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Comparison of indoor concentration of $PM_{2.5}$ between different residences

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Abstract
Building energy conservation plays an important role in energy saving and emission reduction, and the efficiency of new residential buildings is likely to be improved under the policy instruction. To increase the building air-tightness and reduce fresh air supply are usually considered as effective means in energy-efficient buildings which are likely to lead to changes in indoor air pollution such as particulate matters (PM). Three typical residential building models were created in the multi-zone airflow and contaminant transport program CONTAM in order to simulate airflow and $PM_{2.5}$ *concentrations in Nanjing dwellings. The airflow path elements considered for each building model included the exterior wall leakage, interior wall leakage, exterior door and window, etc. Both indoor and outdoor source of* $PM_{2.5}$ *were considered for indoor* $PM_{2.5}$ *concentration comparison and analysis. The results of the simulation and analysis indicated that the concentration of indoor* $PM_{2.5}$ *varied among different residences. The tighter the building was, the less influence of outside pollution on indoor* $PM_{2.5}$ *concentrations, when the doors and windows were closed. With the presence of indoor pollution sources, indoor concentration of* $PM_{2.5}$ *increased rapidly. Increase efficient building ventilation, especially with the presence of indoor sources, was of great significance in improving indoor air quality, reducing the indoor concentration of* $PM_{2.5}$ *and its adverse effect on human health.*

Keywords - Indoor air quality, $PM_{2.5}$***, CONTAM, Residence, Simulation***

1. Introduction

With the rapid development of industrialization and urbanization in China, air pollution has become an increasingly serious concern. Ambient particulate matter (PM) has already become the forth contributor to burden of disease in China, causing cancer, cardiovascular, respiratory diseases, etc[1]. Outdoor particles can transport into the indoor environment through building ventilation such as mechanical ventilation, natural ventilation and infiltration[2]. As most people spend more than 80% of their time in indoor environment especially at home[3, 4], the indoor air $PM_{2.5}$ pollution levels have a significant influence on individual's exposure to ambient $PM_{2.5}$ pollution.

Concentration of $PM_{2.5}$ in residences are affected by the infiltration of outdoor particles, emissions from indoor sources and the removal from the internal air by deposition, filtration and exfiltration [5]. A number of factors have effect on $PM_{2.5}$ infiltration from outside, including building location, height, orientation, sheltering, and permeability of the building envelope, building geometry, ventilation system, weather and meteorology condition[6]. With the demand of building energy conservation, the buildings constructed in recent years tend to be tighter. However, the increase airtightness of buildings are likely lead to changes of the penetration of externally air pollutants. In addition to infiltration, concentrations of $PM_{2.5}$ in dwellings will be affected by emissions from indoor sources such as cooking and smoking [2, 7]. Occupant behavior patterns, including window opening, can also influence indoor $PM_{2.5}$ concentrations[8]. Taking into account all these factors, it is needed to assess the concentration of $PM_{2.5}$ indoors for further understanding of the impact of building environment on occupants exposure.

In this study, a multi-zone indoor air quality and ventilation simulation model was used to model the indoor $PM_{2.5}$ concentrations in residences , and the difference between different residence was analyzed.

2. Materials and methods

2.1 Simulation model

CONTAM 3.2, a multi-zone indoor air quality and ventilation simulation model, was used to simulation indoor $PM_{2.5}$ concentrations of three residences (H01, H02, H03) in Nanjing categorized by the construction year (before 1990, 1991-2000, 2001-2015) in this paper. According to the Statistical Year Book of Nanjing[9], the per capita floor space of urban residents in Nanjing was 36.3 square meters. A family of two adults and one children was simulated living in each 109m^2 apartment, which included two bedrooms, a living room, a study room, a bathroom and a kitchen (Fig.1) . The apartment were modeled as being on a middle floor, with adjoining flats to the sides, above, and below.

