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Experimental Investigation on Indoor/Outdoor $PM_{2.5}$ Concentrations of an Office Building Located in Guangzhou

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Abstract

The Pearl River Delta (PRD) is one of the areas that are facing a serious fine particulate matter ($PM_{2.5}$) pollution in China. In order to grasp the variation law of $PM_{2.5}$ concentrations in the atmospheric environment and its impact on the indoor environment, this research has taken a certain naturally ventilated office building as the monitoring object to constantly monitor its mass concentration of indoor and outdoor $PM_{2.5}$ and meteorological parameters from February to July 2014 and from December 2014 to January 2015 in Guangzhou. During the test period, the external windows and mechanical ventilation system stayed closed and there were no other indoor pollution sources. The survey results showed: (1) among all diurnal variations, the diurnal variation in hourly average mass concentrations for outdoor $PM_{2.5}$ showed that the night experienced greater variation than the day; in terms of seasonal variation, Spring experienced the most severe outdoor $PM_{2.5}$ mass pollution ($115\mu g/m^3$), followed by Winter ($95\mu g/m^3$); (2) the indoor $PM_{2.5}$ mass concentrations were highly correlated with that outdoor, meanwhile the indoor/outdoor $PM_{2.5}$ mass concentrations ratios (I/O ratios) were in a broad range; (3) both outdoor $PM_{2.5}$ mass concentrations and infiltration factors were significantly correlated with meteorological parameters (temperature, wind speed and relative humidity); (4) compared with the related research conducted on Beijing, $PM_{2.5}$ concentrations and infiltration factors in both the two regions were affected by wind speed and relative humidity, but the impact of temperature on outdoor $PM_{2.5}$ concentrations was not discernible in Beijing. The research results can serve as a reference for analyzing the influence rule of outdoor $PM_{2.5}$ situation to the indoor environment in the Pearl River Delta region and its control technology.

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Keywords: Guangzhou region, Infiltration factor, Infiltration ventilation, $PM_{2.5}$, Experimental investiga-tion;

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1. Introduction

Depending on China's Ministry of Environmental Protection, 66 cities within the list of 77 major cities did not meet national air quality standard in 2014. There were only 298 days with good air quality during the year in PRD, and $PM_{2.5}$ was one of the main pollutants. Particles less than 2.5 micrometers in diameter ($PM_{2.5}$) are referred to as "fine" particles. Its inhalation will cause adverse health outcomes, particularly cancer and cardiovascular and pulmonary diseases, because it can carry toxic substances and enter the human respiratory system, even penetrate through lung cells into the blood circulation [1]. Some research reports suggest that the $PM_{2.5}$ concentration in near-road area is obviously higher than that in other areas. Due to the reason of that vast majority of people spend 85%-90% of their time indoor [2], it's important to understand the impact of the atmosphere $PM_{2.5}$ on indoor environment in near-road building.

Factors that influence atmospheric $PM_{2.5}$ concentrations include season, city development scale, geography and environment [3~5]. When emissions remain stable, meteorological condition is the main factor to influence $PM_{2.5}$ concentrations [6,7]. Related studies have shown that increase of the air velocity and mixed layer depth could reduce the concentration of particulate matter. In most cases, however, meteorological parameters have a combined effect on atmospheric $PM_{2.5}$ concentrations. Based on the analysis of the relation between particle concentrations and meteorological conditions, Csavina et al. [8] have found that atmospheric $PM_{2.5}$ concentrations are affected by the comprehensive influence of wind speed and relative humidity seriously. Atmospheric $PM_{2.5}$ can enter the room through the methods of penetration ventilation, natural ventilation, and mechanical ventilation. Based on the indoor and outdoor mass balance equation, Bennett and Koutrakis [9] have adopted the least squares method for fitting the dynamic coefficient of permeability. Although the infiltration factor can be calculated by formula or measured, there were not many researches on the relationship between meteorological parameter and infiltration coefficient.

In order to find out the influence of atmospheric $PM_{2.5}$ pollution on indoor environment, a certain office building was taken as the monitoring point to constantly monitor its indoor and outdoor $PM_{2.5}$ mass concentrations. In the research, we studied the variation of outdoor $PM_{2.5}$ mass concentrations and analyzed the influence of outdoor $PM_{2.5}$ concentrations on indoor. The aforementioned results can provide meaningful reference for the research of atmospheric $PM_{2.5}$ on the indoor environment.

