Wind Engineering Joint Usage/Research Center
FY2019 Research Result Report

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1.   Research Aim

In this study, a coupled particle diffusion model was established to investigate the particle concentration distribution in urban local scale and relationship between indoor and outdoor particle concentrations. This model considered the influence of particle source, underlying surface, building layout, and indoor human activities, etc. Based on this model, we simulated the concentration distribution of $PM_{2.5}$ in a super high-rise residential area in a typical severely cold city in China in winter, and analyzed the vertical distribution characteristics. In addition, the indoor $PM_{2.5}$ concentration levels in a building in this residential area was also simulated, and we mainly analyzed the effect of indoor source emission and opening windows on indoor $PM_{2.5}$ concentration levels.

2.   Research Method

The whole model includes the following two parts: local particle diffusion model (Part I) and indoor-outdoor particle diffusion model (Part II). The description of this model is presented below.

2.1 Part I: Local scale particle diffusion model

The local urban particle diffusion model is based on the urban canopy energy balance model. The model couples the solar radiation, urban layout, building heat and moisture load, local climate, and thermal comfort model and can calculate the thermal climate change in the urban canopy area. The overall framework of the model is shown in Fig. 1. The urban canopy energy balance model can be applied to the simulated calculation of the thermal climate in different types of urban areas such as residential and commercial areas. Further, the model can be used for dynamic simulation of geothermal climate in severely cold regions after testing and verification (Shui et al., 2016; Zhu et al., 2006).
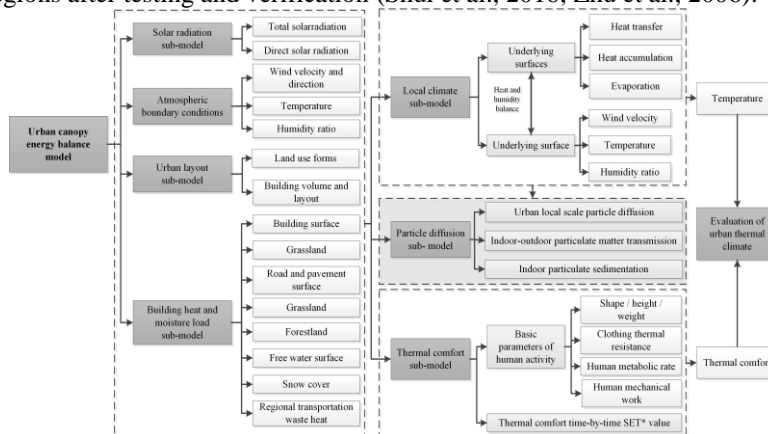

Fig. 1 Technical framework for the local urban-scale particle diffusion model

2.2 Part II: Indoor-outdoor particle diffusion model

As mentioned above, indoor particle concentration level depends on many factors, as shown in Fig. 2. Outdoor particles can enter the indoor environment by mechanical ventilation, natural ventilation and infiltration through cracks of buildings. Besides, indoor human activities like cooking and cleaning and some other processes happening indoors can also influence indoor particle pollution. For cities in the severe cold region in China during winter, mechanical ventilation is rarely took in residential buildings. Therefore, the indoor-outdoor particle diffusion model in this study mainly considers infiltration through window cracks and the natural ventilation by opening windows. In addition, the effect of indoor particle sources is also considered in this model.
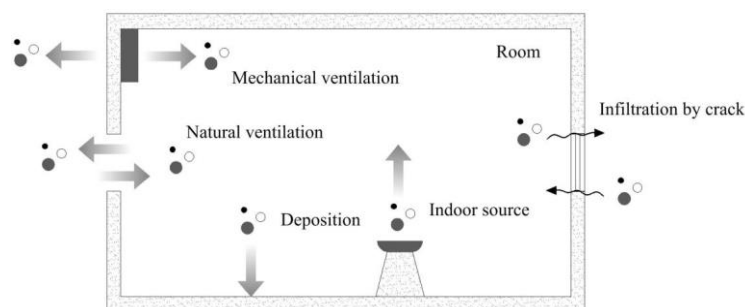

Fig. 2 Origin of particles in indoor environments

2.3 Model validation

In order to ensure the reliability of the model calculation results, it is necessary to validate the accuracy of the model. We validated the accuracy of local scale particle diffusion model and the indoor-outdoor particle diffusion model separately.

