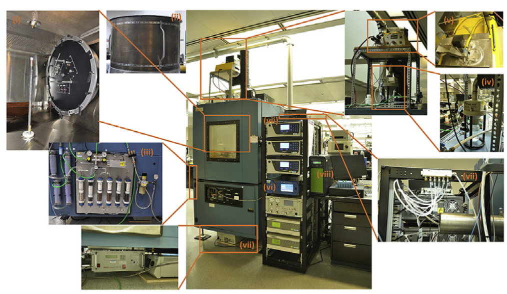
Vasileios Papapostolou, Hang Zhang, Brandon J. Feenstra, Andrea Polidori*

South Coast Air Quality Management District, Diamond Bar, CA 91765, USA

HIGHLIGHTS

- A state-of-the-art laboratory chamber was developed to evaluate air quality sensors.
- This chamber generates stable and reproducible environmental conditions.
- Sensors should be tested under a wide range of T and RH conditions.
- A rigorous sensor testing method was also developed.
- As technology improves a more standardized testing protocol should be developed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 March 2017
Received in revised form 23 September 2017
Accepted 1 October 2017
Available online 4 October 2017

Keywords:
Low-cost sensors
Sensor evaluation
Environmental chamber
Testing protocol
Particle pollutants
Gaseous pollutants

ABSTRACT

A state-of-the-art integrated chamber system has been developed for evaluating the performance of low-cost air quality sensors. The system contains two professional grade chamber enclosures. A 1.3 m^3 stainless-steel outer chamber and a 0.11 m^3 Teflon-coated stainless-steel inner chamber are used to create controlled aerosol and gaseous atmospheres, respectively. Both chambers are temperature and relative humidity controlled with capability to generate a wide range of environmental conditions. The system is equipped with an integrated zero-air system, an ozone and two aerosol generation systems, a dynamic dilution calibrator, certified gas cylinders, an array of Federal Reference Method (FRM), Federal Equivalent Method (FEM), and Best Available Technology (BAT) reference instruments and an automated control and sequencing software. Our experiments have demonstrated that the chamber system is capable of generating stable and reproducible aerosol and gas concentrations at low, medium, and high levels. This paper discusses the development of the chamber system along with the methods used to quantitatively evaluate sensor performance. Considering that a significant number of academic and research institutions, government agencies, public and private institutions, and individuals are becoming interested in developing and using low-cost air quality sensors, it is important to standardize the procedures used to evaluate their performance. The information discussed herein provides a roadmap for entities who are interested in characterizing air quality sensors in a rigorous, systematic and reproducible manner.

Published by Elsevier Ltd.

* Corresponding author.
E-mail address: apolidori@aqmd.gov (A. Polidori).

https://doi.org/10.1016/j.atmosenv.2017.10.003
1352-2310/Published by Elsevier Ltd.

1. Introduction

Studies have shown that air pollutants, such as fine particulate matter ($PM_{2.5}$), ozone (O_3), volatile organic compounds (VOC), and nitric oxides (NO_x), can cause serious respiratory diseases, cardiovascular disorders, and other adverse health effects (Heck et al., 2013; Weichenthal et al., 2011). Conventionally, air quality and pollutant concentrations are monitored by the federal government as well as state and local regulatory agencies using sophisticated and expensive fixed-site instruments (Snyder et al., 2013). The number of monitoring sites is thus limited by the cost of instrumentation and availability of trained personnel to operate and maintain such equipment. Because of their relatively low spatial density, available fixed air monitoring sites are mostly designed to characterize air quality over a wide geographical area. However, they do not typically provide the granularity that is often necessary to fully understand local air quality conditions. Due to recent technological advancements in micro-sensors, embedded systems, and wireless networks, manufacturers have begun marketing low-cost and relatively easy-to-use air quality sensors. These devices, provided they produce reliable data, can significantly augment and improve current ambient air monitoring capabilities. A wide range of sensor applications is now changing the paradigm of air pollution monitoring (Snyder et al., 2013). In its 2014–2018 Strategic Plan, the United States Environmental Protection Agency (U.S. EPA) has recognized the need to extend the existing air pollution monitoring to lower cost measurements (EPA, 2014). Herein, a sensor is considered low-cost if its market cost is less than $2000. If a device is presented as a multi-pollutant sensor device, then the cost per pollutant type should be less than $2000. With the recent commercialization of low-cost and easy-to-use devices, susceptible groups and individuals such as children, seniors, asthmatics, pregnant women, and people interested in measuring air pollution in their communities can monitor air quality and assess potential personal exposure. Citizen scientists and community groups have now access to a wealth of information to better understand how air pollution may impact their neighborhoods (Deville Cavellin et al., 2016; Jiao et al., 2015). Air quality sensors deployed near industrial facilities, such as those for fence-line monitoring applications, can provide empirical data to supplement existing ambient air monitoring infrastructure (Pikelnaya et al., 2013). Portable sensor mounted on a mobile vehicle can also be used to monitor urban air quality and map the spatial variation of traffic related emissions (Hagler et al., 2010; Van den Bossche et al., 2015).

