Study on Influencing Mechanism of Outdoor Plant-related Particles on Indoor Environment and its Control Measures during Transitional Period in Nanjing

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ABSTRACT

Most city trees in Nanjing are *Platanus acerifolia* and *Populus nigra*, which generate many whirling willow catkins in the air during the transitional season, yet little attention has been paid to the health risks, including itchy skin and respiratory infections, on occupants of roadside buildings. Since the air quality of these indoor spaces cannot meet WHO guidelines during the transitional season due to the influence of plant pollutants, a suitable ventilation scheme, together with air filtration measures, is urgently needed. Hence, four ventilation schemes were compared: natural ventilation, no ventilation with the door and windows closed, recirculating ventilation with a ceiling cassette fan-coil unit but no air filter, and recirculating ventilation with a ceiling cassette fan-coil unit and F7 filter. The performance of these modes was evaluated by comparing the effects of outdoor particulate matter on the indoor air quality. The results showed that the larger the particle size, the lower the I/O ratio. Furthermore, the influence of the occupants' activities on indoor particle concentrations cannot be ignored, particularly for large particles, which varied more than small particles according to indoor human activity. Therefore, we suggest operating the ceiling cassette fan-coil unit with an air filter for this application, which can reduce the indoor particle concentration to an acceptable level and decrease the potential health risk posed by plant pollutants.

Keywords: Plant pollutants; Transitional season; Infiltration air; Ventilation modes; Indoor air quality.

INTRODUCTION

It is estimated that city people spend 90% of their time indoors (Klepeis *et al.*, 2001), and occupants usually spend most of the time on working (McCreddin *et al.*, 2013). The life expectancy is estimated to be reduced by 8.6 months per person on average by air pollution such as particulate matter (PM) in EU (WHO, 2013). In 2015, an estimated death of 4.2 million people was caused by exposure to PM_{2.5}, which accounted for 7.6% of the global death rate. Meanwhile, it resulted in disability-adjusted life-years for about 103.1 million people (Cohen *et al.*, 2017).

The working performance was found to be closely related to indoor environment (Fanger, 2010). When there is no strong indoor pollutant source, the sub-micron particle

concentration inside an office building is closely related to the outdoor concentration (Koponen *et al.*, 2001). When the infiltration of PM_{2.5} through the building envelope was studied, it was found that the influence of ambient PM_{2.5} on indoor particle concentration was large for the room with small air change rate (Choi and Kang, 2017). Table 1 illustrates the recent studies on the impact of outdoor PM on the indoor environment.

Outdoor PM_{2.5} concentration has a seasonal variation characteristic in Nanjing (Shao *et al.*, 2017). Although outdoor PM_{2.5} is mainly generated by traffic (Quang *et al.*, 2013), a series of new problems may be caused by planting the inappropriate species of city tree (Willis and Petrokofsky, 2017). In Nanjing, a large number of *Platanus acerifolia* were planted as roadside trees, which would bring shade to the city in summer but also produce a lot of problems at the same time. The seed ball of *Platanus acerifolia* is released with numerous stiff hairs and pollen in the period between April and June each year, which are usually dispersed with the aid of wind (Ruiz and Morales, 2008). Menzel *et al.* (2017) have studied the pollution from pollen in April, and they suggested the countermeasures to this problem. Qiao (1986) scanned the fruit hair of *Platanus*

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Table 1. Literatures on experimental studies of indoor environment in different seasons with ventilation modes.

Reference	Time	Area or volume	Sampling points	Duration	Conclusions
Rim <i>et al.</i> (2017)	Winter	60.8–133 m ³	One outdoors, one indoors	48 h field measurements	Window opening is the main reason for the increase of indoor Particle concentration during the occupied period in urban nurseries.
Se <i>et al.</i> (2016)	Winter of 2013–2014	241 m ³	Two indoors, two outdoors.	2-week periods	Fine filter can be used to reduce the PM exposure rate caused by traffic.
Bhangar <i>et al.</i> (2016)	Jun. 17–21, 2013	30 m ³	One outdoors, one indoors	3.6 days	The main reason of increased I/O ratio in NICU is occupants' activities.
Agarwal and Shiva Nagendra (2016)	June 2015	37.9–44.35 m ²	One indoors	2 days	PM ₁₀ mass concentration decreases with the increase of the height.
Zhao <i>et al.</i> (2015)	Dec. 2013–Feb. 2014	30 m ²	One outdoors, one indoors	3 months	Indoor PM _{2.5} concentration has a positive correlation with outdoor value. PM _{2.5} is also closely related to air velocity and humidity.
Chatoutsidou <i>et al.</i> (2015)	June 2014	40–56 m ³	One outdoors, one indoors	Jun. 2 and 10, 2014 in office A, Jun. 13, 2014 in office B	Outdoor and indoor PM sources have a strong influence on indoor PM ₁₀ concentrations.
Tran <i>et al.</i> (2014)	May 13–July 1, 2009	181–234 m ³	One outdoors, one indoors	Two consecutive weeks	Students' activities have a greater influence on resuspension of 2–10 µm particles than particles less than 2µm.
Oh <i>et al.</i> (2014)	Jun. 29, 2013–Feb. 21, 2014	19.8–115.7 m ²	Two Indoors	Five consecutive days	Air purifier can be used to remove particles and bio-aerosols efficiently in childcare centers of Korea.

