Characterization of Indoor PM$_{2.5}$ Peak: New Indexes and Implications

Shaojie Zhuo$^1$, Yatai Men$^2$, Jinze Wang$^{2*}$, Jie Sun$^3$, Yali Lei$^4$, Wei Du$^3$

$^1$Shanghai Key Laboratory of Forensic Medicine, Institute of Forensic Science, Ministry of Justice, P.R. China
$^2$Laboratory of Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing, 100871, China
$^3$Yunnan Provincial Key Laboratory of Soil Carbon Sequestration and Pollution Control, Faculty of Environmental Science & Engineering, Kunming University of Science & Technology, Kunming 650500, China
$^4$Key Laboratory of Geographic Information Science of the Ministry of Education, School of Geographic Sciences, East China Normal University, Shanghai 200241, China

Received: 2 November 2022
Accepted: 14 December 2022

Abstract

Household air pollution is arising more and more concerns due to its severe impact on human health. In recent years, low cost sensors are more and more popular due to their advantages of data with high time resolution. However, the analysis methods for the large-scale data obtained from sensors are still rare, limiting the expression of the value of the high time resolution data. In this paper, we introduce two new indexes for the characterization of indoor PM$_{2.5}$ peak, aiming to evaluate the speed of the PM$_{2.5}$ increasing and decreasing (namely $K_i$ and $K_d$, respectively) with internal emission sources starting and ending, and the reliability of the indexes was identified by using real world measurement. Large $K_i$ is found in the residential homes during cooking time, indicating the urgent need to control PM$_{2.5}$ emissions from residential energy use and cooking oil. It is found that the $K_i$ and $K_d$ in homes burning solid fuels are higher than that using clean fuels, suggesting the potential benefit of energy transition in residential homes. This study highlighted the importance of various indexes used for indoor PM$_{2.5}$ peak characterization and it is expected to provide new insights for future indoor air pollution study.

Keywords: household air pollution, PM$_{2.5}$ peak, dynamic characteristic, new indexes
Introduction

There is an increasing concern about household air pollution since people spend most time indoors, especially in homes with strong internal sources such as solid fuels combustion and incense burning [1-3]. Globally, it is estimated that more than 3.2 million premature deaths are caused by household air pollution, most of them were observed in developing countries such as India and China [4]. Thus, it is an urgent need to pay more attention to household air pollution for protecting human health.

The measurement of household air pollution had high cost, especially in field measurements. Pollutants bound to PMs (particulate matters) were usually collected on filters and then determined in lab [5-8]. The high cost of field sampling and lab analysis make it difficult for household air pollution measurement, especially with a large sample size. Secondly, although lab analysis could determine various air pollutants such as elemental carbon, organic carbon, and heavy metals [8], the measurement based on filter sampling cannot provide data with high time resolution, thus leaving knowledge gap in the dynamic characteristics of household air pollution [9]. Recently, low cost sensors were widely used to measure household air pollution to obtain high time resolution data of various air pollutants in residential homes such as PMs, CO, and CH4 [10-15]. The advantages such as data with high time resolution and low cost make low cost sensors more suitable for household air pollution measurement. For example, Du et al. used low cost sensors to evaluate the impact of Chinese spring festival overlapping COVID-19 lockdown on household PM2.5 pollution in rural Chinese homes, proving the increase of indoor PM2.5 was locked down on household PM2.5 pollution in rural Chinese homes, showing the increase of indoor PM2.5 pollution when a strong internal emission source was started and ended. In this study, we introduce two new indexes to describe indoor PM2.5 peak focusing on the increasing and decreasing speed of air pollutants, which means, the speed of the air pollutants increasing from baseline value to the maximum value and from the maximum value to the baseline value again. Data from real world measurement was used to identify the reliability of the new indexes and the environmental implication was discussed accordingly. The results are expected to provide new tool for household air pollution research, focusing on the dynamic characteristics of air pollutants.

