VERTICAL CONCENTRATION DISTRIBUTIONS OF ATMOSPHERIC PARTICULATES IN TYPICAL SEASONS OF WINTER AND SUMMER DURING WORKING AND NON-WORKING DAYS
A Case Study of High-Rise Buildings

by

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It is important to understand the vertical distribution characteristics of outdoor particulates concentration in typical seasons of winter and summer when people's living spaces are getting higher and higher above the ground. The different heights of floors (1st, 7th, 11th, 17th, and 27th) of a high-rise building in Xi'an at 8:00 a. m., 12:00 a. m., 3:00 p. m., 6:00 p. m., and 10:00 p. m., respectively, were tested and analyzed in this paper. The results showed that the concentrations on non-working days were much lower than that on working days at different times and on different floors, and the concentrations of particulates were relatively low in summer. The particulates reached the highest at 12:00 a. m. in summer, with the average concentrations of PM_{10}, $PM_{2.5}$, *and* $PM_{1.0}$ *were 37.3 μg/m*^{3}*, 31.6 μg/m*^{3}*, and 29.4 μg/m*^{3}*. While reached the highest at 3:00 p. m. in winter, with the average concentrations of* PM_{10}, $PM_{2.5}$, *and* $PM_{1.0}$ *were 82.4 μg/m*^{3}*, 64.8 μg/m*^{3}*, and 57.7 μg/m*^{3}*. The distribution of atmospheric environment in Xi'an is mainly dominated by small particulates. The particle sizes of low floors are mainly range from 1.0 μm to 2.5 μm, and the high floors are less than 1.0 μm. With the increase of floors and time,* $PM_{1.0}/PM_{2.5}$ *and* $PM_{2.5}/PM_{10}$ *show a trend of first decreasing and then increasing on working days, while* $PM_{1.0}/PM_{2.5}$ *and* $PM_{2.5}/PM_{10}$ *show a trend of first increasing, then decreasing and next increasing on non-working days. In addition, outdoor meteorological parameters will also have a certain impact on particulates concentration distribution. It provides reference values for controlling the particulates concentration in high-rise buildings.*

Key words: *high rise buildings, winter and summer, vertical distribution, working and non-working days, particulates*

Introduction

In recent years, the number of high-rise and super high-rise buildings has gradually increased, which make people's living space had been more extensive. People can work and live at a height of 40 m or more higher height from the ground [1-3]. However, high concentrations of particulates in the environment not only cause inconvenience to daily travel, but also cause

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various diseases in the human body [4, 5], or death [6]. Many people spend 80-90% of their time indoors [7], and good indoor living environment are particularly important, especially for living in high-rise environments.

At present, people have conducted relevant research on the concentration of particulates in the atmospheric environment [8-13]. Mainly focused on the distribution characteristics of particulates [8, 9], correlation with related pollutants [10, 11], comparison before and after heating period [12], and regional distribution of particulates [13]. Although certain research results have been achieved, the research on the vertical distribution of particulates in typical seasons is still insufficient now. The main reasons that the typical seasons of summer and winter are the mainly emission times for atmospheric particulates, and the distribution of particulates at different heights varies with different particle sizes. In addition, the occurrence of high concentration haze is more frequent in winter cities in China [14]. Studying the vertical distribution of particulates in typical seasons will be more meaningful.

Half of people's life is work time and half is rest time at the same time. Besides work, people spent more time are resting. Therefore, it can better provide data reference values for people living at different heights through in-depth understanding of the vertical concentration distribution of atmospheric particulates on working days and on non-working days in typical seasons. There is relatively little research on the variation characteristics of particulates concentration with different heights of floors on working and non-working days in actual work and life, which cannot truly reflect the vertical distribution of particulates under the two working and non-working periods, and even more cannot fully reflect the correlation between working and non-working days and people's living environment [15]. The main reasons are that there is currently a lack of professional monitoring equipment in China, and most research is still conducted around the ground [16]. In addition, sampling analysis is also influenced by weather factors, distribution of pollution sources, and human factors. Therefore, there is relatively little research on the vertical distribution of particulates [17-19]. In fact, people pay little attention the concentration distribution of outdoor atmospheric particulates in different building floors, but more attention the floors, orientation and lighting [20]. Therefore, there is a lack of certain understanding of the air pollution at different heights of high-rise buildings. However, the existing research cannot effectively give the vertical concentration distribution of atmospheric particulates in typical seasons with the increasing demand for indoor environment, especially in winter and summer on working days and non-working days. Therefore, considering the existing aforementioned issues, there are still many shortcomings in recent years in the research on the vertical distribution of atmospheric particulates at different heights of high-rise buildings during the winter and summer seasons on working and non-working days [21].