acerifolia and found that the minimum length of the fruit hair was 14–50 μm and the thickness of fruit hair was about 4.3 μm . It is hard and brittle, so it is easily broken to produce PM_{10} (Qiao, 1986; Cao et al., 2008). Since the average diameter of human skin pores is 0.26–0.3 mm, the fruit hair is likely to go through these pores when it falls onto the human skin, which will cause human skin itching and other uncomfortable effects (Cao et al., 2008). The seeds can even spread a few kilometers away under the wind condition (Nathan et al., 2002). Fruit hair will be ruptured repeatedly after landing onto the ground due to the mechanical force. It will produce inhalable $\text{PM}_{2.5}$ and PM_{10} , which may cause asthma and allergy easily (Zhang et al., 2009). Study has also shown that whirling willow catkins can cause respiratory disease, and shorten the visibility distance of pedestrians. Willow catkins are flammable substances, so they are easily caught fire. Meanwhile, whirling willow catkins will affect the accuracy of some high-precision instruments (Tang et al., 2014).

Using appropriate ventilation modes can reduce exposure to outdoor PM and improve air quality in residential buildings (Liddament, 2000). Natural ventilation is usually encouraged by existing standard in the transitional season in the hot summer and cold winter zone in China (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2012). However, when outdoor pollutant level is quite high, some occupants prefer to close the doors and windows in order to keep from the outdoor pollutants. The building envelope will act as a particulate air filter. The characteristic of infiltration air through the envelope is controlled by particle size and architectural feature (Stephens and Siegel, 2012). Gao and Zhang (2015) found that particles with size 0.05–1 μm can penetrate through the door gap easily. However, so far little attention has been paid to the influence of both the outdoor PM by plant pollutant and the ventilation mode on indoor air quality in transitional season. Therefore, both theoretical and experimental study will be carried out, where special attention will be paid to the influence of PM from plant pollutant.

MATERIALS AND METHODS

Site Characteristics

Experiment was performed in a building in the Hongqiao campus of Nanjing Tech University, which is shown in Fig. 1. There is a main street which is 200 m away to the west of the building. Two one-way streets are 5 m away to the south from the building, respectively. *Platanus acerifolia* are planted as the roadside trees on these roads. There is a river which is 20 m to east of the building, where *Populus nigra* are planted near the river. It is shown that when the floor height is increased from 2 m to 79 m, PM_{10} , $\text{PM}_{2.5}$ and $\text{PM}_{1.0}$ concentrations caused by traffic can be reduced by 60%, 62% and 80%, respectively (Wu et al., 2002). Offices on the seventh floor were chosen as the experimental site in order to reduce the influence by the traffic. The heights of each floor is 3.5 m. The experiment office is 21 m above the ground.

Experiments were conducted in May 2017. The room size was 12.6 m (L) $\times$ 5.78 m (W) $\times$ 3.2 m (H). One ceiling cassette fan-coil unit (CCFU) with the type Gree KFR-120TW/(1251S) Ba-2 was installed in the room. There was no dedicated outdoor air system. For the CCFU, it has a return air grille and four air outlets. The angle between the air supply blades and the ceiling is 60°. In the actual experiment, the maximum air volume is only used with the ventilation mode.

Design of Experimental Scheme

The experiment was conducted in two adjacent rooms with the same structure. The experimental conditions are shown in Table 2.

The experiment with occupied status was conducted during the working hours. The experiments were conducted in two periods including 9:00–11:30 a.m. and 13:30–17:00 p.m. F7 filter (equivalent to MERV 13 filter according to ASHRAE Standard 52.2) was applied in this experiment, which had average filtration efficiency larger than 90% for 0.4 μm particles according to EN 779–2012. It should be

Fig. 1. Schematic diagram of the experimental building.

Table 2. Experimental conditions.

Experiment ID	Windows and doors	Air conditioning	Occupied status	Experiment time
R1-A1-1	Open	Closed	unoccupied	May 1
R1-A1-2	Open	Closed	occupied	May 2
R1-A2-1	Closed	Closed	unoccupied	May 21
R1-A2-2	Closed	Closed	occupied	May 6
R1-A3-1	Closed	F7 filter	unoccupied	May 17
R1-A3-2	Closed	F7 filter	occupied	May 13
R1-A4-1	Closed	no filter	unoccupied	May 16
R1-A4-2	Closed	no filter	occupied	May 14

noted that the fan has been turned on to stir the indoor air under the R1-A2-1 condition (R1 represents Room 1, and A2 represents the working condition of closing the doors and windows without ventilation). It was meant to make indoor particle concentration evenly distributed.

Room Size and Measuring Points

The locations of measurement points are shown in Fig. 2. They were 1.2 m above the floor, where it corresponds to the breathing height of the sitting people. According to GB50325-2010 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2014), two sampling points should be set in a room with area between 50 m² and 100 m². Since the room area was 72.8 m², two indoor sampling points and one outdoor sampling point were set.

Fig. 2. Schematic diagram of the measuring points.