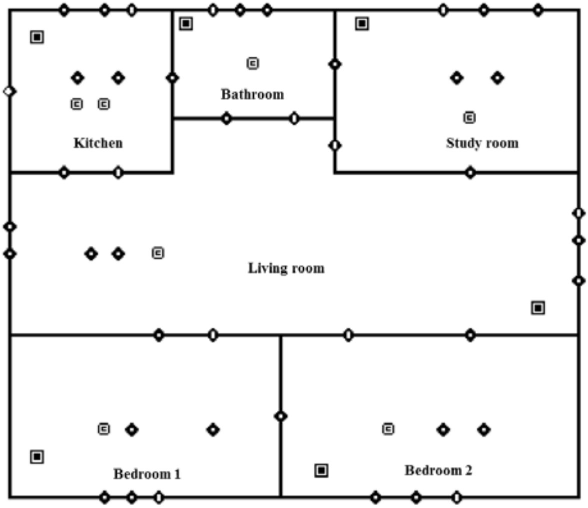

Fig.1 CONTAM schematic of simulated apartment unit in a multifamily building

2.2 Contaminate sources and meteorological data

Based on the study of Jone et al., high $PM_{2.5}$ indoor concentrations relatived to external levels, with cooking and smoking being the two primary sources[10]. The seasonal mean outdoor $PM_{2.5}$ concentrations of Nanjing were obtained according to the hourly $PM_{2.5}$ pollution data between 01/03/2014 and 28/02/2015 collected by he China air quality online environment monitoring platform (http://www.aqistudy.cn/). Weather conditions (e.g. temperature, relative humidity and wind speed) were also got from the same Website. Considering that smoking indoors was not recommended, source of $PM_{2.5}$ from smoking was not included in this study. The emission rate of $PM_{2.5}$ from cooking was assumed to be 1.56 mg/min[11]. The schedule of cooking at weekdays according to the CONTAM schedule Library was used for modeling.

2.3 CONTAM simulations

The mean $PM_{2.5}$ concentrations of 3 residences in four seasons were performed in this study. The infiltration of air was modeled through cracks in the externally exposed facades (including exterior walls, windows and door) and windows when opened. The exterior wall leakage was modeled using an effective leakage area calculated according to the floor area and construction year of the building based on the empirical model proposed by Chan et al[12]. The exterior window and door leakage areas when the window and door closed were calculated according to the design standard for energy efficiency of residential buildings in hot summer and cold winter zone[13], and modeled as narrow opening with discharge coefficient CD=0.6 and flow exponent n=1.0. Two-way flow model was selected when the door or windows opened. Internal walls, floors and ceilings were also given cracks, allowing for the completion of the airflow network, and these airflow path elements were modeled according to the values of the ASHRAELA Library in CONTAM 3.2.

The kitchen fan airflow was set at 1020 m3/h during cooking event. Indoor temperature in summer and winter, were set at 26℃ and 12℃ according to the design standard of thermo-environment for residential building[14]. In transition seasons, the indoor temperature was set 2℃ higher than the corresponding outdoor seasonal mean temperature.

The daily natural ventilation time by open window were 636 min/d in summer, 281 min/d in winter and 454 min/d in transient season, respectively[4]. The occupant window-opening behavior in 4 seasons were assumed in Table 1.

Table 1. Occupant window-opening schedules for CONTAM simulations

No	Season	Schedule
1	Spring	6:30-8:30 17:30-23:00
2	Summer	0:00-8:30 17:30-19:00 23:00-24:00
3	Autumn	6:30-8:30 17:30-23:00
4	Winter	7:00-8:30 17:30-20:40

2.4 Data analysis

The hourly air change rates data in living room output by CONTAM were used for the estimation of $PM_{2.5}$ concentration infiltrated from outdoors, based on the standard single-compartment box model[15]. $PM_{2.5}$ deposition rate was modeled using a deposition rate of 0.19 h^{-1} for each room[15], with a penetration factor of 0.8 when window were closed and 1.0 when windows were opened. For $PM_{2.5}$ generated from indoor source, the hourly concentrations output by CONTAM were used directly. The final concentration of $PM_{2.5}$ indoors were estimated as the sum of $PM_{2.5}$ from both outdoor infiltration and indoor emission.

3. Results and discussion

3.1 Infiltration rate

The seasonal average infiltration rates (F_{inf}) of each residence were simulated in CONTAM, and the results were shown in Fig. 2. Generally, the F_{inf} in autumn was the largest while it was smallest in winter according to the mean value. Wind speed was a meteorological variable that was shown to be positively related to infiltration, presumably by increasing the pressure difference across the shell of the house[16]. The average wind speed in Nanjing was 2m/s in autumn wand 1m/s in winter, and the larger wind speed would contribute to the higher infiltration rates in autumn.