2.3.1 Verification of local scale particle diffusion model

In order to verify the accuracy of the local urban-scale particle diffusion model, the $PM_{2.5}$ mass concentrations were measured, and meteorological conditions were monitored for a residential quarter in Harbin, China, from 0:00 to 24:00 on 21 December 2017. Harbin is located in northeast China, between 44°04´~46°40´ north latitude, and it is a typical severely cold city in China. The sampling site was located at the top of a two-story residential quarter, located away from pollution sources such as roads. The sampler was installed and operated at a height of 8 m above the ground. The test instrument was median-volume total suspended particulate samplers with a sampling flow range of 60–130 L·min^{-1} and set at 100 L·min^{-1} for this study. Further, the district under consideration was about 300 × 410 m^2, including 17 multi-story buildings, open spaces, woodlands, sidewalks, and two main roads (Xiao et al., 2018).

The comparison between the calculated $PM_{2.5}$ mass concentrations at 8 m in the district under consideration and the measured results are shown in Fig. 6. It can be seen that the calculated $PM_{2.5}$ mass concentrations are consistent with the overall change in the trend of the measured results over a day. The results of the model reflect well the change of the $PM_{2.5}$ mass concentrations in the district under consideration caused by the change of traffic flow, as shown in Fig. 3. The maximum value of the measured and calculated $PM_{2.5}$ mass concentrations both appear at 8:00 am. However, compared with the measured results, the calculated $PM_{2.5}$ mass concentrations fluctuated widely. Within a day, the extreme deviation of calculated results was 45.8 μg·m^{-3}, and that of the measured results was 35.0 μg·m^{-3}. Fig. 3 shows the distribution of calculated and measured $PM_{2.5}$ mass concentrations. It can be seen that the calculated $PM_{2.5}$ mass concentrations are relatively lower when compared to the measured results when the traffic densities and the concentrations are lower, while when the concentrations are higher, the calculated $PM_{2.5}$ mass concentrations are relatively higher when compared to the measured results. The difference between the calculated and monitored data may be due to unrecognised particulate point sources.
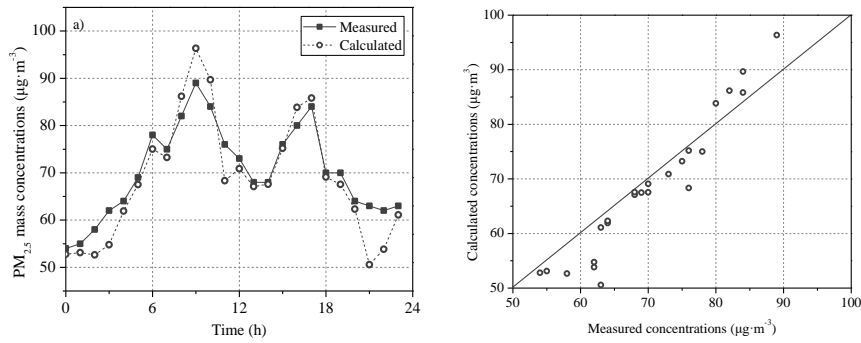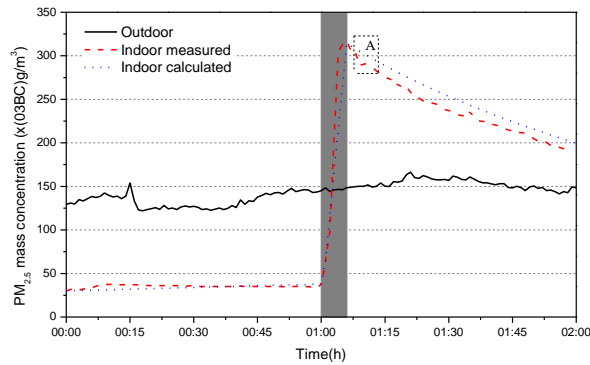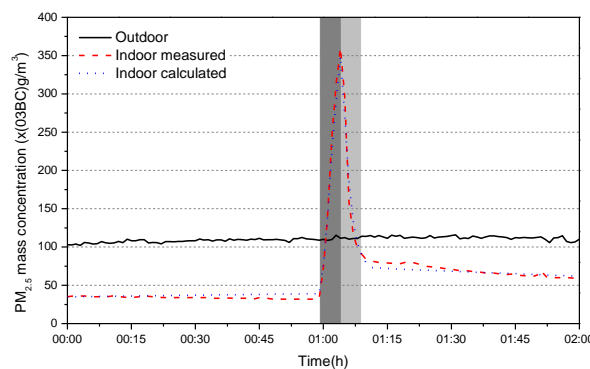
Fig. 3 Comparison of calculated and measured PM$_{2.5}$ mass concentrations at 8 m above the ground

In general, the local scale particle diffusion model can discern the variation in the trend of PM$_{2.5}$ mass concentrations in the district under consideration and reflect the effects of particle sources well. Considering the advantage in calculation time, it is believed that this model can be applied to the long-term dynamic simulation of particle concentration distributions at the local scale in cities.

