Environmental Research 152 (2017) 59–65

Contents lists available at ScienceDirect

Environmental Research

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

Spatio-temporal measurement of indoor particulate matter concentrations using a wireless network of low-cost sensors in households using solid fuels

Sameer Patel[a], Jiayu Li[a], Apoorva Pandey[a], Shamsh Pervez[b], Rajan K. Chakrabarty[a], Pratim Biswas[a,*]

[a] *Center for Aerosol Science and Engineering (CASE), Department of Energy, Environmental and Chemical Engineering, Washington University in St. Louis, One Brookings Drive, St. Louis, MO 63130, USA*
[b] *School of Studies in Chemistry, Pandit Ravishankar Shukla University, Amanaka G.E.Road, Raipur, Chhattisgarh 492010, India*

ARTICLE INFO

Keywords:
Spatio-temporal $PM_{2.5}$
Indoor air quality
Cookstoves
Household air pollution
Low-cost instrumentation

ABSTRACT

Many households use solid fuels for cooking and heating purposes. There is currently a knowledge gap in our understanding of the variations in indoor air quality throughout the household as most of the studies focus on the areas in the close proximity of the cookstove. A low-cost wireless particulate matter (PM) sensor network was developed and deployed in households in Raipur, India to establish the spatio-temporal variation of PM concentrations. The data from multiple sensors were acquired in real-time with a wireless system. Data collected from the sensors agreed well (R^2 =0.713) with the reference data collected from a commercially available instrument. Low spatial variability was observed within the kitchen due to its small size and poor ventilation – a common feature of most rural Indian kitchens. Due to insufficient ventilation from open doors and windows, high PM concentrations similar to those found in the kitchen were also found in the adjoining rooms. The same household showed significantly different post-extinguished cookstove PM concentration decay rates (0.26 mg/m^3-min and 0.87 mg/m^3-min) on different days, owing to varying natural air exchange rates (7.68 m^3/min and 37.40 m^3/min).

1. Introduction

Spatio-temporal monitoring of outdoor and indoor air quality provides critical information about emissions sources, air flow and ventilation, and subsequent personal exposure. For example, in highly polluted cities like Delhi, India, and Beijing, China (Cheng et al., 2016), measurements at a few locations cannot represent pollution levels in the whole city. Similarly, at a much smaller scale, household air pollution measurements near pollution sources such as a furnace or cookstove are insufficient to accurately estimate personal exposure in different parts of the households over different durations. Spatio-temporal pollutant level data provides a way to better model the effect of air circulation on pollutant dispersion and decay rate.

Better characterization of indoor air pollution is critical because residents spend much more time indoors than they spend outdoors (Spengler and Sexton, 1983; Zhang and Smith, 2003; Zhou et al., 2015). The World Health Organization (WHO) reported that poor indoor air quality due to residential solid fuel combustion affects over three billion people. Particulate matter (PM) emissions cause health issues such as acute respiratory infections (ARI), chronic obstructive pulmonary disease (COPD), and cataracts (Smith et al., 2000; Bruce et al., 2000; Ekici et al., 2005; Pokhrel et al., 2005, 2013). WHO has estimated four million premature deaths from illness are attributable to household air pollution from residential solid fuel combustion for cooking and heating. Furthermore, among children under the age of five, pneumonia attributed to inhaled PM accounts for more than half of the total deaths.

The majority of published studies on solid fuel cookstoves and indoor air quality take $PM_{2.5}$ (particulate matter less than 2.5 µm in aerodynamic diameter) measurements using gravimetric methods at limited locations to indicate the levels of personal exposure (Smith et al., 2010; Albalak et al., 2001; Dionisio et al., 2012; Balakrishnan et al., 2004). Real time measurements have only been reported from few field studies on cookstove emissions (Sahu et al., 2011; Leavey et al., 2015) but data on spatial variation of the pollutants in indoor environments is limited because of use of few instruments due to their high cost. Most previous studies have taken measurements near the breathing zone (Albalak et al., 2001; Kar et al., 2012; Leavey et al., 2015; Armendáriz-Arnez et al., 2010) or above the cookstove (Roden et al., 2006) which might not be representative of indoor air quality

---

[*] Corresponding author.
E-mail address: pbiswas@wustl.edu (P. Biswas).

http://dx.doi.org/10.1016/j.envres.2016.10.001
Received 7 July 2016; Received in revised form 18 August 2016; Accepted 3 October 2016

throughout the household. Sampling near the source does not capture parameters other than the source characteristics, a shortcoming that affects the assessment of overall indoor air quality.

The type of cookstove and fuel are not the only factors governing indoor air quality: other factors such as the household layout, kitchen volume, and ventilation characteristics also play important roles which are currently understudied (Clark et al., 2010; Johnson et al., 2011; Chung and Hsu, 2001; Bouilly et al., 2005). Depending on the household characteristics, cookstove emissions can quickly transport to living spaces, thereby affecting other household members (Dasgupta et al., 2006, 2009). A large variation in personal exposure levels have been observed in different field studies, which is attributed to inability to capture the interplay between the household characteristics and indoor air quality (Clark et al., 2013). Moreover, pollutants can stratify vertically exposing individuals with different heights, standing at the same location, to different levels of the same pollutant (Johnson et al., 2011).

Spatio-temporal measurements are essential to correctly estimate personal exposure and to enhance the understanding of household air pollution, but such measurements are currently challenging to accomplish due to the lack of affordable real-time monitors (Clark et al., 2013). To ensure the feasibility of using multiple devices for PM measurement, it is essential that low-cost PM sensors be developed and deployed. Recent developments by many researchers in the design and fabrication of low-cost PM sensors (Wang et al., 2015; Bhattacharya et al., 2012; Chung and Oh, 2006; Kim et al., 2010, 2014; Rajasegarar et al., 2014; Sousan et al., 2016) have made progress toward making such measurements feasible.