2. Methods

2.1. Measurement

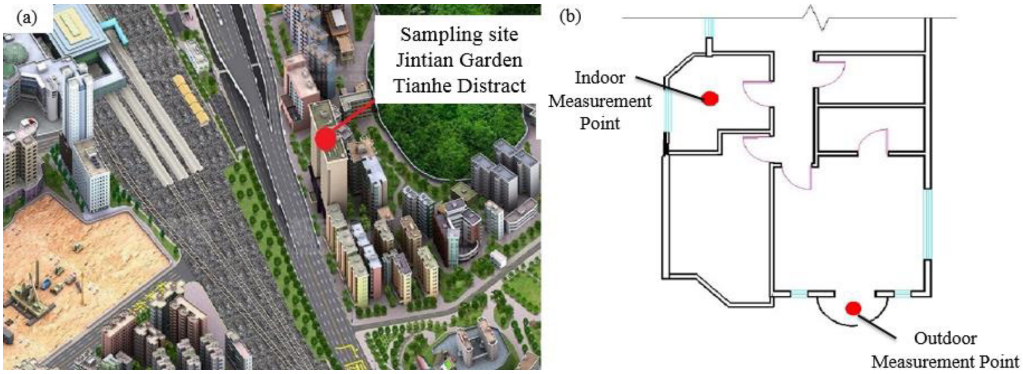

Fig. 1. Location (a) and floor plan (b) of the monitored office

Continuous real-time monitoring of indoor and outdoor $PM_{2.5}$ mass concentrations was conducted from February to July 2014 and from December 2014 to January 2015 at an office building in Guangzhou. Location and floor plan of the monitored office are presented in Fig. 1. Floor area of the room is 10 m^2. The room has exterior windows of steel casement, facing southwest. There were not any central air conditioning ventilation systems inside room. There was no observable particles source inside the room so we considered there was no indoor particle source. At the same time, a same test was set at an office building in Beijing.

2.2. Instruments

Indoor and outdoor $PM_{2.5}$ mass concentrations were monitored using LD-5C(R) line laser particle monitors. The monitor sensitivity was 1μg/m^3. Sampling point of outdoor $PM_{2.5}$ was in the center of a balcony, and 1.5 m above the floor. Sampling point of indoor $PM_{2.5}$ was placed 0.5 m away from the east window and 1.5 m above the floor. The exterior windows of the office building were closed during the measurement time.

2.3. Data processing and analysis

1-hour mean concentrations of $PM_{2.5}$ were calculated by taking 12 samples every five minutes from continuous data of $PM_{2.5}$ mass concentrations. Outdoor $PM_{2.5}$ pollution level was divided into six categories referred to the classified standard of China Environmental Monitoring Station, excellent (0-35μg/m^3), fine (35-75μg/m^3), slight pollution (75-115μg/m^3), medium pollution (115-150μg/m^3), serious pollution (150-250μg/m^3) and severe pollution (>250μg/m^3). According to the climate characteristics, a year is divided into the spring (from March to May), summer (from June to August), autumn (from September to November), winter (from December to February). According to dynamic algorithm mentioned [9], the dynamic infiltration factor was calculated by taking deposition rate as 0.2.

3. Conclusion result and discussion

3.1. Outdoor $PM_{2.5}$ pollution levels and its influence on indoor environment

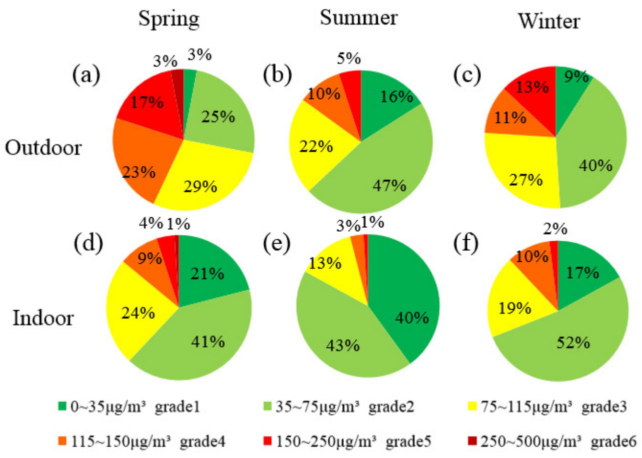

Fig. 2. The variations of indoor (a-c) and outdoor (d-f) $PM_{2.5}$ pollution levels in spring, summer, and winter.