A high-rise building in Xi'an in typical winter and summer working days and non-working days were tested and analyzed in this paper to solve those problems, and the outdoor atmospheric particulates concentration distribution at different heights was also tested. It can provide reference values for the control of atmospheric particulates at different heights of high-rise buildings.

Methods

A high-rise building in Xi'an was selected for testing, with a height of 3.3 m and a total of 29 floors. The standard was used to for testing [22], and different heights of floors were 1st, 7th, 11th, 17th, and 27th floors, respectively, with heights of 1.5 m, 23.1 m, 36.3 m, 56.1 m, and 89.1 m from the ground. The testing time was 8:00 a. m., 12:00 a. m., 3:00 p. m., 6:00 p. m., and 10:00 p. m. Each test point was tested for 10 minutes, and the data were taken as the average of 10 minutes. The testing period is from July 22-24, 2021, and from December 12-15, 2021.

The GRIMM1.109 portable aerosol particle size spectrometer was used to test atmospheric particulates, with a measurement range of 0.1-100000 μg/m^3. The counting range was from 0 to 2000000 particle per L, and particle size between 0.25 μm and 32 μm are divided into 31 channels, with repeatability of 5%. The temperature and humidity parameters during the experiment were measured and recorded using the TSI 7545 air quality instrument. The temperature range was from 0-60 ℃, with error ±0.6 ℃, and resolution 0.1 ℃. The relative humidity range was from 5% to 95% RH, with accuracy ±3.0% RH, and resolution 0.1% RH. The HD37AB1347 indoor air quality monitor was used to measure the wind speed parameters during the experimental process. The wind speed range was form 0-50 m/s, the resolution was 0.01 m/s. The accuracy was ±3.0% of the reading. The reference standard provides concentration limits for each pollutant [23], as shown in tab. 1.

Table 1. Concentration limits for each pollutant [23]

Pollutant	Average time	Concentration [μgm^{-3}]	
PM_{10}	Annually average	40	70
	24 hour average	50	150
$PM_{2.5}$	Annually average	15	35
	24 hour average	35	75

Results and discussion

The variation of particulates concentration on different floors during working days

The variation of particulates mass concentration on different floors during typical working days in winter and summer is shown in tab. 2.

Table 2. Changes in particulates concentration at different vertical heights

Time	Pollutant	Summer working days [μgm^{-3}]					Winter working days [μgm^{-3}]				
		1st	7th	11th	17th	27th	1st	7th	11th	17th	27th
8:00 a. m.	PM10	36.1	36.7	41.1	36.5	35.0	121.2	109.3	89.5	107.6	109.4
	PM2.5	32.8	32.3	31.7	31.6	30.5	103.0	93.0	71.9	92.8	97.3
	PM1.0	31.1	30.3	29.2	29.7	29.0	96.5	86.1	64.3	85.8	89.8
12:00 p. m.	PM10	34.3	34.9	37.0	34.8	38.2	117.8	120.7	120.4	116.2	114.8
	PM2.5	29.8	29.4	29.6	31.7	32.3	96.6	100.2	99.5	95.0	90.9
	PM1.0	27.8	27.3	27.6	29.5	30.4	88.5	92.3	89.8	85.4	81.2
3:00 p. m.	PM10	33.9	47.3	40.8	36.5	33.5	124.9	131.1	125.9	129.8	131.5
	PM2.5	30.4	34.7	31.9	32.1	31.3	107.4	105.3	102.5	103.7	107.4
	PM1.0	29.2	31.2	29.5	30.3	30.2	97.7	95.0	93.5	94.9	96.3
6:00 p. m.	PM10	22.5	34.7	22.3	22.7	20.0	87.3	102.7	102.5	101.7	102.7
	PM2.5	18.0	21.4	18.2	18.1	16.1	77.5	88.7	88.8	88.1	88.1
	PM1.0	15.8	17.3	16.6	16.8	15.0	72.4	83.1	83.0	81.8	82.1
10:00 p. m.	PM10	27.2	28.1	28.1	23.6	22.4	83.7	82.0	89.2	87.5	82.4
	PM2.5	24.9	24.8	22.1	20.8	20.4	71.3	67.7	71.5	72.9	74.6
	PM1.0	23.6	23.2	20.6	19.5	19.3	66.6	62.7	67.4	67.5	69.9