As shown in Fig. 2, the infiltration rates of 3 types of residences ranged from 0.08 to 0.27 h-1 in four seasons with a mean value of 0.18 h^{-1}. The mean infiltration for residence constructed before 1990 (H01), from 1990 to 2000 (H02) and from 2000 to now (H03) were 0.23h^{-1}, 0.18h^{-1} and 0.15h^{-1}, respectively. The infiltration rates of dwellings decreased slightly as the age of the buildings become younger. The results were remarkably consistent with results found in Beijing. In the research conducted by Shi et al., the infiltration rates for residences constructed before 1990 were higher than those constructed from 2000 to 2010[17]. Home age was also found significantly associated with F_{inf} for fine particle in Kearney et al.'s study, and older homes were associated with the highest F_{inf}[7, 16]. This can be attributed to changes in the building code, changes to building materials over time, and deterioration of the building over time[18].

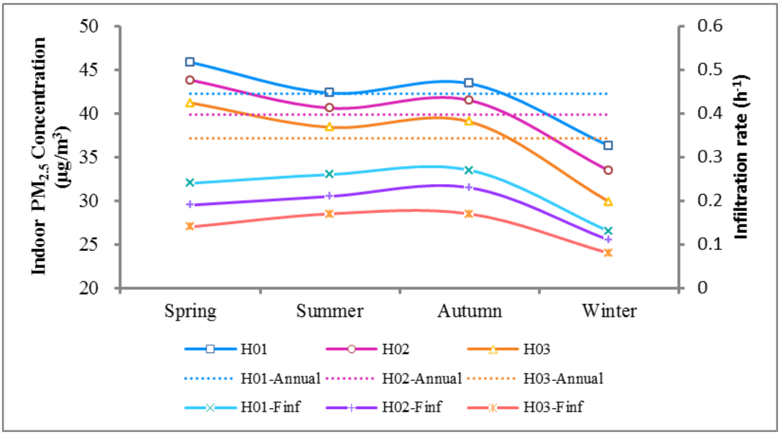

Fig. 2 Seasonal Indoor $PM_{2.5}$ concentration and infiltration rates of different residences

It is worth noting that the main difference of residence F_{inf} mainly came from the exterior wall leakage areas which were calculated by an empirical model conducted by Chan et al[12]. However, as discussed in the research of Shi et al[17], the application of the equation to calculate the leakage area of single dwellings in the United States, for apartment buildings in China was questionable. Furthermore, other building characteristics such as building orientation, area, height, geometry were not considered in this study, which could also have significant influence on the air infiltration from outdoors.

3.2 $PM_{2.5}$ concentration

The annual average indoor $PM_{2.5}$ concentration infiltrated from outdoors in H01, H02 and H03 residences were estimated to be 16.1 μg/m^3, 12.6 μg/m^3 and 9.8 μg/m^3 when the doors and windows were closed. Residences with larger infiltration rate showed higher amounts of pollution infiltration into the indoor air. With the demand of building energy conservation, the newer buildings tend to be tighter than older, which can reduce occupants exposure to indoor $PM_{2.5}$ resulting from ambient sources. However, when the indoor cooking source was considered, the indoor $PM_{2.5}$ concentration increased to 42.23 μg/m^3, 39.89 μg/m^3 and 37.14 μg/m^3 in 3 types of dwelling (Fig.2), respectively, and the indoor concentration decreased slightly as the age of the building decreased, too. The varying trends of the concentration of indoor $PM_{2.5}$ and building infiltration rates with seasons were similar. However, the situation in summer was a little different. The outdoor average $PM_{2.5}$ concentration in summer was lower than other seasons, indicating a lower amounts of pollution infiltration from outside. Moreover, the time which occupants keep the window opened in summer was longer than in other seasons, which was conducive to the spread of indoor $PM_{2.5}$ pollution generated from cooking.

The results of indoor $PM_{2.5}$ concentration stimulated in this study were relatively lower than on-site measurements in other regions in China[19, 20]. This is mainly because that the results modeled by the CONTAM dependent on the range of assumptions and input parameters specified. In particular, $PM_{2.5}$ emission rates from cooking vary greatly, depending on food type, cooking method, appliance and method of measurement[21, 22]. In addition, $PM_{2.5}$ deposition rate, cooking schedule, indoor window-opening behavior and kitchen fan airflows may also change according to the habit of occupants[6, 23, 24], which could also lead to differences in $PM_{2.5}$ concentrations indoors.