The objectives of this study were to deploy a wireless PM sensor network for performance evaluation in households and to demonstrate its utility in providing insights into spatio-temporal distribution of indoor air pollution. Two households in Raipur, central India, using solid fuel cookstoves were selected for this research. To record spatio-temporal PM levels, multiple sensors, sending data wirelessly to a data acquisition system, were installed at different locations in the kitchen and adjoining parts of the household. A commercially available TSI Sidepak (TSI Inc., Minnesota, USA) was collocated with one of the sensors for performance comparison.

2. Methods

2.1. Instrumentation

A key feature of the study was the deployment of multiple low-cost PM sensors and using a wireless network system to collect the data. Sharp GP2Y1010AU0F sensors (Fig. 1) were used in this study owing to their high linearity against the reference instrument (TSI SidePak AM 150) and long-time operational stability (Wang et al., 2015). The operating principle of this sensor is the detection of scattered light from particles; the light source is an infrared emitting diode (IRED) and the detector is a phototransistor that converts the scattered light intensity to a voltage output. More details about the construction and operation principle of the Sharp GP2Y1010AU0F sensor are provided in a previous study (Wang et al., 2015). Two additional components were attached to the sensors to enable wireless transmission of data and create a local area network (Fig. 1). These components include a router (XBEE Series 2) to communicate with the data acquisition system. In this study, a coordinator connected to a computer was used for data collection and storage, but these sensors could readily be connected to the network cloud for real-time data acquisition and processing. Power was supplied to the sensors by 5 V lithium-ion batteries. The total cost of one sensor assembly including the Sharp GP2Y sensor, router, battery and accessories was around USD 50, making it much cheaper than any commercially available light-scattering based PM measurement instrument. The cost could be reduced to USD 25 provided the required parts are procured in bulk directly from the manufacturers..

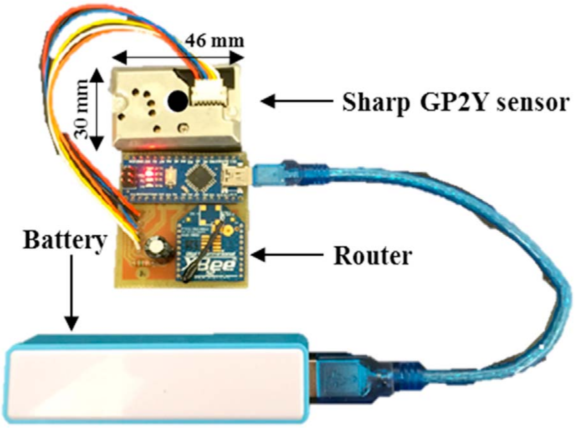

Fig. 1. PM sensor assembly, which includes a Sharp GP2Y sensor, a router mounted on a chip board, and a 5 V lithium ion battery.

The Sidepak and DustTrak (TSI Inc., Minnesota, USA), both with the same operating principle, have been used in multiple laboratory and field studies to measure $PM_{2.5}$ mass concentrations from cookstoves (Sahu et al., 2011; Leavey et al., 2015; Patel et al., 2016; Li et al., 2012; Commodore et al., 2013). A TSI Sidepak AM510 (approximate cost USD 3500) was used to record reference measurements to facilitate the sensor's performance evaluation. The Sidepak operation is also based on light scattering and uses a light source that is a 670 nm emitting diode. This instrument, which comes with impactors with different cut-off sizes, was operated with one to obtain $PM_{2.5}$ concentrations. The Sidepak and the sensors were set to collect data with a frequency of 1 Hz and 0.25 Hz respectively.

2.2. Household characteristics and test plan

The two households selected for this study used U-shaped mud cookstoves (*chulhas*) for cooking meals. The layout of each household is shown in Fig. 2. The first household (Household A), shown in Fig. 2A, had a kitchen (floor area ~5.3 m^2) on the second floor, isolated from the rest of the residential area on the first floor. The entrance door and a window next to it, both open during sampling, were the two main ventilation sources. The window area was permanently covered with a concrete slab consisting of multiple holes in a decorative pattern. The cookstove was located just below the window. The slightly slanted roof, a corrugated metal sheet, formed multiple small openings at the junction of the kitchen walls, and aided in the ventilation. No forced ventilation was present in Household A. The area outside the kitchen front was an open space for children to play, which was also used for air drying the biomass fuels. The PM sensors were installed at the five positions shown in Fig. 2A. Sensors A1 and A2 were installed at the interface of the kitchen and ambient environment to capture the effects of natural dilution and air exchange between the two environments having different PM levels. Plume concentrations were captured by installing a sensor at position A3, directly above the cookstove. Another sensor was installed inside the kitchen at position A4 to investigate the spatial variability within the kitchen. Sensor A5 was installed outside of the kitchen to monitor PM levels corresponding to exposure levels of children present in that area..

Fig. 2B presents the layout of the second household (Household B). With approximately 29 m^2 of floor area, Household B consisted of a kitchen opening to a room which served as a living room; this room was further connected to a bedroom. The two rooms each had one door opening to the ambient environment (towards the backyard and street) providing natural ventilation. Similar to Household A, Household B had no forced ventilation. Only the windows and doors that were open during measurements, and therefore affected indoor air quality, are marked in the layout (Fig. 2B). Household B had a thatched roof with