Measurement Instruments

Agilent 34972A was used to collect data, such as temperature, humidity, air velocity and particle mass concentration. Micro manometer and air capture hood were used for test air flow rate. The nephelometer TSI 8530 was mainly used to test the gravimetric concentration of particles. It was used to validate the accuracy of the particle mass concentration measurement instrument PMS5003. PM_{2.5} and PM₁₀ concentrations were obtained by PMS5003. CLJ-3016L was used for particle number concentration. The ranges for the particle size were 0.3–0.5 μm, 0.5–1 μm, 1–3 μm, 3–5 μm, 5–10 μm and > 10 μm, respectively. The measurement instruments are shown in Table 3.

Air Change Rate (ACR) of Infiltration Air and PM Penetration Factor

The ACR of infiltration air can be measured by monitoring the decay process of the indoor CO₂ concentration. Firstly, both the door and the windows were closed. Secondly, CO₂ was released into the room. Thirdly, the fan was turned on to stir the indoor air. When the difference of indoor CO₂ concentration between the sampling points were less than 1%, the indoor CO₂ concentration can be determined to be uniformly distributed. Fourthly, the indoor CO₂ concentration was recorded. The test conditions for infiltration air have been shown in Table 4.

THEORETICAL ANALYSIS

Lumped Parameter Method for Decay Rate of Particle Concentration

In this study, there was neither indoor particle source nor outdoor air supply. Outdoor air infiltrated into the room through cracks and gaps on the building envelope, as well as the openings around door and windows. The indoor particle balance model can be established according to the mass balance equation (Nazaroff, 2004). The schematic diagram of the indoor particle balance model is shown in Fig. 3. The indoor particle balance equation is defined as Eq. (1):

$$\frac{dC_i}{dt} = C_0 \lambda_L P - C_i (\beta + \lambda_L) - \lambda_F (C_{in} - C_{out}) \quad (1)$$

where C_i is the instantaneous concentration of indoor particle, pc m⁻³; t is the decay time, h; C_0 is the outdoor particle concentration, pc m⁻³; λ_L is the ACR of infiltration air, h⁻¹; P is the PM penetration factor; β is the deposition

Table 3. Measurement instruments.

Parameters	Unit	Type	Accuracy	Range	Applicability
Temperature	°C	DHT11	± 0.5°C	–40–80°C	Ambient temperature
Humidity	%RH	DHT11	± 2%RH	0–100%	Ambient humidity
Velocity	m s ^{–1}	QS-FS	± 0.3 m s ^{–1}	0–32.4 m s ^{–1}	Ambient air velocity
Velocity	m s ^{–1}	TSI 8475-300-1	± 3% F.S.	0–0.5 m s ^{–1}	Air velocity through door gap
Temperature	°C	OMEGA TT-T-36	± 0.5°C	0–100°C	Temperature trough door gap
Particle number concentration	pc/2.83L	CLJ-3016L	± 3%F.S.	10 ² –3 × 10 ⁵ pc/2.83L	Indoor & outdoor particle number concentration
Particle mass concentration	μg m ^{–3}	PMS5003	± 2%	0–500 μg m ^{–3}	Indoor & outdoor particle mass concentration
CO ₂ concentration	PPM	TSI 7575-X	± 3%	0–5000 PPM	Indoor & outdoor CO ₂ concentration
Air flow rate	m ³ h ^{–1}	FLY-1	± 5% F.S.	100–3500 m ³ h ^{–1}	Flow rate through CCFU

Table 4. Test conditions for ACR of infiltration air and PM penetration factor.

Exp. ID	Door and window	Air conditioning	Occupied status	Period	Indoor Temperature (°C)	Indoor Humidity (%)
R1-B1-1	closed	closed	unoccupied	3 h	28.8 ± 0.4	65 ± 7
R1-B1-2	closed	F7filter	unoccupied	3 h	29.1 ± 0.4	71 ± 2
R1-B1-3	closed	No filter	unoccupied	3 h	28.0 ± 0.9	70 ± 8

Fig. 3. Schematic diagram of the indoor particle balance model.

rate of particles, h^{–1}; λ_F is the ACR through the CCFU, h^{–1}; C_{in} is particle concentration at the inlet of CCFU, pc m^{–3}; C_{out} is particle concentration at the outlet of CCFU, pc m^{–3}; dC_i/dt means the variation of indoor particle concentration; C_oλ_LP means the total number of outdoor PM penetrating indoors; C_i(β + λ_L) + λ_F(C_{in} – C_{out}) means the total number of PM loss indoors.

Test on ACR of Infiltration Air

The ACR of infiltration air into the room was tested by measuring the decay rate of CO₂ concentration (Cui *et al.*, 2015). According to the indoor CO₂ mass balance equation, the variation model of indoor CO₂ concentration can be established, which is defined in Eq. (2):

$$\frac{dC_t}{dt} + \lambda_L [C_t - C_{bg}] = 0 \quad (2)$$

where C_t is instantaneous indoor CO₂ concentration, PPM; t is decay time, h; C_{bg} is outdoor CO₂ concentration, PPM;

λ_L is the ACR of the infiltration air, h^{–1}; dC_t/dt is the variation of indoor CO₂ concentration; λ_L(C_t – C_{bg}) means total CO₂ loss indoors.

Based on Eq. (2), Eq. (3) can be derived:

$$\lambda_L = \frac{1}{\Delta t} [\ln(C_a - C_{bg}) - \ln(C_f - C_{bg})] \quad (3)$$

where Δt is the decay time, h; C_a is the initial indoor CO₂ concentration, PPM; C_f is the final indoor CO₂ concentration, PPM.

