INDOOR-OUTDOOR CONCENTRATION OF PARTICULATE MATTER IN A LEAD-ZINC MINE: A CASE STUDY FROM CHINA

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Due to the unique environment of mines, there are significant differences in pollutants in different production and operation locations. This paper takes a case study mine to test and study the distribution of indoor and outdoor particulate matter mass concentration, particle number concentration in three measurement locations, and conduct in-depth analysis of its pollution status and differentiated impact. The results indicated in different locations, the concentration of particle sizes less than 0.3 μm is higher, and the concentration of range of particle sizes is higher indoor than outdoor. The office area has the highest I/O$_n$ value of 1.27 at a particle size of 0.29, the dormitory area also has the highest I/O$_n$ value of 1.31 at a particle size of 0.29, and the flotation plant has the highest I/O$_n$ value of 4.85 at a particle size of 0.375. The mass concentration of indoor and outdoor particulate matter in the flotation plant is higher than that in the office area and dormitory area, with only the concentration in the flotation plant exceeding the standard. The I/O$_c$ values in different locations are all greater than 1, and the indoor particulate matter concentration is higher than that outdoors. The outdoor particulate matter concentration is mainly affected by indoor particulate matter. It can provide reference value for the safe construction of mining environment.

Keywords: *Mining locations; air pollution; concentration; I/O; PM*

1. Introduction

Against the backdrop of continuous global industrialization, mining, as a fundamental industry, occupies an indispensable position in economic development [1]. Mining activities not only provide important resource support for socio-economic development, but also bring a series of environmental problems, among which particulate matter pollution is particularly prominent [2-3]. These particulate matter not only pose a serious threat to the physical health of mining workers, long-term exposure may cause pneumoconiosis, respiratory diseases, etc. [4-5], but also cause damage to the surrounding ecological environment, affecting vegetation growth and reducing atmospheric visibility [6].

Relevant literature showed Inhalable particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$) can penetrate deep into the human respiratory system, deposit in the lungs, and cause various diseases such as pneumoconiosis, lung cancer, asthma, etc. [7-8]. In addition, particulate matter from mines may also contain harmful substances such as heavy metals, radioactive substances, and organic pollutants [9]. After being absorbed by the human body, causing damage to the nervous, immune, and reproductive systems, affecting normal physiological functions, reducing quality of life, and even endangering life.

At present, due to differences in production processes, equipment and facilities, ventilation conditions, and personnel activities in different mining locations, the concentration distribution of particulate matter also varies significantly [10-12]. For example, in mining operations, due to the processes of mining, crushing, and loading ore, a large amount of dust is generated, and the concentration of particulate matter is often high. In office area of the mine, due to relatively less personnel activity and certain protective measures, the concentration of particulate matter is relatively low. The dormitory area of the mine is mainly used for the daily rest and living functions of mining workers. Therefore, the dormitory plant is located further away from the mining operation location, and its environment is relatively safe. At present, there have been some studies on particulate matter pollution in mines, mainly in operation locations such as excavation faces, tunnels, and crushing workshops. During underground mining, operations such as rock drilling, blasting, and transportation also generate a large amount of particulate matter. When a rock drill drills into rocks, it produces a large amount of rock dust. During the transportation of blasted ore, dust may accumulate in the tunnel due to friction between the ore and transportation equipment, as well as limited ventilation conditions in the tunnel. The transportation process of ore from the mining location to the beneficiation plant or other destinations, the generation of particulate matter is also quite severe. The operation process of transportation vehicles, the friction between the wheels and the ground can generate dust. During the bumpy process, some small particles of ore loaded on vehicles may also escape into the air. When the crusher crushes the ore, it crushes the ore into smaller particles, which also generates a large amount of dust.

Significant achievements in domestically and internationally have been made in monitoring technology and pollution prevention for particulate matter in mines [13-15], and strict occupational exposure limit standards have been established, providing important basis for ensuring the health of mining workers. At present, the commonly used monitoring technologies include laser scattering, beta ray absorption, and laser-induced breakdown spectroscopy, which can achieve real-time monitoring of the concentration of particulate matter in mines, effectively reducing the emission concentration of particulate matter in mines. This is conducive to the improvement of relevant regulations and provides scientific basis for formulating mine pollution prevention and control strategies. It also contributes to the development of dust removal equipment and technology in mines. However, there is limited research on particulate matter pollution in flotation plants, office areas, and dormitory areas.

There are still some shortcomings in the current research on the differences in concentration distribution of particulate matter indoor and outdoor mines in different locations and their impacts. Most of the research focuses on monitoring particle concentration in single mining locations or overall mining areas [16], and the comparative analysis between different locations is not comprehensive and in-depth enough, failing to fully reveal the inherent laws and influencing factors of particle concentration distribution in different locations. When studying the concentration distribution of particulate matter, only the influence of a single factor is often considered, while the interaction between multiple factors is ignored, resulting in a certain impact on the accuracy and reliability of the research results [17]. There is relatively little research on long-term monitoring and dynamic changes of particulate matter in mines, and there is a serious lack of research on the concentration distribution of indoor and outdoor particulate matter in different locations of mines. Therefore, the study of the differences in concentration distribution of indoor and outdoor particulate matter in different locations of mines and their impacts is urgent. It plays an important role in achieving sustainable development of mines, protecting the environment, and safeguarding human health that cannot be ignored.

