Research on the Influence of Indoor Relative Humidity on PM2.5 Concentration in Residential Buildings

Ji Zhang¹, Zhihua Zhou¹, *, Chendong Wang¹, Kedi Xue², Yurong Liu³, Mingliang Fang⁴, Jian Zuo⁵, Ying Sheng¹

¹ Tianjin Key Laboratory of Indoor Air Environmental Quality Control, Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, School of Environmental Science and Engineering, Tianjin University, Tianjin, China
² ARTS GROUP Co., LTD., Suzhou, Jiangsu Province, China
³ Wuhan Zhenghua Architectural Design Co., LTD., Wuhan, Hubei Province, China
⁴ School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore
⁵ School of Architecture & Built Environment, Entrepreneurship, Commercialisation and Innovation Centre (ECIC), The University of Adelaide, Adelaide 5005, Australia
*E-mail: zhuazhou@163.com

Abstract. This study presented an experimental analysis to investigate the influence of the RH on PM2.5 concentration in a typical residential building in Tianjin, China. PM2.5 concentrations were measured using an aerosol monitor in different conditions of three RH scenarios, two pollutant sources and two initial pollutant concentrations. It was observed that about 95% of the size of particles produced by cigarette and wormwood are smaller than 1 μm, and the particulate matters produced by wormwood has smaller particle size than that produced by cigarette. Results shows humidification is a practicable method to accelerate the deposition rate of PM2.5. Furthermore, the larger the particle size, and the higher initial pollutant concentration, the more significant influences of the RH on PM2.5 concentration. Considering the requirement of human comfort, the RH is recommended to be controlled at the range of 60%-70% when the indoor PM2.5 pollution is serious. Although humidification can reduce indoor PM2.5 concentration to a certain extent, it cannot reduce the PM2.5 concentration to the permissible range in a short period of time. Therefore, it is recommended to use RH control together with purification device.

1. Introduction

Fine particulate matter with aerodynamic diameter less than 2.5μm (PM2.5) has become the primary pollutant that affects the air quality in China[1]. It is conventionally considered that staying indoors with closed doors and windows should be a wise choice when haze weather comes. However, this strategy could not protect human from exposure to PM2.5 because of the infiltration from vents on air-conditioner as well as from cracks in building envelopes[2]. In addition to outdoor PM2.5 pollutant sources, previously identified predictors of indoor PM2.5 also include indoor combustion, in which smoking and cooking are the most consistently identified sources. Therefore, it is worth to develop measures to remove indoor PM2.5 pollutant for controlling the indoor air quality.

Deposition can significantly reduce indoor PM2.5 concentration, and resulting in reduced inhalation exposures[3]. Previous studies showed that deposition rates varied depending on the particle size[4], and recent evidences have linked particle size effects with collision, adsorption, and condensation. The moisture content in ambient air has certain impacts on the surface properties of the
particulate matter (PM)[5] during these processes, leading to the change of particle size distribution. But the influence of the RH on indoor PM2.5 concentration is still not clear and the appropriate range of the RH for indoor PM2.5 control requires to be determined.

Especially for the areas in northern China where the indoor RH is only about 15% in winter as a result of heating[6], RH control can be utilized to guide the use of humidifiers and consequently achieve both comfortable and healthy indoor environment. Therefore, this study aimed to investigate the influence of the RH on indoor PM2.5 concentration and establish proper RH control method which is in favor of indoor PM2.5 removal. For this purpose, two typical pollution sources of PM2.5 in Chinese residential buildings (cigarette and wormwood) were studied as the objects. The relationship between the RH and PM2.5 concentration with three RH scenarios, two pollutant sources and two initial pollutant concentrations was examined by monitoring PM concentrations. Based on these analyses, the optimal RH controlling strategies for residential buildings to lessen indoor PM2.5 concentration were determined, which is of great practical significance to reduce human exposure to PM2.5.

2. Methods

2.1. Case Room
A study room on the north side of one new apartment in the suburb of Tianjin (38° to 40°N latitude; 116°to 118°E longitude), where has been suffered from serious haze pollution in recent years[7], was selected as the case room. The area of the case room is 16.1m² and the clear height from floor to ceiling is 2.9m. Figure 1 shows the floor plan of the apartment.