I/O Particle Concentration Ratio

Given the fact that both indoor and outdoor particle concentrations will change with time, the average values were obtained by multiple measurements of indoor and outdoor particle concentrations (Challoner and Gill, 2014). Then I/O ratio can be expressed with Eq. (4):

$$\frac{I}{O} = \left(\frac{\sum_{i=1}^n C_{indoor}}{n} \right) \div \left(\frac{\sum_{i=1}^n C_{outdoor}}{n} \right) \quad (4)$$

where C_{indoor} is indoor particle concentration in one time step; C_{outdoor} is outdoor particle concentration in one time step; n is the number of time steps.

Particle Deposition Rate

The deposition rates of particles with different sizes are shown in Table 5 (Feng *et al.*, 2017). The deposition rates of PM_{2.5} and PM₁₀ are 0.4 h^{–1} and 1.0 h^{–1}, respectively (Xie *et al.*, 2013).

Table 5. Deposition rate of particle with different sizes (Feng et al., 2017).

Particle size range (μm)	Deposition rate β (h^{-1})
0.3–0.5	3.484×10^{-3}
0.5–0.7	0.029
0.7–1.0	0.0851
1.0–2.0	0.336
2.0–5.0	1.664

Measurement of PM Penetration Factor

After all the windows and the door were closed, CCFU with F7 filter installed was turned on for 3 hours. When the indoor particle concentration reached the minimum, CCFU was turned off. The indoor particle concentration was increased until it reached stable I/O equilibrium status. The indoor particle balance equation can be expressed with Eq. (5):

$$\frac{dC_i}{dt} = C_0 \lambda_L P - C_i (\beta + \lambda_L) \quad (5)$$

When the indoor particle concentration reached stable, i.e., $dC_i/dt = 0$, the formula can be simplified as Eq. (6). The detailed error analysis can be found in Appendix A as supplementary material.

$$P = \frac{I}{O} \left(\frac{\beta}{\lambda_L} + 1 \right) \quad (6)$$

RESULTS AND DISCUSSION

Outdoor Particle Mass Concentration

Long-time Monitoring

Outdoor $\text{PM}_{2.5}$ and PM_{10} concentrations, ambient

temperature, humidity and air velocity were monitored on 14 days in May of 2017. Results from Fig. 4 show that the daily mean concentrations of PM_{10} on about 6 monitoring days exceeded the limit set by WHO guidelines, while these of $\text{PM}_{2.5}$ on only 4 monitoring days were within the limit value. Considering the health effect on occupants, it is necessary to take measures of air filtration in transitional season. In the experiment, the range of daily average temperature in 14 monitoring days was 18.7–34.0°C. There were only 2 days when ambient temperature was above 30°C. In this case, there was no need for refrigeration cycle. The range of average relative humidity in 14 monitoring days was about 23–75%. The outdoor air velocity fluctuated between 0.6 m s^{-1} and 1.5 m s^{-1} .

Continuous Monitoring of Particle Concentration on One Day

Fig. 5 shows the variation of parameters of ambient air with time on May 22. Particle concentration reached the highest value in the morning, and it fluctuated with time in 1 day. PM_{10} concentration at 9:00–11:30 a.m. was higher than the limit value specified by WHO guidelines. At 2:00–5:00 p.m. during the working time, PM_{10} concentration fluctuated near the limit value from WHO guideline. However, PM_{10} concentration after 5:00 p.m. was within the limit of WHO guideline. $\text{PM}_{2.5}$ concentrations between 8:00 and 9:00 p.m. were higher than the WHO guideline value. The temperature fluctuated within the range of 24–32°C and the air velocity was kept in the range of 0–2 m s^{-1} on this day. The fluctuation characteristic of relative humidity was similar to that of particle concentration. The highest humidity appeared in the morning, while the lower relative humidity occurred in the afternoon. Considering the variation feature of the particle mass concentration in one day, it is recommended that the indoor air filtration measures should be taken in the morning in order to protect occupants' health.

Fig. 4. Sampled outdoor particle concentrations in May of 2017.

Fig. 5. Variation of outdoor particle concentration with time on May 22.

Test of ACR and Penetration Factor

ACR of Recirculating Air

Air capture hood was used to measure the airflow rate of CCFU. Fig. 6(a) shows ACR of recirculating air through CCFU. For the situation of R1-B1-1, CCFU was closed so that ACR of recirculating air was zero. Compared with the situation of R1-B1-3 (CCFU without air filter), the ACR of recirculating air through the CCFU for the situation of R1-B1-2 (with F7 filter installed) was decreased by about 54.00%.

ACR of Infiltration Air and Penetration Factor

ACR of infiltration air is shown in Fig. 6(b). It is suggested in the relevant standard that the ACR in office should be 1.5 h^{-1} at least (Lu, 2008). The ACR of infiltration air was enough to meet the demand for outdoor air. The penetration factor can be calculated from Eq. (6). Chao et al. (2003), Long et al. (2001), Thatcher et al. (2003), Vette et al. (2001) and Zhu et al. (2005) have also performed tests on the penetration factor. Chen et al. (2011) have summarized the penetration factor in the literature. The values of penetration factors for $0.3\text{--}10 \mu\text{m}$ particles were chosen to compare with our results. Comparative results in Fig. 7 show that particle penetration factor of our study was similar to those measured in other literatures. The measured results were as follows: The penetration factors for particles with diameter $0.3\text{--}0.5 \mu\text{m}$, $0.5\text{--}1.0 \mu\text{m}$, $1.0\text{--}3.0 \mu\text{m}$, $3.0\text{--}5.0 \mu\text{m}$ and $5.0\text{--}10.0 \mu\text{m}$ were 0.78, 0.74, 0.51, 0.38 and 0.28, respectively.

