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Original Research

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

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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

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*e-mail: jzwang@stu.pku.edu.cn

bound to PMs (particulate matters) were usually collected on filters and then been 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 CH_4 [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 $PM_{2.5}$ pollution in rural Chinese homes, proving the increase of indoor $PM_{2.5}$ was the most likely associated with the larger solid fuel consumption during the special period [16]. Huang et al. used high time resolution data to describe the real time indoor/outdoor $PM_{2.5}$ ratios, highlighting the important role of solid fuel combustion and cooking on the rapid increase of indoor $PM_{2.5}$ [17]. Zheng et al. confirmed the impact of Chinese cooking on the vertically-resolved indoor $PM_{2.5}$, CO, and CH_4 [18]. All the above studies indicate that it is more and more popular to use sensors to characterize the indoor air pollution in recent years.

However, the available methods to analyze the real time data limited the advantage of the high time resolution data. Most studies still using 1-h resolution, 24-h resolution data for presentation of the data by reducing the time resolution [18-22]. Many of them just describe a peak without any quantitative analysis, obviously fail to take advantage of the value of data fully. Some recent publications try to mine the information of high time resolution data deeply. For example, Men et al. used a method to analyze the indoor $PM_{2.5}$ peak caused by various emission sources to estimate the contributions of sources to indoor $PM_{2.5}$ [23]. Huang et al. calculated the $PM_{2.5}$ peak area to compare the contributions of different fuels combustion and cooking to indoor $PM_{2.5}$ by integrating the time and $PM_{2.5}$ concentrations [17]. However, all the existing methods failed to describe the increasing and decreasing speed of air pollutants when a peak started and ended. In this study, we introduce two new indexes to describe indoor $PM_{2.5}$ 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 $PM_{2.5}$ would keep stable, the concentration during this period could be defined as baseline, which could be considered as the background $PM_{2.5}$ pollution in a residential home. When there are strong emission sources starting (e.g. combustion of solid fuels, cooking, and smoking), the indoor $PM_{2.5}$ 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 $PM_{2.5}$ peak, as seen in Fig. 1.

To describe a $PM_{2.5}$ peak, peak length, peak height, and peak area was found used in previous studies [17, 23]. However, these indexes could not describe the speed of the $PM_{2.5}$ increasing and decreasing of a $PM_{2.5}$ peak, which limited the understanding of the indoor $PM_{2.5}$ variation when strong internal emission sources existed and stopped. Herein, two new indexes are defined as K_i and K_d ($K_{increase}$ and $K_{decrease}$), where K_i means the speed of the $PM_{2.5}$ increasing from the baseline to maximum value when an internal source occurs and K_d means the speed of the $PM_{2.5}$ decreasing from maximum value to the baseline, equations were given as below:

$$K_i = \tan\alpha = P/L1 \tag{1}$$

$$K_d = \tan\beta = P/L2 \tag{2}$$

$$L = L1 + L2 \tag{3}$$

As seen in Fig. 1, P (peak prominences) and L represented the height from baseline to the maximum value and length of the $PM_{2.5}$ peak. It is easy to understand the meaning of these new indexes. When K_i and K_d are larger, the speed of $PM_{2.5}$ 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

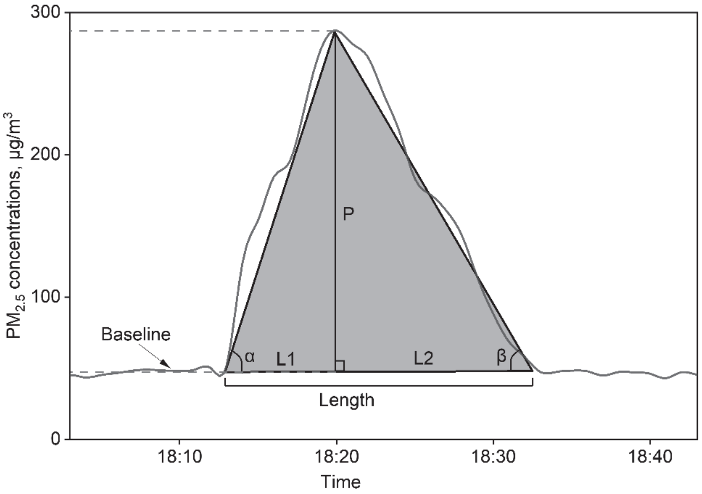

Fig. 1. The schematic diagram of the new indexes introduced in this study.

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.

Table 1. The information of the selected field measurement of $PM_{2.5}$ in indoor air.

Site	Season	Cooking fuel	Sample Size	Measured locations
South	Summer	LPG	4	Kitchen, living room
		Electricity	17	Kitchen, living room
		Wood	6	Kitchen, living room
South	Winter	wood	16	Kitchen, living room
		LPG	22	Kitchen, living room
North	Winter	Briquette	8	Cave dwellings

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 $\mu g \cdot m^{-3} \cdot min^{-1}$, 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 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_d and K_i could be affected by multiple factors, which should be further evaluated in the future.

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

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

Note: a, the maximum value of a $PM_{2.5}$ peak

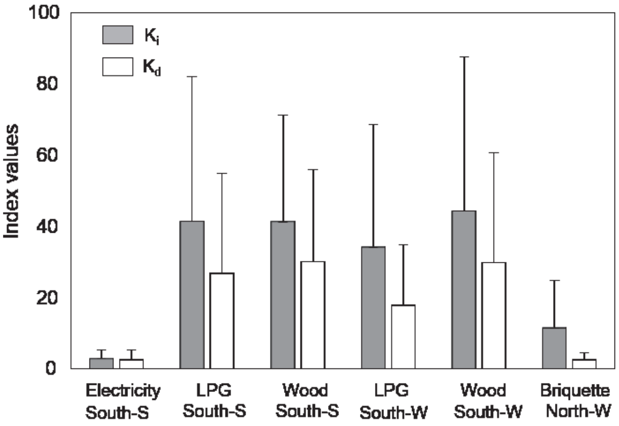

Fig. 2. The K_i and K_d in residential kitchens using different fuels in the measured sites, S and W represent the season summer and winter, respectively.

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.

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Conflict of Interest

The authors declare no conflict of interest.

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