3.3 Influencing factors of indoor $PM_{2.5}$ concentration

Ventilation was an effective way for reducing indoor air pollution. Take winter as example, the results of $PM_{2.5}$ simulation in different residences were presented in Table 2. Under the condition of ventilation, outdoor infiltration were the main contributor of indoor $PM_{2.5}$ pollution. With the higher infiltration rate, the indoor levels of $PM_{2.5}$ in residence H01 derived from outdoors was more than indoor source. For the residence of H02 and H03, indoor source were the dominant source of $PM_{2.5}$ pollution. The average indoor $PM_{2.5}$ concentration for H01, H02 and H03 reduced from 45.85 μg/m^3, 43.67 μg/m^3, 41.84 μg/m^3 to 27.20 μg/m^3, 24.85 μg/m^3, 21.93 μg/m^3, respectively, when the building were ventilated. The difference of indoor $PM_{2.5}$ levels between residences decreased when the buildings were ventilated. Indoor particle concentrations often showed a clear positive relationship with outdoors under ventilation conditions[25], and this may result in the similar indoor $PM_{2.5}$ concentration when the window was opened.

Table 2. Average indoor $PM_{2.5}$ under different ventilation conditions in winter（μg/m^3）

	With ventilation			Without ventilation		
	$PM_{2.5}$ from indoor	$PM_{2.5}$ from outdoor	Total	$PM_{2.5}$ from indoor	$PM_{2.5}$ from outdoor	Total
H01	0.84(2.3%)	35.09(97.7%)	35.92	24.70(47.81%)	26.96(52.19%)	51.66
H02	0.77(2.3%)	32.28(97.7%)	33.04	25.15(51.58%)	23.61(48.42%)	48.76
H03	0.68(2.3%)	28.79(97.7%)	29.47	26.56(57.69%)	19.48(42.31%)	46.04

The diurnal indoor $PM_{2.5}$ concentrations was shown in Fig.3. Cooking had a significant impact on indoor $PM_{2.5}$ concentrations with dramatically increase during cooking events in the morning and evening. The results of this study were consistent with previous researches[10, 26], the particle concentrations indoors often change over time with peaks during cooking events. Under the condition of ventilation, the indoor $PM_{2.5}$ concentration reduced to low levels rapidly, indicating that the influence of building ventilation on indoor pollutions was significant, especially with the presence of strong indoor sources.

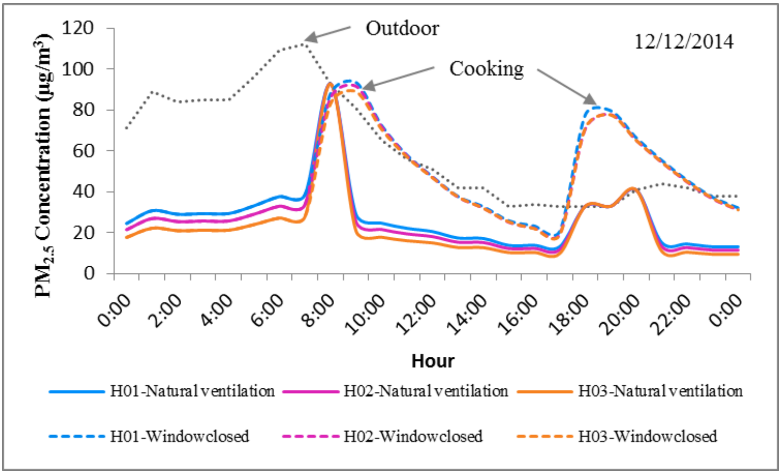

Fig. 3 Diurnal indoor and outdoor $PM_{2.5}$ concentrations with the conditions of ventilation and no ventilation

4. Conclusions

The study has applied a series of model simulations in CONTAM to compare the indoor $PM_{2.5}$ concentrations of residences constructed in different years. The annual indoor $PM_{2.5}$ concentration for 3 residences in Nanjing were estimated to be 42.23 μg/m^3, 39.89 μg/m^3 and 37.14 μg/m^3. Indoor $PM_{2.5}$ concentrations slightly decreased as the age of the buildings became younger. Cooking was the most significant contribution to indoor particle pollution when the building was ventilated by infiltration. Conversely, when the residences were ventilated naturally, outdoor infiltration was the dominant source of indoor $PM_{2.5}$ pollution. Increase building ventilation was an effective method for reducing indoor air pollution, especially when indoor sources existed. The result of this study would be helpful for the understand of indoor air pollutions of different residences and the accurate exposure assessment of people living in different types of residences in the future.

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