From Eq. (6), it is known that the particle penetration factor is influenced by the pressure difference between indoors and outdoors, the size of the door gap, the surface roughness of the door gap, and the temperature difference.

The larger the particle size is, the smaller the particle penetration factor is. For larger particles, the particle penetration factor is relatively smaller because of the influence of gravitational deposition.

Indoor and Outdoor Plant-related Particle Sedimentation

Cao et al. (2008) applied the electron microscope to amplify the fiber-like pollutants, the details of which are shown in Fig. 8. Moreover, except for the influence of *Platanus acerifolia* in the transitional season, there is also cross-contamination of whirling willow catkins, which is shown in Fig. 9.

The atmospheric conditions with and without plant pollutants are compared to investigate the influence of the plant pollutant from ambient air on the indoor air quality. The experimental procedures are as follows: Under different experimental conditions, two petri dishes were placed in the indoor and outdoor areas to settle the particles in the air, and the settling time was 3 hours. The plates were magnified by 50 times under a stereo microscope. Ten pictures were randomly taken on each petri dish to count the number of contaminants in the petri dish and the contamination of the plants. The number of objects is taken as the concentration of plant contaminants in the petri dish. Plant pollutants are counted only by number, regardless of size.

Part of the sedimentation photos is shown in Fig. 10. The deposition morphology of both the seed of *Populus nigra* and fibrous contaminant caused by fruit hair can be clearly seen. The fibrous sediments are the fruit hairs of *Platanus acerifolia*, and the spider-like sediments are the flocks of *Populus nigra*.

Fig. 11 shows the average count of indoor and outdoor particles in the area of 4.92 mm^2 . It can be seen from the

Fig. 6. Characteristics of ACRs of recirculating air and infiltration air indoors. (a) ACR of recirculating air; (b) ACR of infiltration air.

Fig. 7. Comparison on penetration factors between this study and others.

figure that the number of outdoor particles ranges from 20 to 40 particles in the area of 4.92 mm^2 . Particularly, the number of particles from plant pollutants accounts for about 2–10% of total number. From Fig. 12, it can be seen that the number of particles under natural ventilation conditions is the highest. Compared with the internal circulation conditions with CCFU alone, the concentration of indoor particles decreases by approximately 18.21% under the conditions of CCFU with air filters. Moreover, with the above-mentioned experimental procedures, the proportion of plant particles indoors could be decreased by approximately 69.56%. It can be seen that installing air filters in CCFU

can effectively reduce the concentration of indoor plant-related particles.

Indoor Particle Concentration Particle Mass Concentration

Descriptive statistics of indoor particle mass concentrations under different ventilation strategies are shown in Table 6. It was found that the mean value and the standard deviation were not enough to describe the indoor particle concentration. This was because the indoor particle concentration varied with outdoor concentration. Therefore, coefficient of variation (CV) was used to describe the

Fig. 8. The morphology of fruit hair of *Platanus acerifolia* and its enlarged component (Cao et al., 2008).

Fig. 9. Schematics of willow catkins from *Populus nigra* on working table.

Fig. 10. The picture of indoor deposited air pollutants taken by stereo microscope.

fluctuation characteristic of particle concentration, which means the ratio of the standard deviation to the mean value and acts as a measure of relative variability for the particle concentration. It was found that CV in occupied condition was larger than that of unoccupied condition. This was because there was occupants' activity indoors which resuspended the indoor deposited particles. It is clear that the operation of CCFU with F7 filter installed would reduce indoor $PM_{2.5}$ and PM_{10} concentrations. When CCFU with F7 filter was applied, both the indoor $PM_{2.5}$ and PM_{10} concentrations could meet the requirement of WHO guidelines. Compared with the condition of operating CCFU without air filter, the I/O value is statistically significantly different under the condition of operating CCFU with F7 filter by application of *t*-test. This means that installation of F7 filter in CCFU could significantly improve indoor air quality.

Particle Number Concentration

Descriptive statistics of indoor particle number concentrations under different ventilation strategies are shown in Table 7. It can be seen that the CV in occupied condition was larger than that in unoccupied condition. The larger the particle size was, the higher the CV value was. This was because occupants' activities had larger influence on large particle than that for small particle. The CV of outdoor particle concentration remained stable at a low level in all experiments. For indoor particles, it is shown that CV of indoor small particle concentration was similar to that of outdoor small particle concentration. However, CVs of large particles with diameter 3.0–5.0 μm and 5.0–10.0 μm between indoors and outdoors had opposite trend. This was due to the fact that small particle with diameter 0.3–0.5 μm and 0.5–1.0 μm had larger penetration factor, so indoor particle concentrations with diameter 0.3–0.5 μm and 0.5–1.0 μm were easily dominated by outdoor

Fig. 11. The counting concentration of indoor and outdoor botanic particles.