Therefore, based on the above actual situation, this paper takes a case study mine to test and study the distribution of indoor and outdoor particulate matter mass concentration and particle number concentration in three different locations, and conduct in-depth analysis of their pollution status and impact differences. This study contributes to a deeper understanding of the generation, transmission, and diffusion patterns of particulate matter in mines, and providing a scientific basis for precise management of mining environments and offering reference value for the safe construction of mining environments.

2. Methods

2.1. Testing location

The testing location is located in the office area, dormitory area, and flotation plant of a lead-zinc mine in Shaanxi Province. All three types of buildings are built according to the terrain and transportation routes. The office area is relatively close to the dormitory area, with an adjacent distance of 400 m, presenting a similar horizontal opposition position. The flotation plant is relatively far away, about 1500 m away from the office area, presenting an up and down position, which located in the downstream area, and therefore further away from the dormitory area. The indoor and outdoor particle concentrations of the three different locations were tested separately. The height of the test breathing zone was 1.2 m above the ground, and the testing points and requirements were set according to standard [18]. The testing period is from April 10th to 15th, 2024, with clear weather conditions. The wind speed in the atmospheric is moderate, and there have been no extreme weather conditions such as strong winds. Overall, the wind speed is relatively low and in a state of no wind.

2.2. Testing instrument

The GRIMM1.109 aerosol particle size spectrometer was used to test the particle number concentration and mass concentration of particulate matter. Measuring range was 0.1~100.000 μg/m^3 . Counting range was 2000000 P per L, and 31 particle size channels were divided between 0.25~32 μm. The repeatability was 5%. Its working principle is based on single particle light scattering and filter membrane collection (dual element technology). Temperature, humidity, and CO_2 were tested using the IAQ-Calc7525 indoor air quality detector. Temperature range was 0~60 ℃, with error of ± 0.6 ℃. Relative humidity range was 5~95% RH, with accuracy of ± 3.0% RH. CO_2 range was 0~5000 ppm, with accuracy of ± 3.0% of reading or ± 50 ppm. Conduct three sets of tests for each testing location, each consisting of three time periods, morning, afternoon, and evening. Repeat the tests twice for each set, with each test lasting 10 minutes. Take the average of the test results from each location for data analysis to make the results more representative.

2.3. Evaluation

The particle number concentration ratio is calculated as shown in formula (1) [19]:

$$I/O_n = \frac{n_i}{n_o} \tag{1}$$

Where n_i is the concentration of particulate matter indoor (particles/m^3). n_o is the concentration of particulate matter outdoor (particles/m^3).

The mass concentration ratio is calculated as shown in formula (2) [19]:

$$I/O_c = \frac{C_i}{C_o} \tag{2}$$

Where C_i is the mass concentration of particulate matter indoor (μg/m^3). C_o is the mass concentration of particulate matter outdoor (μg/m^3).

3. Results and discussion

3.1. The particle number concentration indoor and outdoor

The changes in the particle number concentration of range of particle sizes indoor and outdoor measurement locations are shown in Table 1

Table 1 The particle number concentration indoor and outdoor

Particle size (μm)	Flotation plant ($\times 10^3$ P·m^{-3})		Office area ($\times 10^3$ P·m^{-3})		Dormitory area ($\times 10^3$ P·m^{-3})	
	outdoor	indoor	outdoor	indoor	outdoor	indoor
＜0.3	41625.94	54863.54	37526.93	40693.75	37792.11	39262.53
0.3~0.5	16825.66	35653.43	14211.55	17487.56	13900.30	16910.45
0.5~1.0	2175.88	2507.37	2080.77	1800.76	2350.94	1770.77
1.0~2.5	756.45	829.59	691.59	498.75	807.37	582.58
2.5~5.0	125.32	269.67	221.32	136.23	174.76	131.53
5.0~10.0	33.73	68.23	23.74	7.55	25.79	34.55
＞10.0	7.25	15.75	3.86	1.23	2.63	4.36

Temperature, 12.6℃~17.9℃, relative humidity, 52.4%~58.7%, wind speed, 0~0.23 m/s

According to Table 1, the concentration of particle sizes less than 0.3 μm is higher in different locations, and as the particle size increases, the concentration decreases. This is consistent with the results given in the literature [20], which verifying the correctness of this paper. When the particle size is 0.5-1.0 μm, the decrease in particle number concentration is significant. Overall, the concentration of range of particle sizes is higher indoor than outdoor, but the office and dormitory areas show the oppolocation trend when the particle size is greater than 0.5 μm, with the outdoor slightly higher than the indoor. The flotation plant is the largest source of particle production.