Fig. 2 shows the distributions of daily indoor and outdoor $PM_{2.5}$ mass concentrations pollution levels in the office building. In the view of seasonal variation, $PM_{2.5}$ pollution is the worst in spring, followed by winter and summer. We can note that 72%, 37%, and 52% of the days in spring, summer, and winter exceed the Chinese environmental air quality standard, respectively. Moreover, there are up to 20%, 6%, and 13% of days having serious pollution levels in each of the aforementioned season. It is clear that when the windows and doors are kept closed, the value of indoor $PM_{2.5}$ concentrations is significantly lower than the outside

3.1.1. Diurnal variation

Fig. 5 indicates the diurnal variations of indoor and outdoor $PM_{2.5}$ mass concentrations by taking one hour as a time resolution and 24 hours of a day as an analytical unit. It shows that the values of outdoor $PM_{2.5}$ mass concentrations at night are higher than those during the day in the three seasons. Meanwhile, all the peak values are observed at 8:00. Compared with that, the minimum values don't appear at the same time, and all of them appear in the afternoon. Diurnal variations of indoor $PM_{2.5}$ mass concentrations show little change in spring, summer, and winter, and the figure in spring is greater than those in summer and winter. After the peak of outdoor $PM_{2.5}$ concentrations, indoor $PM_{2.5}$ concentrations will express a small rise.

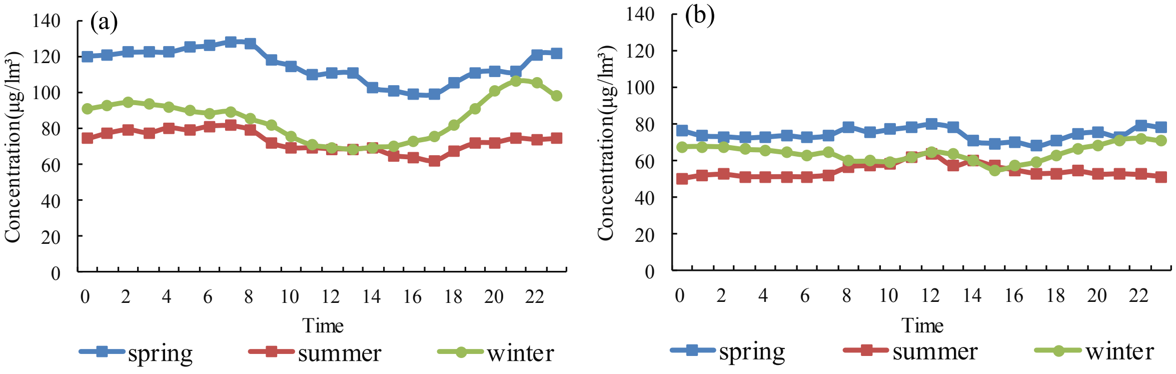

Fig. 3. Diurnal variations of indoor (b) and outdoor (a) $PM_{2.5}$ mass concentrations

At nighttime, atmospheric boundary layer becomes more stable with the decreasing of ground temperature, and atmospheric particles are accumulated continuously. Furthermore, heat stored during the day is released from the envelopes of high-volume-rated buildings in urban areas at night, further leading to a higher temperature in urban areas compared to suburban areas at night. Then the temperature difference results in special local wind and heat island circulation. These factors may result in fact of relatively higher pollutants at night. Similar events have been reported by Wang et al. [10] that a burst of particles formation by nucleation occurred immediately during the reaction of ozone with terpenes and other house-hold products.