![Floor plan of the apartment.](image)

2.2. Experiment Methods
Before the experiment, indoor PM concentration was controlled at a relative low level and the case room was well sealed. In order to eliminate indoor thermal interference, the room temperature was controlled in a range of 25±1°C, which is corresponding to 80% thermal acceptability [8]. Different RH conditions were controlled by a stand-alone air humidifier whose rated voltage is 220V, moisture content is 280mL/h. In the experiment, there were three scenarios with different RH ranges designed for the research objectives, i.e. Scenario 1 with low RH (50%-60%), Scenario 2 with moderate RH (60%-70%) and Scenario 3 with high RH (70%-80%). Cigarette and wormwood was lighted respectively to produce pollutant after the average RH reached the preset value. In addition, two groups of experiments with high initial pollutant concentration (1.73mg/m³) and low initial pollutant concentration (0.91mg/m³) was researched to simulate the general smoking situation of the indoor environment.
2.3. Measurement Methods
A DustTrak™ II aerosol monitor 8530 was used to collect the concentration of PMs. All of PM1, PM2.5, PM4 (respirable particulate matters) and PM10 can be measured by fitting the aerosol monitor with different diameter inlets. The monitor was placed in the center of the case room and 1.2 m above the floor level. The resolution of the measurement is ±0.1% of reading or 0.001mg/m³, whichever is greater. Meanwhile, three temperature and RH self-recorders were used to record indoor temperature and the RH in the case room. They were placed 1 m above the floor level and uniformly arranged in the case room. The measurement accuracy of the self-recorder is ±1%/0.1℃. All these data logging intervals were set as 1 minute.

2.4. Data Analysis Method
Deposition can be an important loss mechanism for PMs in indoor environments. Particle deposition rate was selected as an essential parameter to determine the performance of RH control in this experiment. It can be assessed based on Eq. (1) as given below [9].

\[
\lambda_d = \left(\frac{1}{t}\right) \ln \left(\frac{C_b}{C_e}\right) - \lambda_v
\]

Where \(\lambda_d\) is the deposition rate (mg/(m³·min)); \(C_b\) is the initial PM concentration (mg/m³); \(C_e\) is the final PM concentration (mg/m³); \(t\) is the time between \(C_b\) and \(C_e\) (min); and \(\lambda_v\) is the infiltration rate (\(\lambda_v=0\) in this experiment due to the case room is well-sealed).

3. Results and Discussions

3.1. Particle Size Distribution of PMs Produced by Different Pollutant Sources
40-50%RH was selected as the reference RH range to investigate the particle size distribution produced by two pollutant sources. After 20 times of experiment, a boxplot analysis is shown in Figure 2.

![Boxplot analysis of particle size distribution in 40-50% RH](image)

According to Figure 2, it can be seen that PM1 is the main component of the PMs produced by two pollutant sources, which accounts for 95.2% for cigarette, and 97.1% for wormwood. The total PMs produced by cigarette smaller than 2.5μm diameter accounts for 96.6%, and that produced by wormwood accounts for 98.2%. It can also be seen that the most significant difference between cigarette and wormwood is the PMs whose diameter smaller than 1μm, and that between 2.5 to 4μm, the discrepancy is 2% and 1.6% respectively. Whereas the percentages of PMs with diameter of 1-2.5μm and 4-10μm are almost the same. Therefore, it can be concluded that the PMs produced by wormwood has smaller particle size than that produced by cigarette. Additionally, it can be found in Figure 3 that the experiment result is in normal distribution.

3.2. The Influence of the RH on Particle Size Distribution
The influence of the RH on particle size distribution is discussed by comparison between the results in the RH range of 40%-50% and 70%-80%. The boxplot analysis of particle size distribution produced by cigarette and wormwood were shown in Figure 3.
Figure 3(a) shows a similar variation tendency with (b), that the percentage of PM1 produced by both cigarette and wormwood decreases when the RH increases to 70-80%. The decrease of PM1 percentage is 1.6 times higher when the pollutant source is wormwood than cigarette. Calculation results show that PM1 percentage decreased by 1.6% and 2.6% respectively when the pollutant source is cigarette and wormwood. However, percentages of PMs with diameter larger than 1μm increases when the RH increases to 70%-80%, in particular, the percentage of PMs with diameter of 2.5-4μm increased most significantly, with 0.6% to 1.7% for cigarette, and 0.4% to 1.9% for wormwood. This result indicates that the increase of the RH leads to the agglomeration of fine PMs to form larger PMs. And the smaller the particle size, the more significant the agglomeration phenomenon. In addition, it has been proved that particle size is critical in determining where PMs will settle in the respiratory system[9]. The smaller the particle size, the deeper the particles enter inside the respiratory tract, the greater the harm to human body. Therefore, it can be concluded that humidification is beneficial to prevent PMs from entering the human respiratory system and consequently reduce the harm of PMs to the human body.