As shown in tab. 2, the concentration of PM_{10} showed a trend of first increasing and then decreasing with the increase of building height. While the concentration of $PM_{2.5}$ and $PM_{1.0}$ showed a gradually trend of first decreasing and then increasing. The main reasons are that the temperature is relatively low in the morning and evening, and there is a temperature inversion layer phenomenon [24], which is not conducive to the diffusion of particulates. As a result, the concentration of particulates in the high altitude is lower and higher on the ground. The concentration range of PM_{10} at different heights during summer working days is 20.0-41.1 μg/m^3. The concentration range of $PM_{2.5}$ is 16.1-32.8 μg/m^3, the concentration range of $PM_{1.0}$ is 15.0-31.1 μg/m^3. While the concentration range of PM_{10} at different heights during winter working days is 82.0-131.5 μg/m^3. The concentration range of $PM_{2.5}$ is 67.7-107.4 μg/m^3. The concentration range of $PM_{1.0}$ is 62.7-97.7 μg/m^3. Overall, the concentrations of particulates are generally low during summer working days, the reason is that with the combustion of fossil fuels during the winter heating season intensifies particulates emissions, resulting in higher concentrations of particulates [25]. In addition, relevant literature showed that China's heating system heavily relies on fossil fuels, and the combustion of fuels can cause serious air pollution and greenhouse effect [26]. This conclusion verifies the correctness of the data in this paper.

The variation of particulates concentration on different floors during non-working days

The variation of particulates mass concentration on different floors during typical non-working days in winter and summer is shown in fig. 1.

Figure 1 showed that during non-working days, with the increased of floor heights, the concentration of PM_{10} showed different trends at different times in summer. Most of them showed a trend of first increasing and then decreasing, but there was also a trend of first decreasing and then increasing. The concentration of $PM_{2.5}$ and $PM_{1.0}$ both showed a trend of first increasing, then decreasing and next increasing. At different times during non-working days in winter, the concentration of PM_{10} showed a trend of first decreasing, then increasing, and next decreasing with the increase of building height. However, the concentration of $PM_{2.5}$ and $PM_{1.0}$ showed a gradually decreasing trend. The concentration of particulates on the lower floors is relatively high, while the concentration of particulates on the higher floors is relatively low. The concentration range of PM_{10} at different heights during non-working days in summer is 9.5-39.5 μg/m^3, the concentration range of $PM_{2.5}$ is 8.0-35.2 μg/m^3, the concentration range of $PM_{1.0}$ is 6.9-33.3 μg/m^3. The concentration range of PM_{10} at different heights during non-working days in winter is 25.7-48.1 μg/m^3. The concentration range of $PM_{2.5}$ is 18.0-30.4 μg/m^3, the concentration range of $PM_{1.0}$ is 14.5-26.5 μg/m^3. It can be seen that the concentration of particulates is generally low on non-working days in summer, and overall, the concentration on non-working days is much lower than that on working days. This is because during the working days, there is a high concentration of people and the using of transportation is relatively frequent, while during non-working days, there is relatively less travelling and the frequency of transportation using is also relatively low [27]. Related literature indicates that road traffic is also one of the main causes of pollutant generation [28]. Therefore, the concentration on non-working days is relatively low.

The variation of particulates concentration over time during typical seasons

The variation of particulates concentration over time during typical winter and summer seasons is shown in tab. 3.