3.1.2. Monthly variation

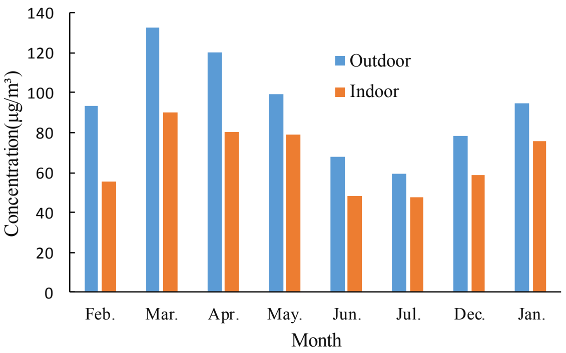

Fig. 4. Monthly variations of indoor and outdoor $PM_{2.5}$ mass concentrations

Fig. 4 shows the change of indoor and outdoor $PM_{2.5}$ concentrations along with month. This research indicates that the values of outdoor $PM_{2.5}$ concentrations in spring are high than those in summer and winter.

Wind shift may be one of the reasons for the monthly variation of $PM_{2.5}$ concentrations. In Guangzhou, the wind direction will change with Asian monsoon activity. Under the influence of the Asian monsoon, north wind with high concentrations of $PM_{2.5}$ prevails in winter and spring. In contrast to the chilly north wind, south wind can bring clean marine air.

3.2. Relationship between meteorological conditions and $PM_{2.5}$ concentrations in Guangzhou

3.2.1. The influence of outdoor wind speed

In general, the magnitude of wind pressure acting on buildings and the air exchange rate will be influenced by the change of outdoor wind speed directly. As showed in Fig. 5, the change in outdoor wind speed has an impact on outdoor $PM_{2.5}$ mass concentrations and infiltration factors, which are calculated by the equation in Section 1.4. Meanwhile, both indoor and outdoor $PM_{2.5}$ mass concentrations are negatively correlated with outdoor wind speed. When the outdoor wind speed is less than 1m/s, for example, the value of outdoor $PM_{2.5}$ mass concentrations will reach a moderate pollution level in spring and winter; at the same time, the indoor $PM_{2.5}$ mass concentrations in winter will exceed the air quality standard.

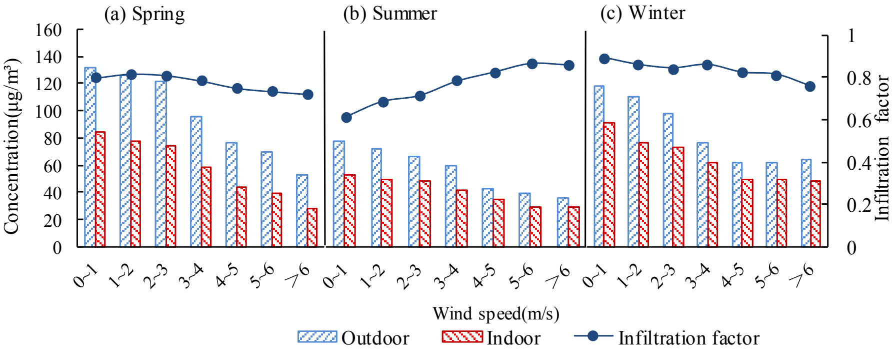

Fig. 5. Effect of outdoor wind speed on $PM_{2.5}$ mass concentrations and infiltration factors during spring (a), summer (b), and winter (c).

In addition, the influence of the change in outdoor wind speed on infiltration factors also changes with the seasons. In summer, infiltration factors rise with wind speed increase. When the outdoor wind speed is less than 1m/s, average infiltration factors is 0.61; when the outdoor wind speed is greater than 6m/s, the figure is increased to 0.89. Compared with that, infiltration factors are not changed with the factor of wind speed significantly in spring and winter, which needs to be explored in future research.

3.2.2. The influence of outdoor relative humidity

Fig. 6 shows the relationship between outdoor relative humidity and $PM_{2.5}$ mass concentrations. There has been a positive correlation between $PM_{2.5}$ mass concentrations and outdoor relative humidity in each season, and infiltration factors are negatively correlated with outdoor relative humidity. In spring, the value of outdoor $PM_{2.5}$ mass concentrations is less than 75 μg/m³ when outdoor relative humidity is below 40%, and this figure is higher than 115 μg/m³ (slight pollution) when outdoor relative humidity is higher than 80%. In summer, value of $PM_{2.5}$ mass concentrations is stable with low humidity and is accelerated rapidly at the time of humidity more than 70%; this value can also rise to 100μg/m³ as humidity higher than 90%, which is higher than others. A similar variation rule is found in winter. Relative humidity can accelerate the formation of atmospheric particles to a certain extent, mainly acting on the formation of secondary species and the growth process due to condensation and coagulation. All these factors make $PM_{2.5}$ concentrations positively correlated with relative humidity.