Methods and Materials

The Introduction of the New Indexes

Usually, if there is no internal emission source or strong air pollutants input from outdoor air, the indoor PM2.5 would keep stable, the concentration during this period could be defined as baseline, which could be considered as the background PM2.5 pollution in a residential home. When there are strong emission sources starting (e.g. combustion of solid fuels, cooking, and smoking), the indoor PM2.5 would increase rapidly from the baseline to a maximum value, then decreasing to the baseline again after the emission sources stopped. The process was defined as a PM2.5 peak, as seen in Fig. 1.

To describe a PM2.5 peak, peak length, peak height, and peak area were found useful in previous studies [17, 23]. However, these indexes could not describe the speed of the PM2.5 increasing and decreasing of a PM2.5 peak, which limited the understanding of the indoor PM2.5 variation when strong internal emission sources existed and stopped. Herein, two new indexes are defined as K_i and K_d (K_i for increasing and K_d for decreasing), where K_i means the speed of the PM2.5 increasing from the baseline to maximum value when an internal source occurs and K_d means the speed of the PM2.5 decreasing from maximum value to the baseline, equations were given as below:

\[ K_i = \tan \alpha = P/L_1 \]  
\[ K_d = \tan \beta = P/L_2 \]  
\[ L = L_1 + L_2 \]

As seen in Fig. 1, P (peak prominences) and L represented the height from baseline to the maximum value and length of the PM2.5 peak. It is easy to understand the meaning of these new indexes. When K_i and K_d are larger, the speed of PM2.5 from the baseline to maximum value and from the maximum value to
the baseline would be quicker. In other words, the variation of PM$_{2.5}$ per unit in terms of time is larger.

Selected Homes and Real Time PM$_{2.5}$ Measurements

To verify the environmental implication of the new indexes, field data measured in homes located in southern and northern China with different residential energy patterns, locations, and seasons were selected from our previous studies. The south site was located in Hunan province and the north site was located in Shanxi province. In the south site, local residents used biomass and/or clean fuels such as liquefied petroleum gas (LPG) for cooking. The typical cooking stove using solid fuels was traditional built-in place brick stoves equipped with an outdoor chimney. Most local households were usually with one kitchen, one living room and 2-3 bedrooms. To investigate the seasonal difference of indoor air pollution, measurements were conducted both in summer and winter time. In the north site, the rural residents usually lived in cave dwellings without separate kitchen, living room, and bedroom, which means a dwelling was used as kitchen, living room, and bedroom at the same time. Only measurements in winter were conducted in the north site. The detailed information of these measurements was provided in Table 1. It should be noted that the daily PM$_{2.5}$ concentrations of these homes were previously published, which could be found elsewhere [5, 16, 17]. However, the high time resolution data was never used for the assessment of the new indexes, which are introduced for the first time in this paper.

For indoor air pollution measurement, the optical real-time PM$_{2.5}$ monitors (Zefan Technol., China) were used in the filed campaigns, which were the same with our previous studies [5, 24]. The PM$_{2.5}$ data was recorded with a 5-second interval for 24 hours. Before the field campaign, all the PM$_{2.5}$ monitors were calibrated for at least 15 days against a particulate matter monitor (model 5030 synchronized hybrid ambient real-time particulate monitor, Thermo Scientific). In the field, the PM$_{2.5}$ samplers were placed at the height of 1.5 m above the ground and 1.0 m away from stoves and walls.

Data Analysis

Identification of the indoor PM$_{2.5}$ peak followed the method adopted by Men et al. [23]. Briefly, the contribution of outdoor infiltration was firstly deducted from the total concentration of indoor PM$_{2.5}$, thus the time series of indoor-originated PM$_{2.5}$ contribution
was obtained. After moving average firstly in the time series to reduce the noise, peaks were sought by simple comparison of neighboring values and specifying conditions for a peak’s properties such as height, width, prominence, etc. At the same time, the time of peak appearance, the set threshold, and the distance between adjacent peaks were also considered for peak filtering. In this paper, the calculations of $K_i$ and $K_d$ were added in the model at the same time. Other formal analysis was conducted by SPSS 21.0 (IBM Corporation, Armonk, NY, USA) at a statistical significance ($p$ value) level of 0.05.