The development of reliable low-cost air quality sensors is complex. These devices have to detect one or more specific target pollutants while being inert to interferent species and meteorological parameters. They also have to be calibrated to give accurate readings, which often requires the need of specialized and expensive reference instrument. Furthermore, various algorithms and processing procedures are used to convert the sensor's signal to air pollution concentrations. Therefore, not all low-cost sensors are reliable or able to provide meaningful air quality information (Williams et al., 2014). Consequently, their performance needs to be fully characterized under various pollutant levels and different environmental conditions to assure data quality.

Environmental chambers have been an indispensable tool in studying gas-phase atmospheric chemistry (Cocker et al., 2001) and pollutant exposure (Papapostolou et al., 2013) because they can provide controlled environments. Over the past years, there have been several studies on sensor performance evaluation that involved environmental chambers. At EPA, a glass exposure chamber was constructed to evaluate the performance of O_3, nitrogen dioxide (NO_2) and VOC sensors (Williams et al., 2014, 2015). Temperature and relative humidity (RH) were controlled by an air conditioning system, supplemented with heating pads, dry ice, and a water bubbler. Important parameters such as linear correlation coefficient, detection limit, concentration resolution, response time, and temperature and RH influences were examined. Yet, due to the chamber size limitations and restricted resources, the intra-model variability, the effect of interferents and weather conditions were not tested in those studies. Joint Research Center (JRC) has published a series of technical reports and papers describing its efforts in evaluating and calibrating gaseous sensors (Spinelle et al., 2014). In the JRC laboratory testing approach, an “O”-shaped ring-tube exposure chamber was developed to evaluate an ozone sensor (model B4-O3, Alphasense, UK) under controlled temperature, RH, wind velocity, and gaseous interferent concentrations. The sensor reported highly linear output, good precision, and little baseline drift, but it was sensitive to NO_2 and was affected by hysteresis due to RH variations. Although this work was conducted for an ozone sensor, it provided important guidelines for other gas sensors evaluation. In another study, three particle sensors, including Shinyei PPD42NS, Samyoung DSM501A and the Sharp GP2Y1010AU0F, were evaluated in a customized acrylic chamber where particulate atmosphere was created by burning incense (Wang et al., 2015). The method was limited in scope, as the system could not generate stable and reproducible particulate environment, thus was not appropriate for systematic evaluation of PM sensors of different types. Additionally, a Shinyei PPD42NS particulate sensor was also evaluated in a chamber, but only under ambient temperature and RH conditions (Austin et al., 2015). Similar studies (Northcross et al., 2013; Sousan et al., 2016a, 2016b) have definitely expanded our understanding on the potential and limitations of low-cost air monitoring devices. Nonetheless, there has not been any effort to develop methods, protocols, and procedures to systematically evaluate the performance of low-cost particle and gaseous sensors under a wide range of environmental conditions.

Herein, we describe the development of a state-of-the-art chamber system for the performance evaluation of low-cost air quality sensors. To the best of our knowledge, this integrated chamber system is the first that can generate stable and reproducible environmental conditions with diverse temperature, RH, and known PM and gas concentration profiles. The chamber system is coupled with an array of FRM, FEM, and BAT reference instruments for comparison purposes. In this paper, we focus on the development of methods and the validation of the chamber's ability to generate a wide range of environmental conditions. Indicative laboratory experiments are presented to exemplify the practical application of the chamber system and the testing methods. A summary of all available laboratory testing results conducted within Air Quality – Sensor Performance Evaluation Center (AQ-SPEC) can be found on a dedicated website (www.aqmd.gov/aq-spec). Our sensor evaluation results indicate that sensor performance can be better characterized when parameters such as accuracy, precision, detection limit, climate susceptibility, and the effect of interferents are investigated systematically.

2. Methodology

2.1. Chamber system overview

A chamber system, designed by the AQ-SPEC team, hardware developed and integrated by AmbiLabs (Warren, RI), has been installed inside the South Coast Air Quality Management District's Chemistry Laboratory (Fig. 1 and Figure S-1).

The chamber system consists of:

i) A professional grade environmental test chamber (G-Series Elite, model GD-32-3-AC, Russells, Holland, MI) capable of