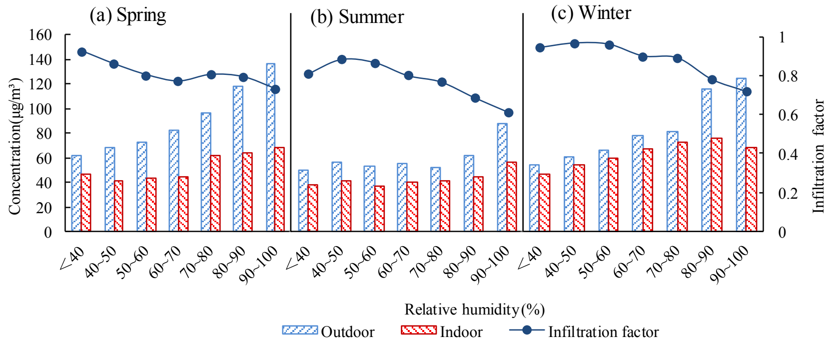

Fig. 6. Effect of outdoor relative humidity on $PM_{2.5}$ mass concentrations and infiltration factors during spring (a), summer (b), and winter (c).

Furthermore, this research indicates that infiltration factors will decrease with the increase of relative humidity. The partial reason is a certain relationship between outdoor relative humidity and wind speed. When the value of outdoor wind speed is big, water vapor will be blown into the sky, leading to relative humidity near the ground decreases obviously, and vice versa.

3. The influence of outdoor temperature

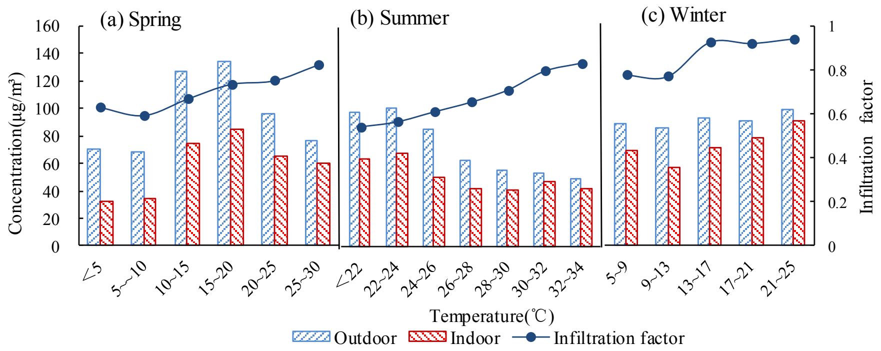

Fig. 7. Effect of outdoor temperature on $PM_{2.5}$ mass concentrations and infiltration factors during spring (a), summer (b), and winter (c).

Lapse rate of temperature and pressure-difference caused by heat could affect indoor and outdoor $PM_{2.5}$ concentrations. The relationship between outdoor temperature and $PM_{2.5}$ mass concentrations in spring, summer, and winter is reflected in Fig. 7. The graph shows that the value of outdoor $PM_{2.5}$ concentrations is around 100 μg/m³ when the temperature is below 24 ℃ in summer. With temperature increase, the atmospheric lapse rate also goes up, leading to more intense activities of particles and the dilution of $PM_{2.5}$ in the air. High temperature helps to promote the atmospheric vertical convection and accelerate the diffusion of particles, causing their mass concentration decrease. However, the variation rule is not clear in Fig. 7, which needs further research.

During the test, the infiltration factors are negatively related to outdoor temperature. Taking summer as an example, when the outdoor temperature is lower than 22℃, the average permeation factor is 0.6. In addition, the corresponding figure is 0.8 at 25~30℃. These phenomena are caused by the pressure-difference, which decided by heat.