2.3.2 Verification of indoor-outdoor particle diffusion model

The comparison between the calculated results and the measured results are shown in Fig. 4a. It can be found that the calculated PM$_{2.5}$ mass concentrations are consistent with the growth trend of the measured value during the source emission (shaded area in Fig. 4a), which indicate that the model can effectively reflect the influence of indoor source on indoor particle concentrations. At the end of the calculation, the measured PM$_{2.5}$ mass concentration was 192 μg/m^3, and the calculated concentration was 199.5 μg/m^3, which was about 7.5 μg/m^3 higher than the measured result, indicating the decay rate of calculated PM$_{2.5}$ mass concentration after the source emission is a little lower than the measured results. As shown in the A area of Fig. 4a, the measured indoor PM$_{2.5}$ mass concentrations decreased rapidly due to some external interferences, but they are basically consistent with the decay trend of the calculated value after that.

(a) Indoor source emission without window opening

(b) Open the window after indoor source emission.

Fig. 4. Comparison of calculated and measured indoor PM$_{2.5}$ mass concentrations.

In general, although the indoor-outdoor particle diffusion model cannot fully reflect the influence of all factors on indoor particle concentrations, the model can grasp the variation of indoor particle concentrations during some important activities well, such as indoor source emission and window

opening. This model can be used to evaluate the relationship between indoor and outdoor particle concentrations for buildings in cities in the severe cold region.

3. Research Result

3.1 Numerical simulations

For the simulation space, a super high-rise residential district in Harbin was selected to simulate the vertical $PM_{2.5}$ mass concentration distribution during the heating season of 2017–2018. Since the heating season in Harbin is identified to range from 16 October to 15 April of the next year, the specific method of division is from the 16th day of a certain month to the 15th day of the next month (i.e., the first calculation month ranged from 16 October–15 November).

The target simulated district is a super high-rise residential area with a total area of about 90,000 m^2 and includes 10 residential buildings. The layout of these buildings in the residential area is that of a regular parallel-type layout (as shown in Fig. 5). According to statistics, the plot ratio of the residential area is 3.38, and after 'uniformity' treatment, all buildings are simplified into single-storey buildings with an area of 950.4 m^2, height of 3.3 m and 33 floors.

Fig. 5 Target simulated and surrounding district

As for the simulation of indoor-outdoor particle diffusion, we selected one of the buildings in residential area as the simulation object. The area of each residential home is 95.58 m^2 including eight exterior windows as shown in Fig.6. During simulation, the indoor temperature was set as constant value of 23°C, and we used the simulation results of particle concentration distribution in local scale as the outdoor conditions. In order to study the effect of outdoor particulate matters on indoor $PM_{2.5}$ mass concentrations, the mass concentration change of indoor $PM_{2.5}$ was simulated within one month without the indoor particulate source and only considering the seepage of the window.
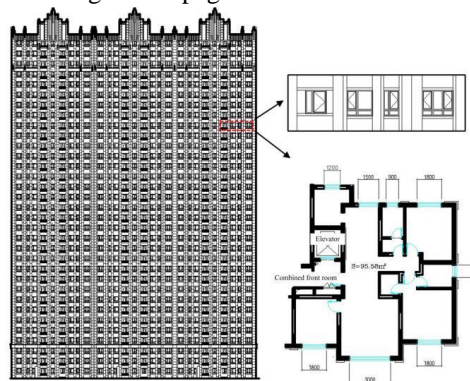

