The Relationship between Indoor and Outdoor PM2.5 Concentrations in the Severe Cold Region of China: Based on a Long-term Field Experiment

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Abstract

The objective of this study is to analyze the characteristic of indoor particles and the connection between indoor particles and outdoor particles. A long-term sampling and measurements of fine particulate matter (PM2.5) has been carried out around an resident area in Harbin (a typical urban in Chinese severe cold regions), which including indoor PM2.5 concentrations in two different types of residences, outdoor PM2.5 concentrations in the residential area, and PM2.5 concentrations near the regional heat source which supply heat for the residential area. This study analyses the affection of people's behavior on the indoor PM2.5 characteristic, the characteristic of PM2.5 in different seasons especially the uncommon characteristic during the heating season, and the influence of weather conditions (temperature, relative humidity, wind speed and solar radiation) on the characteristic of PM2.5. Besides, it shows the influence of outdoor atmospheric PM2.5 on the indoor environment is very strong based on the analysis of I/O ratios, outdoor PM2.5 is the main source of indoor PM2.5. If the outdoor haze intensifies, indoor PM2.5 concentrations will increase significantly.

Keywords- PM2.5; concentration; indoor; outdoor; I/O ratios

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1. Introduction

In recent years, fine particulate matter pollution has been one of the most serious environmental pollution issues in China. Several studies have found that PM2.5 showed strong relationships with respiratory, cardiovascular and reproductive (Ebelt ST, Wilson WE and Brauer M, 2005). Now, the air quality is getting worse, besides people spend most of their time indoors, so it is becoming more important epidemiologic and exposure studies should pay more attention to the influence of outdoor particles on indoor particles (Schweizer, C et al., 2007).

There are many studies showing that there is strong relationship between indoor particle and ambient particle (Chun Chen & Bin Zhao, 2011; Avril Challoner & Laurence Gill, 2014), and especially in the high-rise buildings which were built more and more (Jo W K & Lee J Y, 2006).

I/O ratios are the most commonly used parameter to describe the connection between indoor and outdoor pollutants, and it can respond to the relationship between indoor and outdoor pollutants concentrations directly. I/O ratios are defined as following:

$$I/O = \frac{C_{in}}{C_{out}} \quad (1)$$

As for particulate pollution, C_{in} is the indoor particle mass concentration and C_{out} is the outdoor particle mass concentration.

There have been lots of studies that using I/O ratios to estimate the relationship between indoor and outdoor particles, Chen and Zhao measured concentrations of PM2.5, PM10, particles of 0.001-0.5um and particles of 0.5-15um in Nepal (Chun Chen & Bin Zhao), and results showed that the largest value of I/O ratios happened in a common residence, and the smallest value happened in a unmanned telephone equipment room. Besides, there were some studies showing that I/O ratios of PM2.5 are lower than those of PM10 (Rojas-Bracho, L, Suh, HH and Koutrakis, P, 2000; Liu DL & Nazaroff WW, 2003).

The main source of indoor PM2.5 consists of two categories mostly: indoor PM2.5 concentration of outdoor origin by infiltration and ventilation, and the indoor generated PM2.5 by indoor source such as cooking, cleaning and smoking. So different ambient environment and different building design can influence indoor PM2.5 concentration, and different human behavior can influence the indoor PM2.5 concentration at the same time. This study aims to understand the impact of ambient PM2.5 characterization on indoor PM2.5 characterization by comparing sampling results of indoor and outdoor PM2.5 and the impact of human behavior on indoor PM2.5 characterization by comparing sampling results of two different indoor environments.

Harbin is a typical urban in Chinese severe cold regions, and its heating period lasts 6 months (from October 15th to April 15th next year), so heating is one of the most important source of PM2.5 in Harbin, and in this study, analysis about the specific characterization of PM2.5 at the heat source have been made.

2. Methods

2.1 Instrument

Instruments of measuring PM2.5 concentration is Qingdao Laoying 2030 type median traffic intelligent TSP sampler of which sampling flow is 60~130L/min and was set at 100L/min in this study, and it can work in Harbin winter outside because the application temperature of which is -30~99℃. Sampling filters are 90mm Whatman quartz microfiber filters. The sampling was made in 5 months (3 days a month), which lasts for 8 hours one day (from 9:00am to 5:00pm).