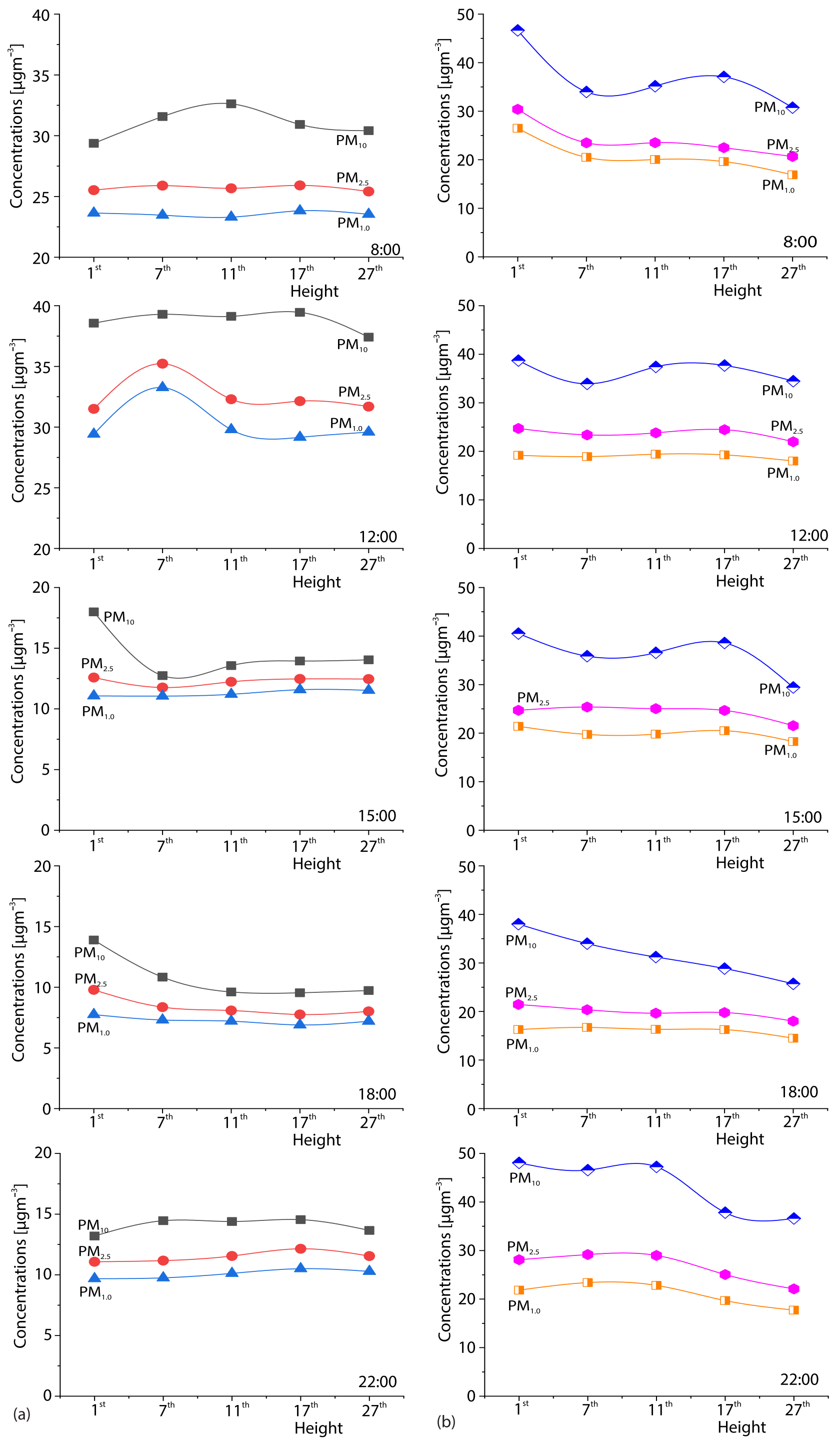

Figure 1. Changes in particulates concentration at different vertical heights; (a) summer working days and (b) winter working days

Table 3. The variation of particulates concentration in typical seasons at different times

Time	Summer [μgm^{-3}]			Winter [μgm^{-3}]		
	PM_{10}	$PM_{2.5}$	$PM_{1.0}$	PM_{10}	$PM_{2.5}$	$PM_{1.0}$
8:00 a. m.	34.0	28.7	26.7	72.1	57.9	52.6
12:00 a. m.	37.3	31.6	29.4	77.2	60.1	53.2
3:00 p. m.	26.4	22.2	20.7	82.4	64.8	57.7
6:00 p. m.	17.6	13.4	11.8	65.5	53.0	48.2
10:00 p. m.	20.0	17.0	15.7	64.1	49.1	44.0