3.3. Compared with the related research in Beijing

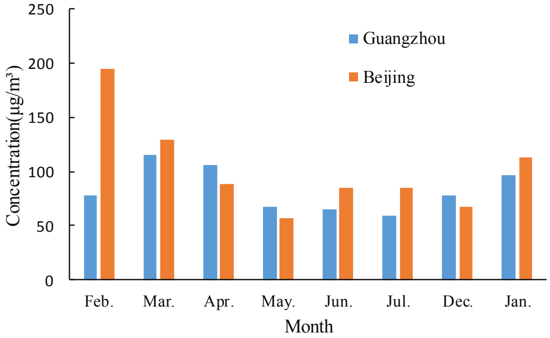

Fig. 8. Monthly variations of indoor and outdoor $PM_{2.5}$ mass concentrations in Guangzhou and Beijing

Beijing-Tianjin-Hebei is one of the seriously polluted air regions in China. Therefore, it is necessary to contrast the change characteristics of $PM_{2.5}$ concentrations in different areas. Fig. 8 shows the distributions of outdoor $PM_{2.5}$ concentrations in Beijing and Guangzhou from February to July 2014 and December 2014 to January 2015 respectively. According to Fig. 8, outdoor $PM_{2.5}$ concentrations have the same change trend in Beijing and Guangzhou, except for February. With spring coming on, outdoor $PM_{2.5}$ concentrations in both aforementioned places decrease gradually and may reach the minimum in summer. In contrast, the figure begins to increase in winter.

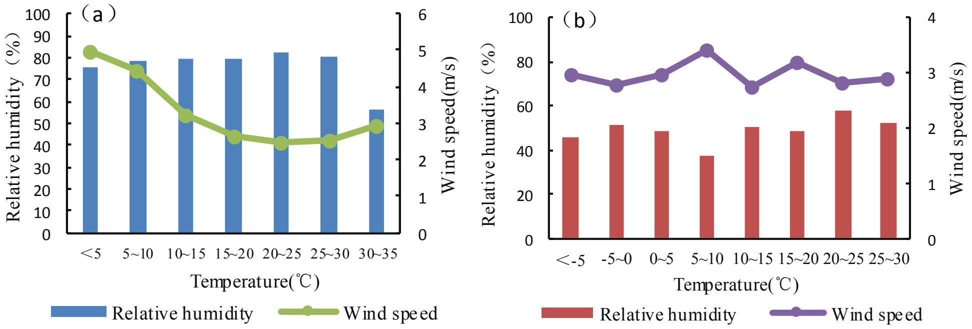

Fig. 9. Relationships of the meteorological parameters in Guangzhou (a) and Beijing (b).

The relationship between outdoor temperature and other meteorological parameters during the measuring period is shown in Fig. 9. It indicates that the temperature is highly correlated with wind speed in Guangzhou. When outdoor temperature is below 5℃, maximum wind speed can be found in the outdoor space, and the high speed can dilute particles in air. In addition, as the temperature increases, outdoor wind speed gradually decreases. Compared with the situation in Guangzhou, there is not an obvious relationship between temperature and wind speed in Beijing. In conclusion, wind speed that under the low temperature condition may also be one of the factors that cause the differences in Guangzhou.

4. Conclusion

The time series of indoor and outdoor $PM_{2.5}$ mass concentrations in an office building were monitored during the period from February to July 2014 and from December 2014 to January 2015 in Guangzhou. The findings were summed up as follows:

1. $PM_{2.5}$ pollution was serious in Guangzhou, and spring and winter were the most polluted seasons.

2. Under the circumstances that doors and windows were closed and there were no indoor sources, the outdoor $PM_{2.5}$ may penetrate into the indoor space.

3. The outdoor $PM_{2.5}$ mass concentrations were affected by meteorological parameters. Among them, the outdoor $PM_{2.5}$ mass concentrations were negatively correlated with weed speed and positively correlated with relative humidity. The higher the temperature is, the faster the $PM_{2.5}$ will diffuse.

4. The influence rules of relative humidity and wind speed of outdoor $PM_{2.5}$ concentrations in Guangzhou was in accordance with the case in Beijing. However, due to the difference in the correlation between temperature and other meteorological parameters, a stronger connection was found between temperature and outdoor $PM_{2.5}$ concentrations in Guangzhou.

Acknowledgements

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