2.2 Sampling site

During the sampling, 4 sampling sites were sited at a residential area around a regional heat source (as shown in Figure 1). The outdoor sampling sites located on the roof of a two-story building, and south of this sampling site is a major roadway. There are 2 different indoor sampling sits (Indoor-1 and Indoor-2) located in 2 resident families, the style of Indoor-1 is more modern, the material of the windows is plastic with better sealing performance, and there are 4 people living in this residence, cooking everyday normally, and cleaning sometimes. The style of Indoor-2 is comparatively old, windows of which are double wooden windows, and there is only one old man living in this residence, and the way of life is relatively sample with no cooking. Besides, neither Indoor-1 nor Indoor-2 exists smoking source or mechanical ventilation. The temperature of Indoor-2 is a little higher than Indoor-1 in winter, because the first family pay more attention to artificial ventilation in winter. The heat source sampling site is located in an open space near the regional heat source, and the sampling at the heat source only carried out during heating periods.

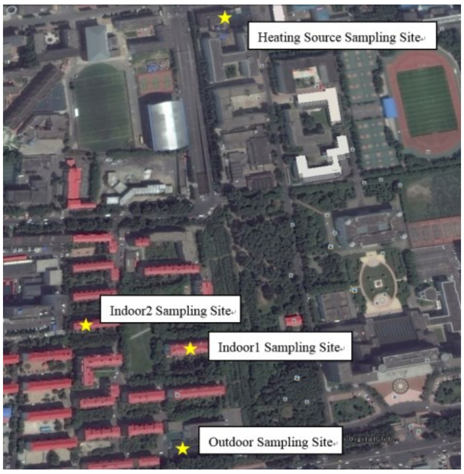


Figure 1 Sampling site location in a residential area in Harbin

2.3 Sampling protocol

Sampling of PM2.5 conducted simultaneously indoors and outdoors. Sampling location was 1.5m above the floor of each sampling site which is the height of a person's breathing zone approximately (as shown in Figure 2) (Li Zhao et.al, 2015).

Figure 2 Sampling equipment setup at sampling site

3. Results and Discussion

3.1 The PM 2.5 mass concentration of different sampling sites

The concentration of particles usually can be expressed in two ways, the mass concentration and the number concentration, and the mass concentration was used more commonly, We counted the daily average PM2.5 mass concentration of 4 different sampling sites in 5 months (as shown in Figure 3).

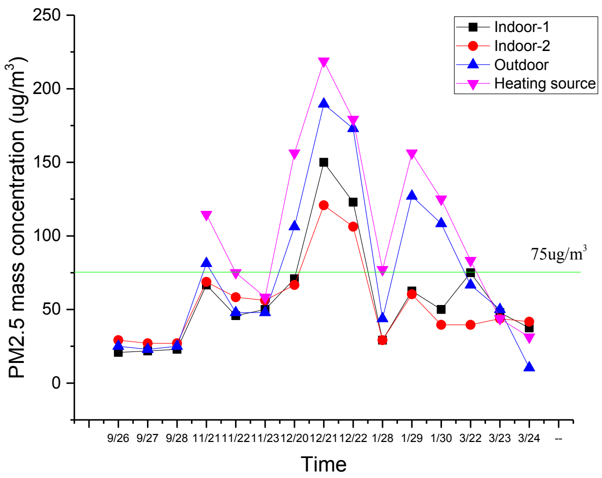


Figure 3 PM2.5 mass concentration with sampling says of different sampling sites

The PM2.5 mass concentration of 4 different sampling sites changes with time in the same tend, and in the medium-term of heating seasons, values are higher than other periods. Besides, PM2.5 concentrations of heating source are higher than outdoor, especially in the medium-term of heating seasons.

The maximum of PM2.5 mass concentration at 4 different sampling sites are 150.02ug/m3 (Indoor-1), 120.84ug/m3 (Indoor-2), 189.63ug/m3 (outdoor), 218.80ug/m3 (heating source), respectively, all happened in December. According to the Ambient Air Quality Standard (GB3095-2012), China's PM2.5 limit value is 75ug/m3, and during the measurement, the number of days higher than 75ug/m3 were 3 days in 15 days (Indoor-1), 2 days in 15 days (Indoor-2), 6 days in 15 days (outdoor), 9 days in 12 days (heating source). The proportion of days that are higher than the Chinese limit values is obviously greater outdoors, especially at the site of heating source, showed in the Figure 3.

3.2 I/O ratios

With the same outdoor PM2.5 mass concentration, I/O ratios of Indoor-1 and Indoor-2 vary with different indoor environments (as shown in Figure 4). As for the same indoor sampling site, I/O ratios vary in a large range (Indoor-1: 0.46-1.12, Indoor-2: 0.37-1.18) due to different sampling periods. Larger I/O ratios happened in early and late of heating seasons, while smaller values happened in the medium-term of heating seasons. Most of I/O ratios are less than 1 no matter at Indoor-1 or Indoor-2, and especially at the date of the ambient PM2.5 mass concentration is very high, I/O ratios became very low conversely. I/O ratios of Indoor-1 and Indoor-2 are different because of the different indoor environments, different ventilation conditions and different human behaviors, but variation trends are the same.