Table 3 showed that with the extension of time, the concentration of PM_{10} showed a trend of first increasing, then decreasing, and next increasing in summer. While the concentration of $PM_{2.5}$ and $PM_{1.0}$ both showed a trend of first increasing, then decreasing, and next increasing. The concentration of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ all showed a trend of first increasing and then gradually decreasing in winter. The particulates reached the highest at 12:00 a. m. in summer, with the average concentrations of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ were 37.3 μg/m^3, 31.6 μg/m^3, and 29.4 μg/m^3. While reached the highest at 3:00 p. m. in winter, with the average concentrations of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ were 82.4 μg/m^3, 64.8 μg/m^3, and 57.7 μg/m^3. This is related to human activities, lifestyle habits, weather and other conditions in the testing location [29]. There is often a phenomenon of temperature inversion under the influence of cold high pressure in the morning, while the outdoor temperature is not too high, which is not conducive to the diffusion of fine particulates. With time goes on, there is sufficient sunlight, solar radiation increases, and ground temperature increases rapidly. As a result, the inversion phenomenon gradually disappears, and particulates gradually diffuses into the high altitude [30]. In the afternoon, particulates are carried by vehicles, and the resuspension effect intensifies, with some particulates gradually spreading into the high air. The nighttime cooling gradually intensifies the phenomenon of temperature inversion, and the amount of particulates near the ground gradually increases. While the temperature in winter is relatively lower in the morning, and particulates are not easily diffused at night, which resulting in a relatively high concentration in the morning. As people travel daily, the concentration of particulates gradually increases. But with the increase of atmospheric temperature, the movement of particulates is accelerated. In addition, the movement of people and transportation after work hours will also intensify the movement of particulates [21], as a result, there is a decreasing trend in its concentration. At night, with the effect of the inversion layer, the concentration of particulates increases again. Therefore, the vertical distribution of different concentrations of particulates at different times are mainly affected by the phenomenon of temperature inversion. This conclusion is consistent with relevant research results [20, 31], which verifying the correctness of this paper.

The variation of particulates counting concentration with different floors

The variation of particulates counting concentration on different floors during the typical winter and summer seasons on working and non-working days is shown in fig. 2.

From fig. 2, it can be seen that with the height of the floor increases, the particle size of less than 1.0 μm showed a trend of first decreasing and then gradually increasing. The difference in particle size of less than 1.0 μm during working days and non-working days in summer is 0.036% and 0.057%, respectively. While the difference in particle size of less than 1.0 μm during working days and non-working days in winter is 0.014% and 0.032%, respectively. The