Fig. 6 Building elevation and floor plan of the tenants

3.2 Simulation results and discussion

3.2.1 Weekly variation of $PM_{2.5}$ mass concentrations in the residential area

In this section of the study, the weekly average $PM_{2.5}$ mass concentration distribution in the typical month (16 January–15 February) was analysed and focused on two characteristic concentrations: the $PM_{2.5}$ mass concentrations at 8 m and spatial-average $PM_{2.5}$ mass concentrations within the canopy. Fig. 11 shows the change in $PM_{2.5}$ mass concentrations at 8 m and the spatial average within the canopy. It can be found that there is a clear consistency in the time trend between the $PM_{2.5}$ mass concentrations at 8 m and vehicular

flows. However, due to the influence of background concentrations and other factors, obvious differences may appear in certain time periods. For example, in the interval indicated in red in Fig. 7, there was a significant fluctuation in the background $PM_{2.5}$ mass concentrations, which resulted in a significant variation between the $PM_{2.5}$ mass concentrations at 8 m and the traffic flow. Compared to the $PM_{2.5}$ concentrations at 8 m in the district under consideration, the consistency between the spatial-average particle concentrations within the canopy and the traffic flow is not very significant. The results indicated that vehicular emissions and fugitive road dust influenced the near-ground $PM_{2.5}$ mass concentrations more significantly. Further, due to the differences in the time characteristics of traffic flow between weekdays and weekends, there are significant differences in the distribution of $PM_{2.5}$ mass concentrations over time, on weekdays and weekends.
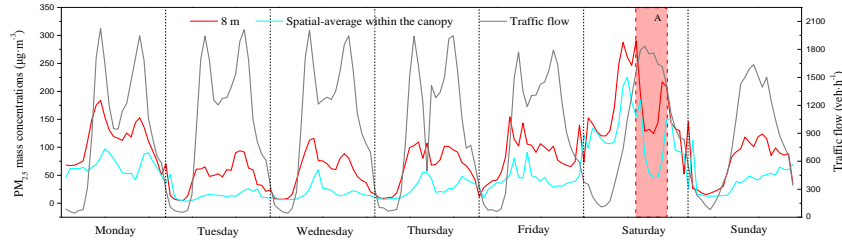

Fig. 7 Hourly changes in vehicular flow and changes in $PM_{2.5}$ mass concentrations at 8 m and the spatial average within the canopy

For Monday and Sunday, correlation analysis between vehicular flows and $PM_{2.5}$ mass concentrations at 8 m and the spatial average within the canopy are respectively showed in Fig. 8. It can be observed that the correlation between vehicular flows and $PM_{2.5}$ mass concentrations at 8 m are stronger, and the correlation between the spatial-average $PM_{2.5}$ mass concentrations within the canopy and vehicular flows is generally negligible.

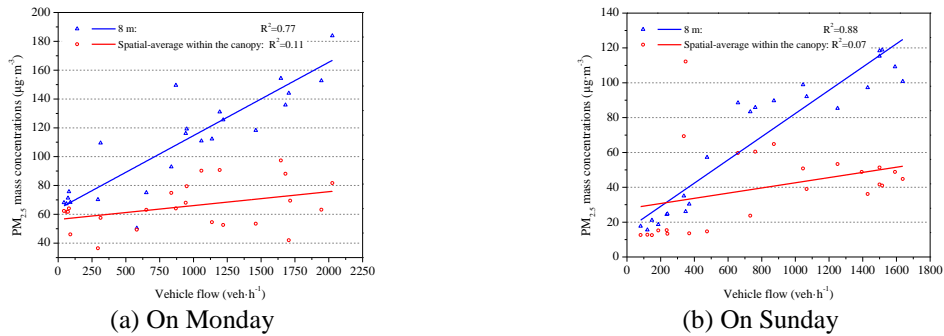(a) On Monday   (b) On Sunday

Fig. 8 Correlation analysis between traffic flow and $PM_{2.5}$ mass concentrations at 8 m and the spatial average within the canopy

3.2.2 Monthly variation of $PM_{2.5}$ mass concentrations in the residential area

Fig. 9 shows the frequency increase curve of $PM_{2.5}$ mass concentrations at 8 m and the spatial-average within the canopy for the typical month (16 January–15 February). The frequency increase curve shows an increasing trend at first, followed by a decreasing trend. The concentration below 132.74 $\mu g \cdot m^{-3}$ accounted for more than 80% at 8 m, while for the spatial-average $PM_{2.5}$ mass concentration within the canopy, the concentration was below 80.87 $\mu g \cdot m^{-3}$ for more than 80%.