I/O ratios not only can describe the relationship between indoor and outdoor particle concentration simply, but also can determine whether outdoor particles are the main source to indoor particles preliminarily (Zhang Zhenjiang et al., 2013; Li Y G & Chen Z D, 2003). A greater range of variation indicates that the different measuring day can influence the I/O ratio obviously, and there are big differences between indoor and outdoor concentrations of different residences.

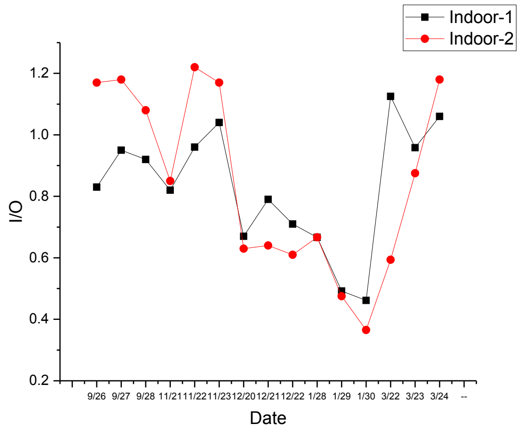


Figure 4 I/O ratios with sampling days of Indoor-1 and Indoor-2

3.3 The relationship between meteorological conditions and I/O ratio

In previous studies, many researchers have proved that different meteorological condition can influence the particle concentration and the correlation between indoor and outdoor particle concentration by varying degrees (Qing Yu Meng et al., 2009; Dilinuer ·TALIP et al., 2011; Yang Han et al., 2015). Meng et al. conducted the nonparametric regression to analyze the relationship between the infiltration factor and the outdoor temperature quantitatively, and liner regression to analyze the relationship between infiltration factor and indoor-outdoor temperature differences. The result demonstrated that there is a certain degree of correlation between the infiltration factor and the temperature. Dilinuer ·TALIP et al. measured the ambient particle mass concentration and meteorological parameters constantly from 9th 2008 to 2nd 2010 in Urumqi City, and the result showed that there is significant negative correlation between winds and particle mass concentration and the precipitation is also an important factor to impact the atmospheric fine particles mass concentration. Yang Han et al. estimated the influence of meteorological conditions on ambient air PM2.5 concentrations and temporal trends of PM2.5 in indoor and outdoor air.

The temperature difference is one of the momentum that lead to the connection of indoor and outdoor particles. In this study, relationships between I/O ratios and the indoor-outdoor temperature difference of Indoor-1 and Indoor-2 are weak negative correlation (as shown in Figure 5), and slopes are negative and not significant at the level of 0.05. According to Figure 5, the indoor-outdoor temperature difference is not the main influence factor to the ability that outdoor PM2.5 penetrate into the residence, but there are negative correlations as a certain extent.

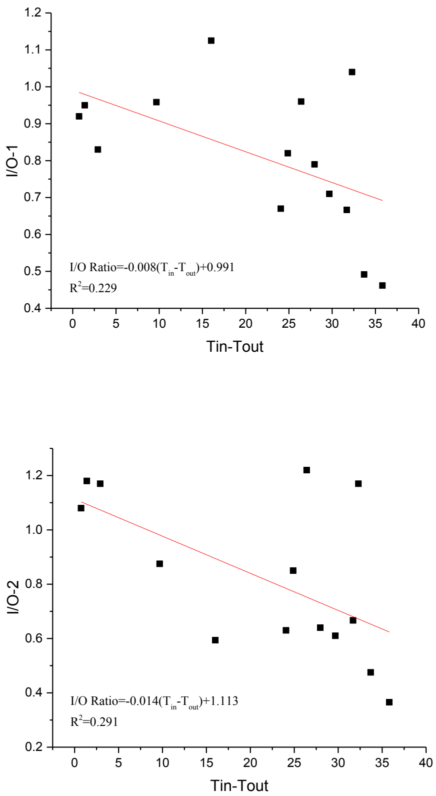


Figure 5 Correlation between I/O ratios and indoor and outdoor temperature difference

Besides, analyses about the correlation between I/O ratios and differences of the relative humidity and wind speed have been carried out, and the correlation was very weak.

3.4 The correlation analysis between indoor and outdoor PM2.5 mass concentration

The correlation between indoor and outdoor particles can estimate the contribution to indoor particles of outdoor origin, in this study we selected paired values of indoor and outdoor PM2.5 mass concentrations to conduct linear regression analysis (as shown in Figure 6).