### Results and Discussion

#### Overall Description of Indoor PM$_{2.5}$ Peak

As seen in Table 2, the characteristics of indoor PM$_{2.5}$ peak caused by cooking activities show large variations among different sites, seasons, and locations. The peak heights and prominences in kitchens are significantly higher than that in the living rooms ($p<0.05$). This is not strange since the internal sources were mostly occurred in kitchens, the emitted PM$_{2.5}$ from kitchen was diluted when transferred to the corresponding living rooms [16]. It is also found that in winter, the peak heights and prominences were higher than that in summer. In winter, the dominant cooking fuel was solid fuels, different from that in the summer, which was dominated by LPG and electricity. The combustion of solid fuels could emit lots of PM$_{2.5}$, which lead to a considerable increase of indoor PM$_{2.5}$ sharply [25, 26]. While in summer, the use of electricity for cooking emitted less PM$_{2.5}$, which was mainly from the cooking oil since the popular Chinese cooking method is stir-frying [27]. In the north site, the peak heights and prominences in winter were similar to the results of southern kitchens in summer, but lower than southern kitchens in winter ($p<0.05$). In the cave dwellings, the cooking stoves were also used for space heating, which means the baseline values of indoor PM$_{2.5}$ would be high in the cave dwellings, thus the cooking activities lead to a less increase of indoor PM$_{2.5}$ [5]. However, the daily average of indoor PM$_{2.5}$ in cave dwellings are the highest among the selected sites ($p<0.05$).

It could be found that the lengths of indoor PM$_{2.5}$ peak in cave dwellings are the highest among the sites, again indicating that the strong need for space heating caused longer peak lengths. In our previous study, we had discussed the peak area of indoor PM$_{2.5}$ in homes using different fuels, which is estimated by integrating the time and PM$_{2.5}$ concentrations [17]. The peak area of cooking activity relying on solid fuel combustion is several folds higher than that of electricity. Although peak area is a suitable index for the direct contribution of internal sources, it could not show the speed of PM$_{2.5}$ change during the peak process. For a better description of PM$_{2.5}$ peak, $K_i$ and $K_d$ should be included in the future studies.

#### 3.2 $K_i$ and $K_d$

The new indexes $K_i$ and $K_d$ introduced firstly were calculated and provided in Table 2. The values of $K_i$ ranged from 9.5±12 to 41±41 μg·m$^{-3}$·min$^{-1}$, indicating the rapid increase of indoor PM$_{2.5}$ when there are internal emission sources indoor. It’s interesting to find that higher $K_i$ than that $K_d$ were observed in all sites, which means that the longer time for the PM$_{2.5}$ to reduce from the highest value to the baseline again than that from the baseline to the maximum value. In the south site, the $K_i$ and $K_d$ in kitchen in winter are higher than that in the summer and similar result was found for living room, which is also caused by the more consumption of solid fuels in winter (5.6 kg/household in summer and 20.4 kg/household in winter, respectively). Strangely, the $K_i$ and $K_d$ in the cave dwellings were relatively lower than other sites. The most possible reasons might be the much higher baseline values of PM$_{2.5}$ in the dwellings limited the space for the PM$_{2.5}$ increase, which is mentioned above. On the other hand, the significant longer peak length in the north site associated with the strong need of space heating also contributed to the lowest $K_i$ and $K_d$ values.

As seen in Fig. 2, the $K_i$ and $K_d$ also show large variations among kitchens using different fuels. It could be found that $K_i$ in homes using different fuels is still higher than $K_d$, again indicating the reduction of indoor PM$_{2.5}$ from the maximum value to the baseline value needs more time. In the south site, homes using

Table 2. The overall description of indoor PM$_{2.5}$ peak of the selected homes.