(a) $PM_{2.5}$ mass concentrations at 8 m

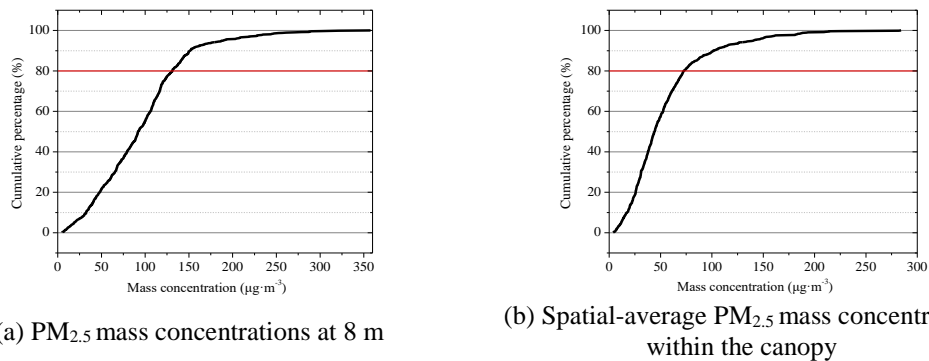(b) Spatial-average $PM_{2.5}$ mass concentrations within the canopy

Fig. 9 Cumulative percentage of $PM_{2.5}$ mass concentrations in the typical month

Fig. 10 shows the vertical distribution of $PM_{2.5}$ mass concentrations within the canopy at the same time (11:00) and different days of the typical month (16 January–15 February), including both weekdays and weekends. It can be seen that although the concentration levels of different days differ greatly, the vertical distribution law is obeyed relatively closely, and the vertical gradient of the overall $PM_{2.5}$ mass concentrations was between 0.7~1.14 $\mu g \cdot m^{-3} \cdot m^{-1}$. The results showed that due to the time distribution characteristics of the particle source and meteorological conditions, the vertical distribution of $PM_{2.5}$ mass concentrations at the same time at different days in the residential area was relatively close. This implies that there are certain similarities and regularity in the vertical distribution of $PM_{2.5}$ mass concentrations between days.
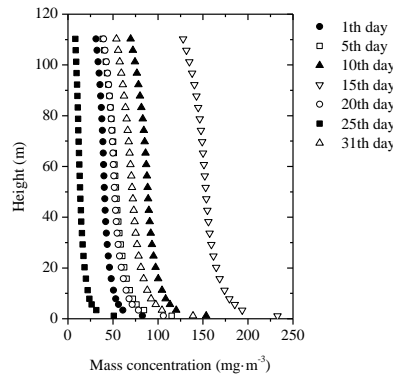

Fig. 10 Vertical distribution of $PM_{2.5}$ mass concentrations within the canopy at the same time on different days in the typical month

3.2.3 Analysis of $PM_{2.5}$ mass concentrations distribution during the heating season

According to the daily average $PM_{2.5}$ mass concentration limit corresponding to the air quality index of each level (Table 1), the distribution of $PM_{2.5}$ pollution level at 8 m in the residential area during the entire heating season was statistically obtained, as shown in Fig. 11. It can be seen that the air quality proportion of 'good' was the highest, followed by light pollution. However, during the entire heating season, the pollution level of $PM_{2.5}$ at 8 m in the residential area was not 'excellent'. This may not exactly match the actual forecast because the meteorological bureau sampling test usually ignores the vertical distribution of the concentration. The monitoring instrument is placed on the roof or a monitoring tower, and its height is higher than 8 m, resulting in the predicted air quality being slightly better than the calculation result.

Further, the distribution of $PM_{2.5}$ pollution levels at 8 m for the six calculation months of the heating season in the simulated area was calculated (Fig. 11). Among them, severe pollution only occurred from 16 October–15 November, and the proportion reached 15.62%, which was close to the actual situation. The reasons for haze weather in the urban area can be accounted for by the superimposed effects of coal-fired heating and the burning of straw in the suburbs (Han et al., 2015). Compared with the other five calculation months, it can be found that the proportion of days in which the $PM_{2.5}$ mass concentration level was below the pollution concentration limit in the third and fourth calculation months was significantly less than the other three calculated months due to the lower temperature and heat supply. The best calculation month for air quality was the fifth calculation month, and the proportion of days in which the $PM_{2.5}$ quality concentration level was below the pollution concentration limit reaches 75%.