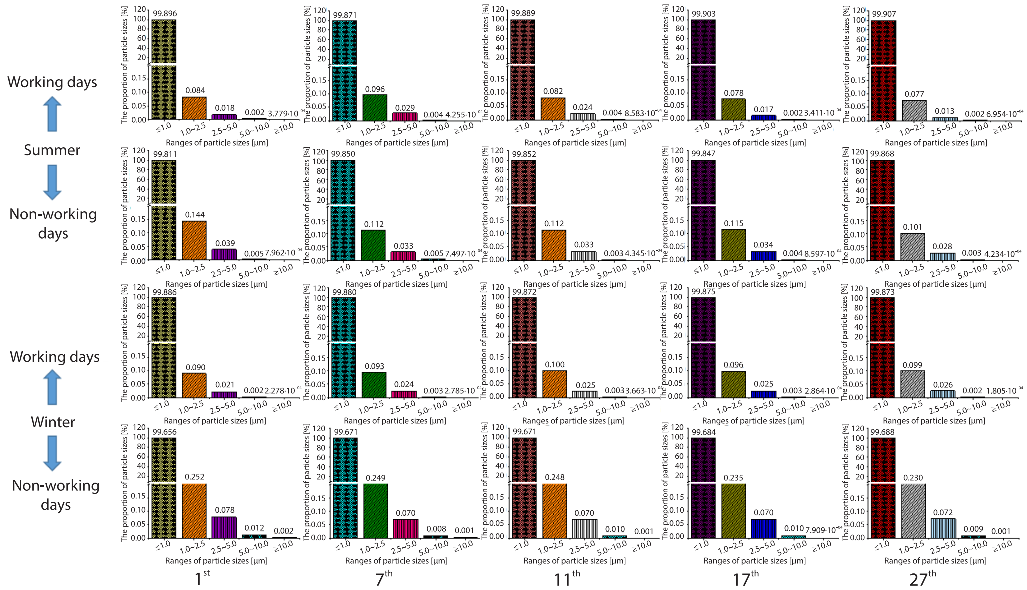

Figure 2. Trend of average particulates counting concentration variation at different heights

particle size from 1.0-2.5 μm and above 2.5 μm showed a trend of increasing first and then gradually decreasing. For the particle size from 1.0-2.5 μm, the difference during working days and non-working days in summer is 0.019% and 0.043%, respectively. While the difference during working days and non-working days in winter is 0.010% and 0.022%, respectively. For the particle size larger than 2.5 μm, the difference during working days and non-working days in summer is 0.017% and 0.013%, respectively. While the difference during working days and non-working days in winter is 0.004% and 0.012%, respectively. The main reasons are that large particulates are relatively heavy, and will settle down due to their own gravity. Therefore, there are relatively fewer large particulates in the atmosphere, especially in high floor. While small particulates are lighter, and will be suspended in the air [32]. However, small particle size particulates are more susceptible to the influence of the external environment, such as temperature, wind speed, humidity, *etc*., which have certain fluctuations. Overall, the particle sizes of low floors are mainly range from 1.0-2.5 μm, and the high floors are less than 1.0 μm. The concentration of particulates in summer is lower than that in winter. This is because the temperature in winter is relatively low, which is not conducive to the movement of particulate matters. As a result, the particulates stay in the air and have a relatively high concentration. While the temperature in summer is relatively high, which accelerating the movement of particulate matter, and resulting in a relatively low concentration of particulate matter in summer. The results of this paper is consistent with the trend of literature results, which verifying the correctness of this paper [33]. Figure 3 shows the changes in counting concentration of particulates with different particle size ranges at different times.

It can be seen that with time delay, the particle size of less than 1.0 μm showed a trend of first decreasing, then increasing, and next decreasing from fig. 4. The average concentrations of particulates during summer working days, summer non-working days, winter working days, and winter non-working days were 99.9%, 99.8%, 99.9%, and 99.7%, respectively. Overall,

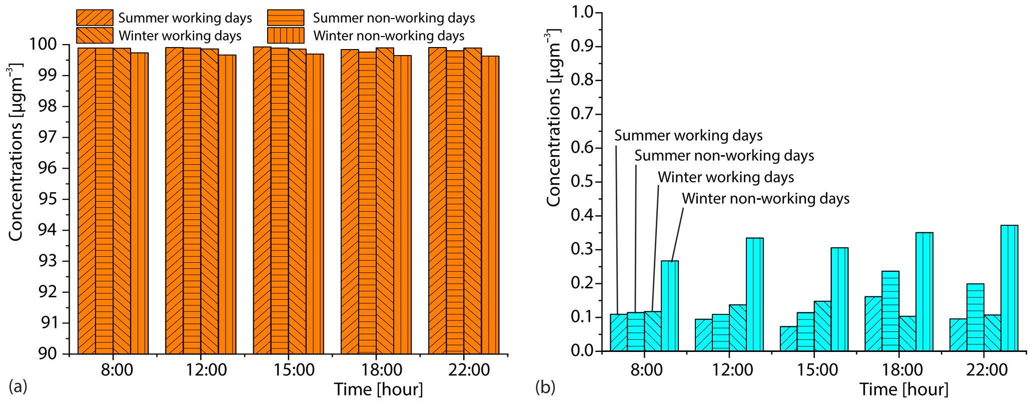

Figure 3. Counting concentration changes of particulates concentration at different times; (a) particle size less than 1.0 μm and (b) particle size larger than 1.0 μm