Fig. 12. The ratio of the plant-related particles to the total particles.

value. However, large particle with diameter 3.0–5.0 μm and 5.0–10.0 μm had lower penetration factor, so occupants' activities would exert more important influence on concentration of large particles.

I/O Ratio

Effect of Different Conditions on I/O Ratio

It is shown from Fig. 13 that under R1-A3 and R1-A4 conditions, $\text{PM}_{2.5}$ I/O ratio of occupied condition was larger than that of unoccupied condition by 10.34% and 33.76%, respectively. While for PM_{10} , the corresponding I/O ratios were increased by 19.68% and 40.63%, respectively.

However, for R1-A2 situation, $\text{PM}_{2.5}$ and PM_{10} concentrations in occupied condition were smaller than that in unoccupied condition by 0.21% and 2.87%, respectively. Challoner and Gill (2014) obtained the similar conclusion with this experiment in Site N₅, where the I/O ratio under unoccupied condition was larger than that under occupied condition. In this paper, I/O ratio under unoccupied condition was larger for R1-A2 situation, which was owing to the operation of indoor fan before the experiment. For the R1-A1 situation, $\text{PM}_{2.5}$ and PM_{10} I/O ratios under the occupied condition were less than that under unoccupied condition by 5.68% and 12.22%, respectively. While for R1-A2 situation

Table 6. Descriptive statistics of indoor particle mass concentrations under different ventilation strategies.

		Mean	St. Dev.	CV	Geo. Mean	Median	Percentile 5.0	Percentile 95.0
Indoor								
R1-A1-1	PM _{2.5}	30.57	0.98	0.03	30.55	30.24	28.98	32.13
	PM ₁₀	49.95	2.08	0.04	49.91	49.80	46.64	52.96
R1-A1-2	PM _{2.5}	26.85	6.71	0.25	26.22	25.20	21.42	39.69
	PM ₁₀	41.27	8.90	0.22	40.47	38.73	32.41	55.33
R1-A2-1	PM _{2.5}	31.43	0.91	0.03	31.42	31.21	29.94	33.13
	PM ₁₀	52.21	2.11	0.04	52.17	52.65	48.60	55.89
R1-A2-2	PM _{2.5}	39.49	5.32	0.13	39.18	38.43	34.02	47.88
	PM ₁₀	64.03	6.06	0.09	63.79	63.07	58.49	72.72
R1-A3-1	PM _{2.5}	17.63	1.56	0.09	17.56	17.64	15.12	20.16
	PM ₁₀	24.95	2.92	0.12	24.79	24.50	21.34	30.04
R1-A3-2	PM _{2.5}	13.05	1.80	0.14	12.93	12.60	10.71	17.01
	PM ₁₀	18.36	2.74	0.15	18.17	17.39	15.02	23.71
R1-A4-1	PM _{2.5}	15.99	1.26	0.08	15.94	15.93	14.01	18.47
	PM ₁₀	22.39	1.98	0.09	22.31	21.87	19.44	25.92
R1-A4-2	PM _{2.5}	20.05	2.07	0.10	19.94	20.16	17.01	23.56
	PM ₁₀	30.33	4.52	0.15	30.00	30.04	23.71	38.41
Outdoor								
R1-A1-1	PM _{2.5}	32.63	3.09	0.09	32.50	31.31	29.31	38.64
	PM ₁₀	53.50	4.78	0.09	53.30	52.61	47.44	62.10
R1-A1-2	PM _{2.5}	30.17	1.15	0.04	30.14	29.98	27.98	31.98
	PM ₁₀	49.51	2.36	0.05	49.45	50.03	44.85	52.61
R1-A2-1	PM _{2.5}	30.34	1.70	0.06	30.29	30.49	27.84	33.14
	PM ₁₀	50.90	3.28	0.06	50.79	50.88	46.57	56.92
R1-A2-2	PM _{2.5}	38.24	2.23	0.06	38.18	38.30	34.64	41.97
	PM ₁₀	64.08	2.46	0.04	64.04	63.83	60.38	68.14
R1-A3-1	PM _{2.5}	26.56	1.22	0.05	26.53	26.65	24.65	28.64
	PM ₁₀	42.61	2.08	0.05	42.55	42.26	38.81	45.71
R1-A3-2	PM _{2.5}	17.65	1.11	0.06	17.62	17.95	15.99	19.32
	PM ₁₀	25.26	2.06	0.08	25.18	25.01	22.43	28.46
R1-A4-1	PM _{2.5}	26.18	5.75	0.22	25.67	24.52	19.88	35.13
	PM ₁₀	41.66	9.28	0.22	40.73	39.67	29.75	55.19
R1-A4-2	PM _{2.5}	20.85	2.10	0.10	20.75	20.65	17.32	24.65
	PM ₁₀	31.95	4.54	0.14	31.63	31.05	25.88	39.68

where the window and the door were closed and CCFU was turned off, the I/O ratios were larger than that under R1-A1 condition.

Fig. 14 illustrates the variation of indoor and outdoor particle concentrations under occupied and unoccupied conditions. The fluctuation of particle concentration under occupied condition was relatively large. Average indoor PM_{2.5} concentration was lower than outdoor value. Indoor particle concentration under unoccupied condition remained more stable. In 1 hour, the indoor particle concentration became almost the same as the outdoor value. Tran *et al.* (2014) found that the particle mass concentration of indoor PM₁₀ varied a lot due to occupants' activities, whereas the outdoor PM₁₀ mass concentration was less variable. Our finding agreed well with their conclusions.