Table 1 Daily average $PM_{2.5}$ mass concentration limits for each pollution level

Pollution level	Excellent	Good	Slightly pollution	Mild pollution	Moderately pollution	Severe pollution
$PM_{2.5}$ daily average concentration limit （$\mu g \cdot m^{-3}$）	35	75	115	150	250	350

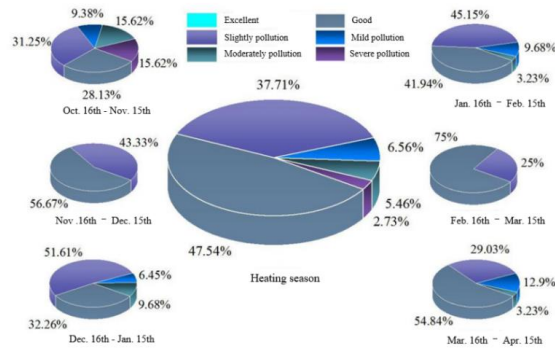*Environmental Air Quality Index (AQI) Technical Regulations, 2012

Fig. 11 Distribution of PM$_{2.5}$ pollution levels at 8 m in the simulated district during the heating season and in each calculation month

3.2.4 PM$_{2.5}$ mass concentration relationship between indoor and outdoor

According to the outdoor PM$_{2.5}$ mass concentration and outdoor weather conditions, the change of the indoor PM$_{2.5}$ mass concentration was calculated. Fig. 12 shows the hourly indoor and outdoor PM$_{2.5}$ mass concentrations on the 1st floor on calculated month. It can be seen that the indoor PM$_{2.5}$ mass concentrations changed with that outdoors in conditions with no indoor particle sources, but the indoor PM$_{2.5}$ mass concentrations are significantly lower than the outdoor concentrations. Moreover, it can be seen from the figure that there is a certain time lag for indoor PM$_{2.5}$ mass concentrations relative to outdoors: the indoor concentrations raised or fell after the outdoor concentrations raised or fell for a while. In addition, we simulated the indoor and outdoor PM$_{2.5}$ concentrations throughout the January and analyzed the results, it can be seen from Fig. 13 that the correlation between indoor and outdoor PM$_{2.5}$ mass concentrations is not very significant (R^2 = 0.614) due to the time lag of indoor concentrations.
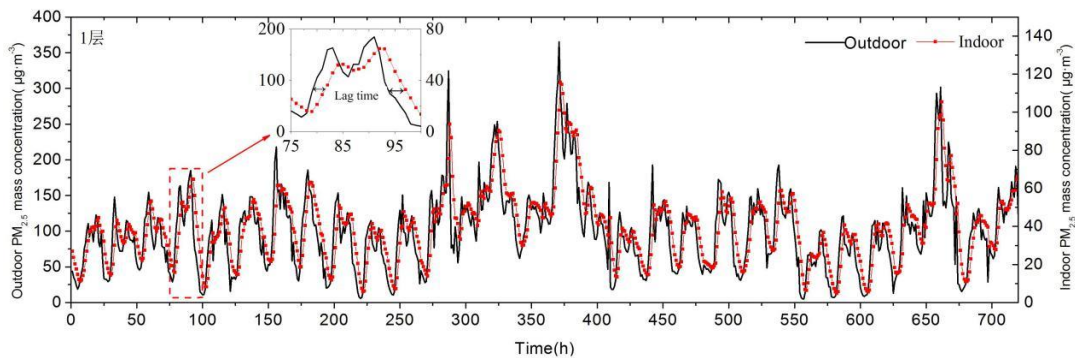

Fig. 12 Hourly indoor and outdoor PM$_{2.5}$ mass concentrations.

Based on the time lag of indoor PM$_{2.5}$ mass concentrations, this study used the cross-correlation analysis method to analyze the correlation between the temporal indoor and outdoor PM$_{2.5}$ mass concentrations, and the correlation coefficient was used to evaluate the correlation degree between indoor and outdoor PM$_{2.5}$ mass concentrations. The biggest correlation coefficient is 0.95 when the lag time is 2 h, and it can be considered that there is a lag of about 2 hours for indoor PM$_{2.5}$ mass concentrations relative to outdoors in conditions of complete infiltration in the residential home.
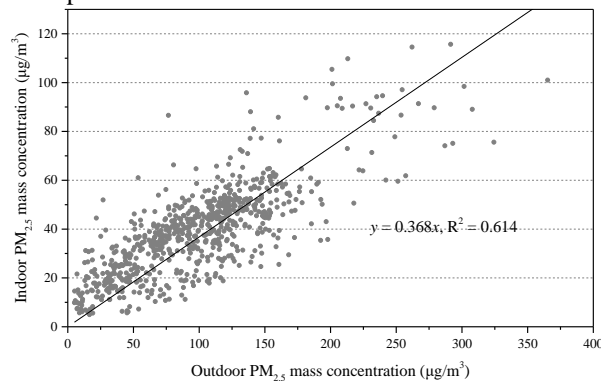

Fig. 13 Correlation analysis between indoor and outdoor PM$_{2.5}$ mass concentrations.