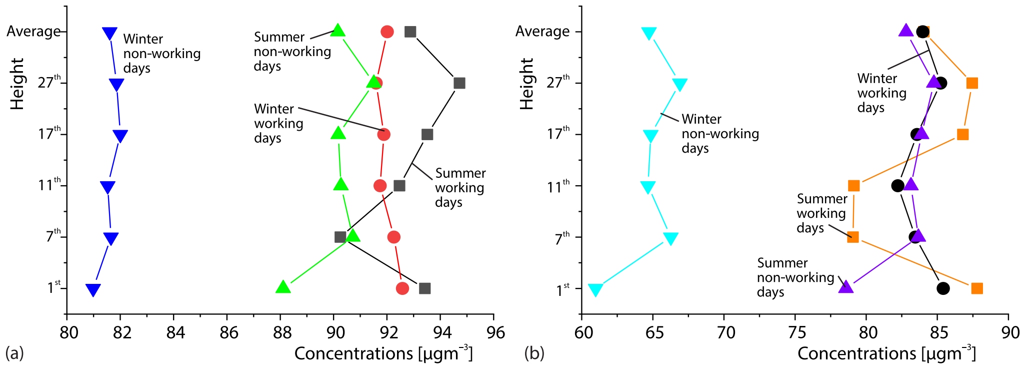

Figure 4. Changes in $PM_{1.0}/PM_{2.5}$ and $PM_{2.5}/PM_{10}$ at different heights; (a) $PM_{1.0}/PM_{2.5}$ and (b) $PM_{2.5}/PM_{10}$

the particulates concentration during the working day period were higher than that during the non-working day period. The particle size of larger than 1.0 μm showed a trend of first increasing and then decreasing, mainly due to the influence of gravity on large particulates and the influence of temperature, which quickly settles to the ground [34]. On the other hand, it indicates that the main distribution of atmospheric particulates in Xi'an is smaller particles, which is consistent with the results of relevant literature and verifies the correctness of this paper [11,12, 35].

The variation of relative content of particulates with different floors

The relative content of particulates on working and non-working days in typical winter and summer seasons varies with different floors, as shown in fig. 4.

Figure 4 showed with the height increases, both $PM_{1.0}/PM_{2.5}$ and $PM_{2.5}/PM_{10}$ showed a trend of first decreasing and then increasing during the working day period. On non-working days, both $PM_{1.0}/PM_{2.5}$ and $PM_{2.5}/PM_{10}$ showed a trend of first increasing, then decreasing, and next increasing. With the increase of building height, the variation range of $PM_{1.0}/PM_{2.5}$ on working days ranges from 90.3-94.7%, with an average of 92.4%. The variation range on non-working days ranges from 81.0-91.5%, with an average of 85.9%. The average of $PM_{1.0}/PM_{2.5}$ on working days is 6.6% higher than that on non-working days. At the same time, with the increase of building height, the variation range of $PM_{2.5}/PM_{10}$ during working days ranges from 79.1-87.8%, with an average of 84.0%. The variation range on non-working days ranges from 61.0-84.8%, with an average of 73.8%. The average of $PM_{2.5}/PM_{10}$ on working days is 10.2% higher than that on non-working days, and the particle property in summer is lower than that in winter. It can be seen that the atmospheric environment in Xi'an is mainly composed of small particles, which are relatively light in quantity and can be suspended in the air, as a result small particles are high in atmospheric. This is consistent with the conclusions given in the literature [11, 12, 35]. The distribution of relative concentration of particulates over time is shown in fig. 5.