3.3. The Influence of the RH on PM2.5 Concentration

The deposition rate was used to analysed the influence of the RH on PM concentration in three scenarios with different RH ranges, two pollutant sources and different initial pollutant concentrations. The variation of PM2.5 concentration is shown in Figure 4. The regression and variance analysis is shown in Table 2.

Take the condition that particles produced by cigarette with high initial concentration for example, the deposition rate of PM2.5 concentration is 0.0019 mg/(m³·min), 0.0054 mg/(m³·min) and 0.0071 mg/(m³·min) in Scenario 1, Scenario 2 and Scenario 3 respectively (R² > 0.9, F< 0.01). The results indicate that the higher the RH, the higher the PM2.5 deposition rate, and the faster the indoor PM2.5 removal. Similar results can be found in the conditions regardless of pollutant resource or initial pollutant concentration.

Different pollutant sources will lead to different composition and characteristic of PMs. When the initial pollutant concentration is in high level, the PM2.5 deposition rate is 0.0019 mg/(m³·min) and 0.0015 mg/(m³·min) for cigarette and wormwood in Scenario 1, respectively. In addition, it is 0.0054 mg/(m³·min) and 0.0045 mg/(m³·min) in Scenario 2 and 0.0071 mg/(m³·min) and 0.0059 mg/(m³·min) in Scenario 3, respectively (R² > 0.9, F< 0.01). The result indicates that the PM2.5 deposition rate produced by cigarette is higher than that produced by wormwood. Therefore, it can be concluded that, when the PM2.5 concentration is the same, the smaller the particle size, the lower the PM2.5 deposition rate, and the less influence of the RH on PM2.5 concentration.

The influence of the RH on PM concentration under different initial pollutant concentrations were also investigated. The result in Table 2 indicates that the PM2.5 deposition rate with high initial concentration is higher than that with low initial concentration, when the RH is constant. In addition, the difference of PM2.5 deposition rates between Scenario 2 and 3 are lower than that between Scenario 1 and 2 when the initial pollutant concentration is high, while that situation is the opposite
when the initial pollutant concentration is low. Therefore, considering the requirements for human comfort, the indoor RH can be controlled in the range of 60%-70% for good PM2.5 control performance when the indoor PM2.5 pollution is serious. However, when the pollutant source occurs in the room with low PM2.5 concentration, the control of RH does not work significantly, unless the RH can be increased to 70%-80% by the humidifier for a short period of time, in case of thermal discomfort caused by high RH.

![Figure 4. Variations of PM2.5 concentration under pollutant source of cigarette](image)

**Table 2. Regression and variance analysis of PM2.5 concentration variation**

| Items | Pollutant Sources | Initial Concentration | Deposition Rate (mg/(m³·min)) | Multiple R | $R^2$ | Standard Error | Significance F |
|-------|-------------------|-----------------------|-------------------------------|------------|------|----------------|---------------|
| **Scenario 1** | Cigarette | High | -0.0019 | 0.9815 | 0.9633 | 0.0066 | 4.65E-44 |
| | Low | -0.0014 | 0.9717 | 0.9443 | 0.0059 | 1.07E-38 |
| | Wormwood | High | -0.0015 | 0.9948 | 0.9897 | 0.0028 | 2.83E-60 |
| | Low | -0.0012 | 0.9859 | 0.9719 | 0.0036 | 1.74E-47 |
| **Scenario 2** | Cigarette | High | -0.0054 | 0.9972 | 0.9945 | 0.0071 | 2.36E-68 |
| | Low | -0.0022 | 0.9718 | 0.9444 | 0.0095 | 1.02E-38 |
| | Wormwood | High | -0.0045 | 0.9974 | 0.9947 | 0.0059 | 7.04E-69 |
| | Low | -0.0017 | 0.9953 | 0.9907 | 0.0030 | 1.12E-61 |
| **Scenario 3** | Cigarette | High | -0.0071 | 0.9818 | 0.9638 | 0.0246 | 3.07E-44 |
| | Low | -0.0033 | 0.9513 | 0.9051 | 0.0194 | 7.43E-32 |
| | Wormwood | High | -0.0059 | 0.9872 | 0.9746 | 0.0171 | 8.69E-49 |
| | Low | -0.0034 | 0.9791 | 0.9587 | 0.0128 | 1.65E-42 |