3.2.5 I/O of PM$_{2.5}$ mass concentration

In order to compare the relationship between indoor and outdoor PM$_{2.5}$ mass concentrations in different floors of buildings, five typical floors are taken from bottom to top to analyze the calculation results, which are the 1st floor, the 9th floor, the 17th floor, the 25th floor and the 33rd floor. Fig. 14 shows the hourly I/O ratios of PM$_{2.5}$ mass concentrations for different building floors in the calculated month.

It can be seen that the trends of I/O ratios for different floors are relatively consistent and their values were less than one in most cases. Besides, the difference in values of I/O ratio between different floors was not very significant. Due to the above-mentioned time lag of indoor PM$_{2.5}$ mass concentration relative to the outdoor, there will be a phenomenon that the indoor concentration does not decrease when the outdoor concentration is lowered, so a high I/O ratio occured during the calculation. For example, at 3:00 on February 8, 2018, the outdoor PM$_{2.5}$ mass concentration on the first floor of the building dropped rapidly from 63.29 μg·m^{-3} to 7.07 μg·m^{-3}, however, at this time, the concentration in the room dropped slowly, so the I/O ratio reached 3.06.
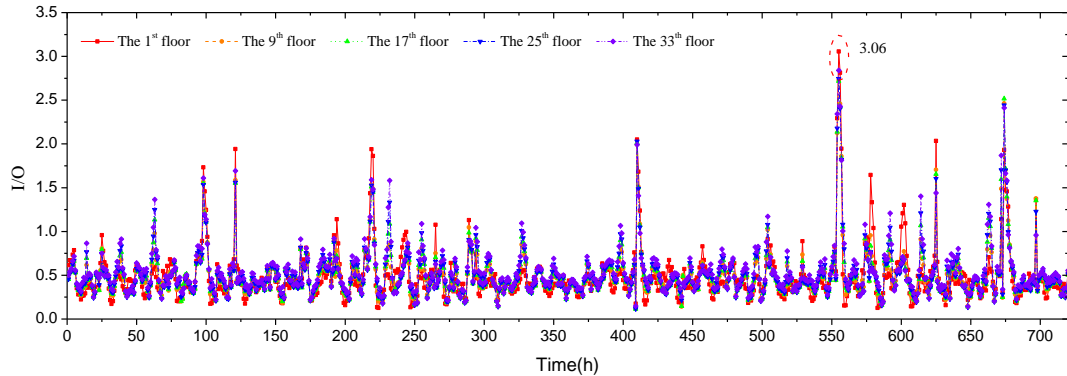

Fig. 14. Hourly I/O ratios of PM$_{2.5}$ mass concentrations for different building floors

3.2.6 Distribution of PM$_{2.5}$ pollution levels

According to the Ambient Air Quality Standard (GB3095-2012), the air quality can be divided into six categories according to the air quality index: excellent, good, light pollution, moderate pollution, heavy pollution and serious pollution, and the corresponding daily average PM$_{2.5}$ mass concentration limits are shown in Table 2. The indoor and outdoor PM$_{2.5}$ pollution level distributions for different floors of the building in January was showed in Fig. 15. The results showed that the air quality in each floor is all significantly better that outdoors. In addition, although the air exchange rates and I/O ratios were higher for higher building floors, the indoor air quality is gradually increased as the outdoor PM$_{2.5}$ pollution level reduce with the height. As the presentation of Fig. 15, except for the daily average indoor PM$_{2.5}$ mass concentration at the 1st floor was higher than the "good" level pollution concentration limit (75 μg/m^3), the daily average mass concentrations of the other four typical floors were all lower than that concentration limit. For the 9-33 floors, the grade of "excellent" accounted for a large proportion, which indicated that the building envelope could block the outdoor PM$_{2.5}$ entering indoors effectively when there is only infiltration.

Table 2 Daily average PM$_{2.5}$ mass concentration limits for each pollution level.