The quantitative relationship between indoor PM2.5 mass concentration and outdoor PM2.5 mass concentration can be calculated by the mass balance equation, the equation can be expressed as follows (Wenjing Ji & Bin Zhao, 2015; E. Diapouli et.al, 2013):

$$C_{in} = \frac{a \cdot P}{a+k} C_{out} + \frac{Q_{is}}{(a+k) \cdot V} \quad (2)$$

Where C_{in} is the indoor PM2.5 mass concentration ($\mu g/m^3$), C_{out} is he outdoor PM2.5 mass concentration ($\mu g/m^3$), P is the PM2.5 penetration factor, a is the air exchange rate per hour (h^{-1}), k is particle deposition rate (h^{-1}), Q_{is} is the indoor PM2.5 source strength ($\mu g/h$), V is the volume of the room (m^3). Totally 69 groups of penetration factor and deposition rate of PM2.5 have been calculated based on the size dependent particle penetration factor and deposition rate recommended by Nazaroff (Nazaroff WW, 2004; Liu DL & Nazaroff WW, 2001; Riley WJ, McKone TE, Lai ACK and Nazaroff WW,2002).

The infiltration of outdoor particles to indoor particles can be estimated by a characteristic parameter, the infiltration factor ($F_{\inf}$). The infiltration factor corresponds to the fraction of outdoor PM2.5 that enter an indoor space and remain suspended, which can be expressed by the following equation:

$$F_{\inf} = \frac{a \cdot P}{a+k} \quad (3)$$

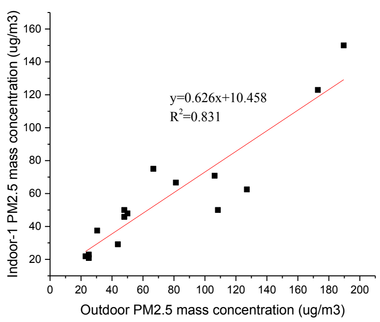
Thus, equation (2) can be expressed as following:

$$C_{in} = F_{\inf} \cdot C_{out} + \frac{Q_{is}}{(a+k) \cdot V} \quad (4)$$

According to the equation (4), the slope of the fitting curve represents the $F_{\inf}$, and the intercept represents the term of $\frac{Q_{is}}{(a+k) \cdot V}$, which expressing the indoor PM2.5 emission strength. Defining the contribution rate of outdoor particles on indoor particles: $\rho = \frac{F_{\inf} \cdot C_{out}}{C_{in}} \times 100\%$ and according to fitting results, the quantitative analysis of the source of the indoor PM2.5 can be made (as shown in Table 1).

Table 1: Estimates of PM2.5 of ambient origin using mass balance model.

Site	Indoor-1	Indoor-2
Infiltration factor(F_{inf})	0.626	0.461
Indoor generated PM2.5	10.458	19.097
Contribution rate(ρ)	82.05%	64.83%



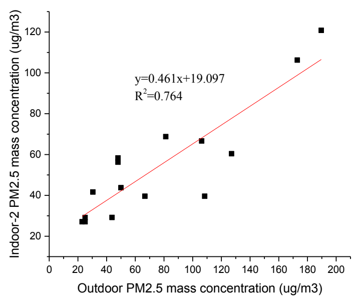


Figure 6 Correlation between indoor and outdoor PM2.5 mass concentration

According to Table 1, the indoor PM2.5 emission strength of Indoor-2 is stronger than Indoor-1, so the contribution rate of Indoor-2 is lower than Indoor-1. The infiltration factor of Indoor-1 is 0.626, Indoor-2 is 0.461 contrastively, the reason maybe the ventilation condition of Indoor-1 in better than Indoor-2, so particle can penetrate into the residence more simply.

4. Conclusion

This paper analyses the characteristic of PM2.5 mass concentration in the typical severe cold urban (Harbin) by scene sampling, and then assess the relationship between indoor and outdoor PM2.5 mass concentration mainly by using two parameters: I/O ratio and infiltration factor. Several conclusions have been drawn by this work:

1) In the medium-term of heating seasons, PM2.5 mass concentrations would increase obviously, and at the heating source sampling site, PM2.5 concentrations were significantly higher than other 3 sites, and the rate that out of limits was much higher.
2) I/O ratios would be different with different building design of residence, types of windows and human behaviors would influence I/O ratios, but in the same ambient environment, variation trends of I/O ratios were the same.
3) The meteorological conditions, including indoor-outdoor temperature differences, indoor-outdoor relative humidity differences, and ambient wind speed, influenced PM2.5 mass concentrations and I/O ratios to varying degrees, the correlation with temperature differences was weak negative correlation, but the correlation with relative humidity differences and wind speed was too weak.
4) The correlation between indoor and outdoor PM2.5 mass concentration was stronger (R2=0.831, R2=0.764), and in different residences, the infiltration factor would be different, and there would be distinction in emission strength of indoor PM2.5 and contribution rate of outdoor PM2.5 on indoor PM2.5.

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