<table>
<thead>
<tr>
<th>Site</th>
<th>Season</th>
<th>Location</th>
<th>H (μg/m$^3$)</th>
<th>P (μg/m$^3$)</th>
<th>L (min)</th>
<th>$K_i$ (μg·m$^{-3}$·min$^{-1}$)</th>
<th>$K_d$ (μg·m$^{-3}$·min$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>South</td>
<td>Summer</td>
<td>Kitchen</td>
<td>324±300</td>
<td>295±299</td>
<td>27±30</td>
<td>26±30</td>
<td>20±25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Living room</td>
<td>200±230</td>
<td>170±229</td>
<td>22±14</td>
<td>17±31</td>
<td>11±15</td>
</tr>
<tr>
<td>South</td>
<td>Winter</td>
<td>Kitchen</td>
<td>594±394</td>
<td>495±396</td>
<td>23±26</td>
<td>41±41</td>
<td>26±28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Living room</td>
<td>357±279</td>
<td>256±289</td>
<td>31±37</td>
<td>21±29</td>
<td>13±18</td>
</tr>
<tr>
<td>North</td>
<td>Winter</td>
<td>Cave dwelling</td>
<td>367±122</td>
<td>165±103</td>
<td>87±64</td>
<td>9.5±12</td>
<td>2.1±2.0</td>
</tr>
</tbody>
</table>

Note: a, the maximum value of a PM$_{2.5}$ peak
Characterization of Indoor PM2.5 Peak...

electricity owe the lowest values of $K_i$ and $K_d$ than that using LPG and wood, it was not strange since using electricity emitted the least PM$_{2.5}$. In summer time, homes using wood and LPG had similar $K_i$ values, however, homes using wood had higher $K_d$ values than that using LPG. It was previously reported that the indoor air pollution could be influenced by various factors, such as fuel type, the rate of indoor/outdoor air exchange, the duration of cooking time, the cooking style [15, 25, 28-31]. Thus, it is also reasonable to assume that the $K_i$ and $K_d$ could be affected by multiple factors, which should be further evaluated in the future.

Implications for Indoor Air Quality

High time resolution data is crucial for understanding the dynamic characteristics of indoor air pollution and the short-term effect such as asthma, acute lower respiratory infection etc. [32-34]. Recently, low cost sensors are becoming more and more popular in indoor air measurement. However, the lack of analysis method for the large data set limited the value of high time resolution data. In this study, new indexes are introduced for better evaluation of indoor PM$_{2.5}$ peak and the rising and decreasing speed when a peak occurred are well described. The results highlight the significant contribution of solid combustion and cooking activity to indoor air pollution by quantitative description. In our view, various indexes such as peak height, peak length, peak prominence, peak area as well as $K_i$ and $K_d$ should be taken into consideration when describing the peak of indoor air pollution to take advantage of high time resolution data. Indoor air pollution is much crucial since people spend most time indoor, thus the pollution characteristics including concentrations, spatial heterogeneity, and dynamic variation should be concerned to fully understand the pollution characteristics of indoor air pollution and protect human health. This study aimed to provide new tools for data analysis obtained from low cost sensors based on high time resolution. However, some limitations should be kindly noted. First, considering the large spatial and temporal variations of indoor air pollution, the field data used for the reliability identifying of the new indexes was limited, more measurements should be conducted to further improve the data analysis, especially on the influencing factors such as cooking style, indoor-outdoor air exchange rate, and the structure of residential households. Second, only PM$_{2.5}$ peak associated with cooking activities were discussed, other internal sources such as space heating and smoking were not included in the discussion. In the future, measurement in different sites and seasons and in urban and rural homes are especially welcomed, and we hope our analysis method could be used in more and more studies focusing on indoor air pollution.

Conclusions

To provide new analysis tools for high time resolution data measured in indoor air, new indexes are introduced to describing the air pollutants variation per unit in terms of time. From real world measurement, we found that the speed of air pollutants concentration increase is faster than decrease and faster in kitchens than in living room. Homes using clean fuels such as electricity had lower $K_i$ and $K_d$ than that using solid fuels. The new indexes together with available indexes such as peak height, peak length, peak prominences, and peak area could work together to describe air pollutant peaks, which is crucial for understanding of indoor air pollution and indoor exposure assessment. More future studies are welcomed to focus on the high time resolution data mining.

Acknowledgments

The authors all thank the rural residents who help us in the field measurement. This work received no financial support.

Conflict of Interest

The authors declare no conflict of interest.

References


and Taiwan. Aerosol and Air Quality Research, 22 (11), 2022.