Comparison with Other Studies

Comparison of the I/O ratios with other references is shown in Table 8. The I/O ratio with natural ventilation was between I/O ratios of smoking and non-smoking rooms in research from Horemans and Van Grieken (2010). With no ventilation condition, the measured I/O ratio in this study

was larger than those obtained from Zhao *et al.* (2015) and Challoner and Gill (2014). Part of the reason may be related to the operation of fan before the experiment. With mechanical ventilation, I/O ratio measured in this study was similar to the value measured by Kuo and Shen (2010) during the period of dust storm. For mechanical ventilation with F7 filter installed in CCFU, the measured I/O ratio value was larger than the value measured by Chatoutsidou *et al.* (2015), but it was similar to the value measured by Challoner and Gill (2014).

Effect of Particle Size on I/O Ratio

I/O ratios for particles with different sizes are presented in Fig. 15. The larger the particle size was, the lower the I/O ratio was. This is applicable to all the scenarios except for the R1-A1-1 condition which is more related to the outdoor concentration. This is due to the fact that small particle has a larger penetration factor which means that indoor small particle is greatly affected by ambient environment. Compared with particles larger than 0.5 μm in the same condition, the I/O ratio for particles in the size

Fig. 13. I/O ratios of $PM_{2.5}$ and PM_{10} under both occupied and unoccupied conditions.

Fig. 14. Indoor and outdoor particle concentrations in R1-A1 situation.

range of 0.3–0.5 μm was larger. The impact of outdoor particle concentration on indoor particle concentrations with size 3.0–5.0 μm and 5.0–10.0 μm was smaller. Gao and Zhang (2015) found that 0.05–1 μm particles were more likely to penetrate through the slit. This agrees with the finding in the current study, where particles with size less than 1 μm were greatly influenced by outdoor particles. For the 3.0–5.0 μm and 5.0–10.0 μm particles, they were affected by the indoor occupants' activities. When I/O ratios in R1-A1-1 and R1-A2-1 conditions were compared, it was found that I/O ratios for particle with diameter 0.3–0.5 μm and 0.5–1.0 μm between R1-A2-1 situation

(infiltration) and R1-A1-1 condition (natural ventilation) are close to each other. This is because the penetration rate through the door gap for particle with diameter 0.3–0.5 μm and 0.5–1.0 μm is very large. However, for particle with diameter 1.0–3.0 μm , 3.0–5.0 μm and 5.0–10.0 μm , the I/O ratio under R1-A1-1 situation (natural ventilation) is slightly larger than that under R1-A2-1 condition (infiltration when windows and doors are closed). This is because the indoor particle concentration in R1-A1-1 situation is more influenced by outdoor concentration. Compared with R1-A4-1 condition, the I/O ratio of R1-A3-1 condition for particles with diameter 0.3–1.0 μm was smaller. This is

Table 7. Statistics of particle number concentrations under different ventilation strategies.