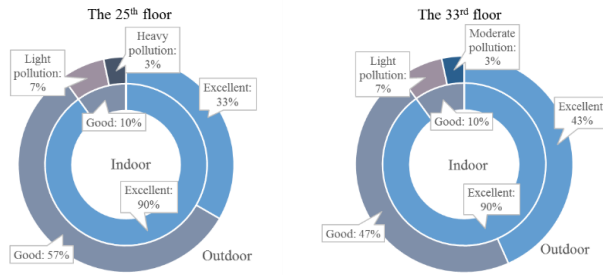| Pollution level	Excellent	Good	Light pollution	Moderate pollution	Heavy pollution	Serious pollution
Concentration limits	35 μg/m^3	75 μg/m^3	115 μg/m^3	150 μg/m^3	250 μg/m^3	350 μg/m^3
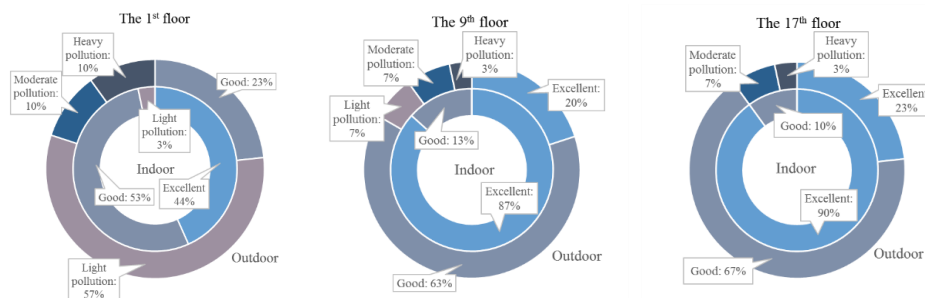
Fig. 15 Distribution of PM$_{2.5}$ pollution levels of different building floors during a month.

4. Published Paper etc.

[Underline the representative researcher and collaborate researchers]

[Published papers]

1. Y. Xiao, J. Liu*, H. Liu, P. Gao. Residential indoor-outdoor relationships of PM2.5 and elements during a heating season in Harbin. Building Science, 35(2): 29-34，2019 (in Chinese with English abstract)

2. Y. Xiao, Y. Lv, Y.W. Zhou, H. Liu and J. Liu*. Size-resolved surface deposition and coagulation of indoor particles. International Journal of Environmental Health Research, 2019(3): 1-17

3. Y. Xiao, J.J. Zhao, H. Liu, L.N. Wang, M.Z. Yue, J. Liu*. Dynamic prediction of PM2.5 diffusion in urban residential areas in severe cold region based on an improved multilayer urban canopy model. Sustainable Cites and Society (minor revision after first review)

4. Y. Xiao, J.J. Zhao, H. Liu, Y. Lv, J. Liu*. Indoor-outdoor relationship of PM2.5 mass concentrations in severe cold regions based on simulation,

* Corresponding author

[Presentations at academic societies]

1.
2.

[Published books]

1.
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[Other]

   Intellectual property rights, Homepage etc.

5. Research Group

1. Representative Researcher

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2. MingZhou Yu (Professor, China Jiliang University)

3. Ye Xiao (former PhD student, Harbin Institute of Technology)

4. Jianjian Zhao (PhD student, Harbin Institute of Technology)

6．Abstract (half page)

Research Theme：Unsteady Diffusion of Atmospheric Particulate Matter in Cities of Northern China Based on Multiscale Integrated Numerical Simulation

Representative Researcher (Affiliation)：Jing Liu, Ye Xiao and Jianjian Zhao (HIT), Lina Wang (FU), Mingzhou Yu (CJU)

Summary・Figures

This study established the urban local scale particle diffusion model and the indoor-outdoor particle diffusion model for cities in severe cold regions, and investigated the particle diffusion process and concentration distribution in a residential area and between indoor and outdoor environments by simulation. Several conclusions can be drawn from this study:

1)The vehicle emissions and road fugitive dust influenced the near-ground $PM_{2.5}$ mass concentrations significantly, and the $PM_{2.5}$ mass concentrations in canopy gradually decreases from the ground as the increase of the height, but the vertical distribution gradient varied at different time to some degree due to the time changes of traffic flow.

2)With the change of outdoor $PM_{2.5}$ mass concentrations, there is time lag for indoor concentrations in conditions of complete infiltration. For the relationship between indoor and outdoor $PM_{2.5}$ mass concentrations on different floors in buildings, the results showed that the daily average I/O ratios increased as the increase of floor height.

3)Indoor particle sources can significantly increase the indoor $PM_{2.5}$ mass concentrations, and the increase of indoor source emission durations and the enhancement of emission intensity can both exacerbate that influence. Opening windows after indoor source emission can effectively accelerate the decay of the indoor $PM_{2.5}$ concentrations, and increasing the window opening areas and window opening durations can better promote the concentration decay but could not shorten the effect lasting time significantly.