Furthermore, with the PM2.5 concentration decreased for 1 hour, it was still higher than the requirement of average indoor PM2.5 concentration specified in Chinese related standard (0.075mg/m³) [10], and much higher than that specified in ASHRAE related standard (0.015mg/m³) [11]. Therefore, although humidification can reduce indoor PM2.5 concentration to a certain extent, it cannot reduce the PM2.5 concentration to the permissible range in a short period of time. It is recommended to use RH control together with purification device to reduce indoor PM2.5 concentration rather than using RH control independently.
4. Conclusions

(1) About 95% of the size of particles produced by cigarette and wormwood are smaller than 1μm, and the particulate matters produced by wormwood have smaller particle size than that produced by cigarette. In addition, RH can change the particle size distribution of indoor particles, and the smaller the particle size, the more significant the agglomeration phenomenon.

(2) Humidification is a practicable method to accelerate the deposition rate of PM2.5 by enlarging its size, consequently reduce indoor PM2.5 concentration. Furthermore, the larger the particle size and the higher initial pollutant concentration, the more significant influences of the RH on PM2.5 concentration. Considering the requirement of human comfort, the RH is recommended to be controlled at the range of 60%-70% when the indoor PM2.5 pollution is serious.

(3) The effect of humidification on PM2.5 concentration control is limited. It is recommended to use RH control together with purification device to reduce indoor PM2.5 concentration rather than using RH control independently.

5. Acknowledgments

This work was supported by Tianjin Municipal Science and Technology Commission (Contract No. 18ZXAQSF00040).

6. References

[1] Liu X G, Li J, Qu Y, Han T, Hou L, Gu J, Chen C, Yang Y, Liu X, Yang T, Zhang Y, Tian H and Hu M 2013 Formation and evolution mechanism of regional haze: A case study in the megacity Beijing, China Atmos. Chem. Phys. 13 4501–14

[2] Chen C and Zhao B 2011 Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor Atmos. Environ. 45 275–88

[3] Thatcher T L, Lai A C K, Rosa M J, Sextro R G and Nazaroff W W 2002 Effect of room furnishing and air speed particle deposition rates indoors Low. Berkeley Natl. Laboratory 36 1–17

[4] Long C M, Suh H H, Catalano P J and Koutrakis P 2001 Using time- and size-resolved particulate data to quantify indoor penetration and deposition behavior Environ. Sci. Technol. 35 2089–99

[5] Bateman A P, Gong Z, Liu P, Sato B, Cirino G, Zhang Y, Artaxo P, Bertram A K, Manzi A O, Rizzo L V., Souza R A F, Zaveri R A and Martin S T 2016 Sub-micrometre particulate matter is primarily in liquid form over Amazon rainforest Nat. Geosci. 9 34–7

[6] Cao B, Luo M, Li M and Zhu Y 2016 Too cold or too warm? A winter thermal comfort study in different climate zones in China Energy Build. 133 469–77

[7] Zhang X, Shi M, Li Y, Pang R and Xiang N 2018 Correlating PM 2.5 concentrations with air pollutant emissions: A longitudinal study of the Beijing-Tianjin-Hebei region J. Clean. Prod. 179 103–13

[8] Song Y, Sun Y, Luo S, Hou J, Kim J, Parkinson T and De Dear R 2017 Indoor environment and adaptive thermal comfort models in residential buildings in Tianjin, China Procedia Eng. 205 1627–34

[9] Thatcher T L and Layton D W 1995 Deposition, resuspension, and penetration of particles within a residence Atmos. Environ. 29 1487–97

[10] Chen D, Liu X, Han J, Jiang M, Xu Y and Xu M 2018 Measurements of particulate matter concentration by the light scattering method: Optimization of the detection angle Fuel Process. Technol. 179 124–34

[11] Krasnov H, Katra I, Novack V, Vodonos A and Friger M D 2015 Increased indoor PM concentrations controlled by atmospheric dust events and urban factors Build. Environ. 87 169–76