		Particle number (particles L ⁻¹)					Temperature T (°C)	Humidity RH (%)	Air velocity V (m s ⁻¹)
		0.3–0.5 µm	0.5–1.0 µm	1.0–3.0 µm	3.0–5.0 µm	5.0–10.0 µm			
Indoor	R1-A1	Mean	21747.30(49392.08)	1312.56(2385.84)	189.80(371.73)	39.61(64.14)	24.82(26.54)	57.24(41.07)	N.A.
		St. Dev.	5031.43(5632.81)	2939.90(5978.76)	67.80(155.56)	20.09(35.74)	0.37(0.50)	0.81(1.61)	
		CV	0.15(0.09)	0.14(0.12)	0.15(0.30)	0.51(0.56)	0.01(0.02)	0.01(0.04)	
		Min	26527(58395)	19012(41858)	821(1583)	5(24)	24(26)	56(39)	
		Max	50336(80109)	31464(63206)	2044(4324)	137(212)	25(27)	61(43)	
	R1-A2	Mean	128222.80(81309.83)	147588.40(40543.61)	12730.73(1310.93)	142.60(36.91)	24.03(28.67)	61.30(53.37)	
		St. Dev.	3490.61(7538.72)	7648.04(3994.28)	1906.35(465.03)	41.66(35.86)	0.18(0.47)	0.78(0.70)	
		CV	0.03(0.09)	0.05(0.10)	0.15(0.36)	0.29(0.97)	0.01(0.02)	0.01(0.01)	
		Min	122128(71081)	137692(36033)	10503(836)	76(7)	24(28)	59(52)	
		Max	136378(103682)	165496(52267)	17177(2771)	285(159)	25(29)	63(55)	
Indoor	R1-A3	Mean	16624.61(24672.47)	12107.79(15259.02)	712.21(378.18)	20.20(10.19)	27.03(26.02)	59.91(36.02)	
		St. Dev.	2497.78(3607.69)	3104.77(3141.47)	398.12(178.15)	16.74(5.77)	0.16(0.15)	2.65(1.10)	
		CV	0.15(0.15)	0.26(0.21)	0.56(0.47)	0.83(0.57)	0.01(0.01)	0.04(0.03)	
		Min	13970(19425)	9333(10906)	446(151)	4(2)	27(26)	53(33)	
		Max	24511(35456)	22368(25535)	2488(1159)	113(42)	28(27)	64(37)	
	R1-A4	Mean	35471.42(41298.44)	34478.62(22199.30)	2307.30(761.72)	49.71(9.48)	27.13(23.24)	42.87(37.26)	
		St. Dev.	4099.81(1923.84)	6826.15(1952.97)	1379.44(426.48)	64.80(10.61)	0.33(0.62)	1.21(2.64)	
		CV	0.12(0.05)	0.20(0.09)	0.60(0.56)	1.30(1.12)	0.01(0.03)	0.03(0.07)	
		Min	29596(38867)	26323(20291)	1303(395)	14(1)	27(22)	39(33)	
		Max	46026(47635)	51187(27836)	7301(2324)	1651(290)	28(24)	44(43)	
Outdoor	R1-A1	Mean	86040.40(83684.76)	59873.28(68575.56)	2078.33(3087.82)	269.84(699.07)	19.64(28.10)	71.05(31.42)	1.13(1.00)
		St. Dev.	3750.72(15852.63)	4382.69(15445.07)	122.57(926.45)	30.75(259.22)	0.54(1.45)	1.84(5.40)	
		CV	0.04(0.19)	0.07(0.23)	0.06(0.30)	0.11(0.37)	0.03(0.05)	0.03(0.17)	
		Min	76666(66265)	53215(52440)	1811(2046)	206(456)	19(25)	67(25)	
		Max	96086(128358)	72469(111741)	2386(9911)	343(3085)	21(30)	75(41)	
	R1-A2	Mean	134622.90(88568.6)	210837.10(53695.49)	23176.90(1688.30)	4083.08(294.43)	24.26(29.23)	51.35(45.39)	0.72(1.20)
		St. Dev.	6787.42(8622.60)	9573.66(3801.84)	1577.15(198.85)	252.31(44.67)	0.50(0.79)	1.25(3.16)	
		CV	0.05(0.10)	0.05(0.07)	0.07(0.12)	0.06(0.15)	0.02(0.03)	0.02(0.07)	
		Min	117824(79659)	186407(47309)	21220(1326)	3695(211)	23(27)	49(41)	
		Max	143462(112795)	225045(63751)	27736(2204)	4819(437)	25(30)	54(52)	
Outdoor	R1-A3	Mean	25891.93(56861.74)	22517.85(47168.96)	2206.06(2269.94)	450.99(484.97)	31.12(24.86)	43.60(33.20)	0.87(0.69)
		St. Dev.	847.43(2696.77)	1170.57(2673.63)	140.94(137.80)	42.46(44.66)	0.34(0.86)	1.74(1.10)	
		CV	0.03(0.05)	0.05(0.06)	0.06(0.06)	0.09(0.09)	0.01(0.03)	0.04(0.03)	
		Min	23926(51704)	20642(41715)	1931(1987)	382(382)	30(24)	40(30)	
		Max	32733(61903)	28204(58405)	2598(2820)	705(657)	32(27)	47(35)	
	R1-A4	Mean	43028.81(47859.13)	46309.21(47858.84)	6052.74(2705.05)	1316.07(574.49)	26.96(23.24)	33.22(37.26)	1.50(0.61)
		St. Dev.	4339.28(17361.89)	4503.60(14403.96)	312.01(181.84)	65.92(23.10)	0.81(0.62)	1.09(2.64)	
		CV	0.10(0.36)	0.10(0.30)	0.05(0.07)	0.12(0.12)	0.03(0.03)	0.03(0.07)	
		Min	35617(28418)	39943(29074)	5105(2292)	810(457)	26(22)	31(33)	
		Max	53736(134694)	57341(136385)	6753(3187)	1606(791)	29(24)	36(43)	

Note: The number in parentheses denoted that the room was obtained under unoccupied condition with the same condition.

Fig. 15. Effect of particle size on I/O Ratio.

due to the air filter that was applied under R1-A3-1 condition. When I/O ratios in R1-A2-1 and R1-A4-1 were compared, it was found that I/O ratios for particles with size 0.3–10 μm can be reduced by operation of CCFU. Compared with R1-A4-1 situation, the operation of CCFU with F7 filter in R1-A3-1 situation can be used to efficiently decrease the I/O ratios for particles examined in this study, especially those with size 0.3–3.0 μm .

CONCLUSIONS

- (1) The percentage of plant-related particles in the outdoor air can reach 2–10% during the transitional season in Nanjing. It is necessary to consider corresponding air filtration measures indoors due to the risk of allergenicity.
- (2) During the one continuously monitored day, the outdoor particle concentration reached its maximum in the morning, which means that indoor air filtration should be conducted accordingly.
- (3) In the scenario with infiltration, the studied room achieved the air change rate specified in the standard. The penetration factors of particles sized 0.3–0.5 μm , 0.5–1.0 μm , 1.0–3.0 μm , 3.0–5.0 μm and 5.0–10.0 μm were 0.78, 0.74, 0.51, 0.38 and 0.28, respectively.
- (4) The variation in the indoor particle concentration (expressed as the CV value) was larger when the room was occupied. The I/O ratio decreased as the particle size increased, and the indoor concentration was strongly affected by fluctuations in the outdoor concentration for particles smaller than 1 μm . By contrast, the indoor concentration of larger particles (3.0–10 μm) was more significantly impacted by occupant activity.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

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