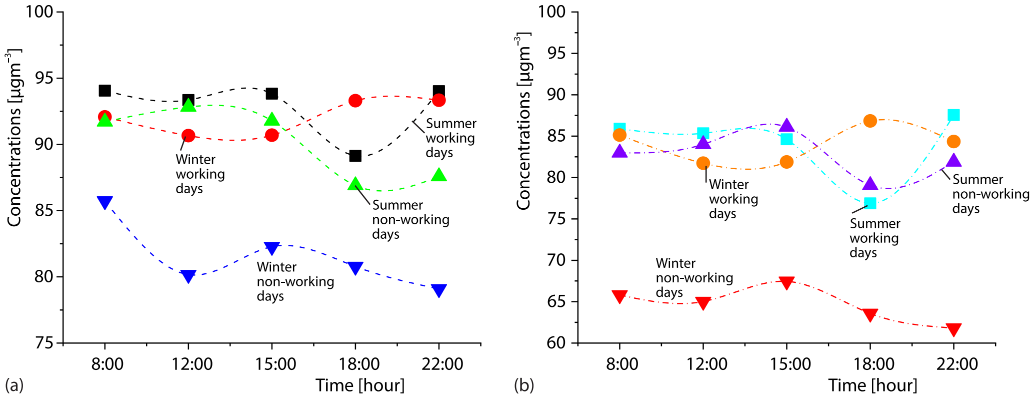

Figure 5. Changes in $PM_{1.0}/PM_{2.5}$ and $PM_{2.5}/PM_{10}$ at different times; (a) $PM_{1.0}/PM_{2.5}$ and (b) $PM_{2.5}/PM_{10}$

Figure 5 showed that with time increases, $PM_{1.0}/PM_{2.5}$ and $PM_{2.5}/PM_{10}$ also showed a trend of first decreasing and then increasing during the working day period. On non-working days, both $PM_{1.0}/PM_{2.5}$ and $PM_{2.5}/PM_{10}$ showed a trend of first increasing, then decreasing, and next increasing. With the increase of time, the variation range of $PM_{1.0}/PM_{2.5}$ on working days ranges from 90.7-94.1%, with an average of 93.7%. The variation ranges on non-working days ranges from 79.1-92.8%, with an average of 83.3%. The average of $PM_{1.0}/PM_{2.5}$ on working days is 10.4% higher than the average on non-working days. At the same time, the variation range of $PM_{2.5}/PM_{10}$ during working days ranges from 76.9-87.5%, with an average of 85.9%. The variation range on non-working days ranges from 61.8-86.1%, with an average of 71.9%. The average of $PM_{2.5}/PM_{10}$ on working days is 14.0% higher than the average on non-working days. It can be seen that time changes have a greater impact on the average of $PM_{1.0}/PM_{2.5}$ and $PM_{2.5}/PM_{10}$ compared to floor height changes, which is 3.8% and 3.8% higher on working days than on non-working days. This is because large number of small particles in the environment are more prone to diffusion, and also affected by temperature, which resulting in significant changes in the concentration of small particles [36]. The relative content of particulates during summer working days and non-working days is relatively high at different times. This is because the summer temperature is relatively high, there is sufficient sunlight, and the near surface inversion layer is damaged, which causing some damage to atmospheric stability [30]. This conclusion is consistent with the results given in the literature, which verifying the correctness of this paper [37]. The relative content of different particulates also showed fluctuating changes over time.

Conclusions

The concentration distribution of particulates in a high-rise building in Xi'an at different vertical heights in typical winter and summer seasons was tested and analyzed in this paper. The following conclusions are: The concentrations on non-working days were much lower than that on working days at different times and on different floors, and the concentrations of particulates were relatively low in summer. The particulates reached the highest at 12:00 in summer, with the average concentrations of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ were 37.3 μg/m^3, 31.6 μg/m^3, and 29.4 μg/m^3. While reached the highest at 3:00 p. m. in winter, with the average concentrations of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ were 82.4 μg/m^3, 64.8 μg/m^3, and 57.7 μg/m^3. With the height of the floor increases, the particle size of less than 1.0 μm showed a trend of first decreasing and then gradually increasing. The particle size from 1.0-2.5 μm and above 2.5 μm showed a trend of increasing first and then gradually decreasing. The distribution of atmospheric environment in Xi'an is mainly dominated by small particulates. The particle sizes of low floors are mainly range from 1.0-2.5 μm, and the high floors are less than 1.0 μm.With the increase of floors and time, $PM_{1.0}/PM_{2.5}$ and $PM_{2.5}/PM_{10}$ show a trend of first decreasing and then increasing on working days, while $PM_{1.0}/PM_{2.5}$ and $PM_{2.5}/PM_{10}$ show a trend of first increasing, then decreasing and next increasing on non-working days. Time changes have a greater impact on the average of $PM_{1.0}/PM_{2.5}$ and $PM_{2.5}/PM_{10}$ compared to floor height changes, which is 3.8% and 3.8% higher on working days than on non-working days.

In addition, outdoor meteorological parameters will also have a certain impact on particulates concentration distribution. It provides reference values for controlling the particulates concentration in high-rise buildings.

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