The main reason is related to the self factors of small particle size. Large particle size directly settles due to gravity, while small particle size continuously diffuses in the air [21], which resulting in significant differences. But it also indirectly indicates that the concentration of pollutants in the workplace is higher than that in the living environment, and the dust producing areas in the workplace need to be controlled more closely to effectively reduce pollutants from the source.

3.2. Indoor and Outdoor Particle Size Distribution

The proportion of range of particle sizes in measurement locations is shown in Figure 1.

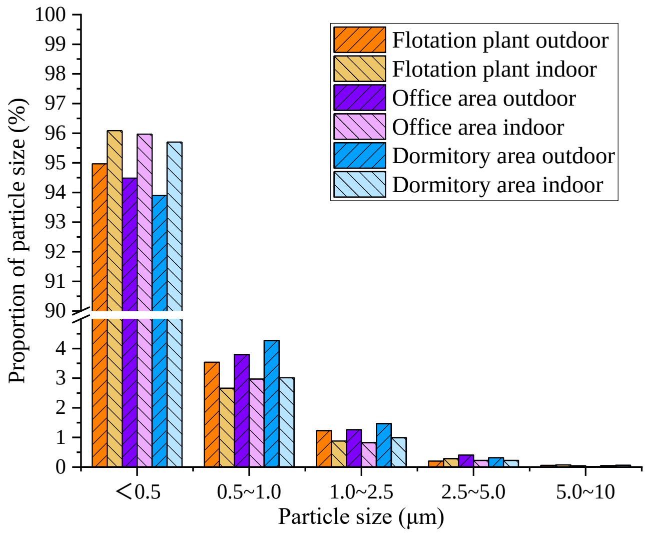

Fig. 1 Distribution of different particle size fractions indoor and outdoor

Figure 1 showed during the testing period, the proportion of particle size less than 0.5 μm was the highest in different locations. For particle size less than 0.5 μm, the indoor proportion is higher than the outdoor proportion. The differences in the proportion of particles indoor and outdoor the flotation plant, office area, and dormitory area are 1.12%, 1.49%, and 1.81%, respectively. When the particle size is 0.5-1.0 μm, the outdoor proportion is higher than the indoor proportion, with differences of 0.87%, 0.83%, and 1.25%, respectively. When the particle size is 1.0-2.5 μm, the outdoor proportion is still higher than the indoor proportion, with differences of 0.35%, 0.44%, and 0.47%, respectively. When the particle size is greater than 2.5 μm, there is not much difference between indoor and outdoor.

Particle size of 0-2.5 μm account for about 99.62% indoor the flotation plant, while those outdoor the flotation plant account for about 99.73%. Particle size of 0-2.5 μm account for about 99.76% in the office area, while those outdoor the office area account for about 99.55%. Particle size of 0-2.5 μm account for about 99.71% in the dormitory area, while those outdoor the dormitory area account for about 99.63%. This indicates that dust in different locations is mainly composed of fine particles, and as the particle size increases, its proportion in the environment decreases. Due to factors such as personnel activities, the proportion of fine particles indoor the office and living areas is slightly higher than outdoor, and these particles are more likely to enter the human body and cause serious harm [22]. Therefore, it is necessary to strengthen the purification capacity of fine particles in various places in the mining area and create a safe production and living environment.

3.3. I/O$_n$ of particle size in measurement locations

The I/O$_n$ of different particle size fractions in measurement locations are shown in Figure 2.

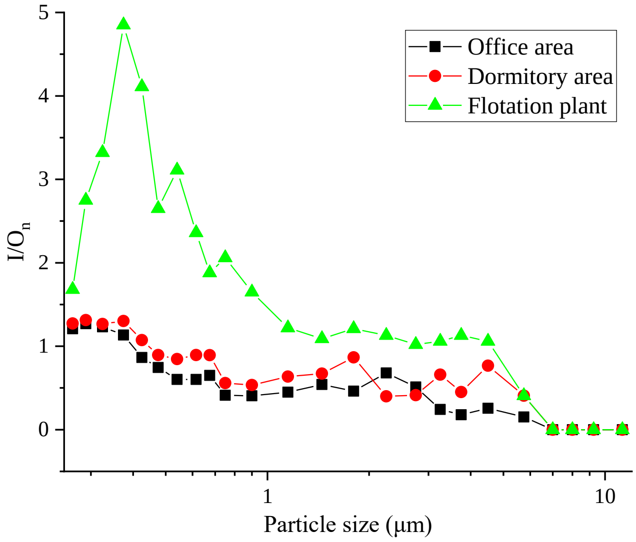

Fig. 2 I/O$_n$ variation of different particle size fractions in measurement locations

According to Figure 2, the average I/O$_n$ value greater than 1 in the office area, dormitory area, and flotation plant are the particle size of 0.265-0.375 μm, 0.265-0.425 μm, and 0.265-4.500 μm, respectively. While the average I/O$_n$ value less than 1 are the particle size of 0.375-5.750 μm, 0.425-5.750 μm, and 4.500-5.750 μm, respectively. This is because smaller particles are less likely to settle, while larger particles settle to the ground due to their own gravity. At this time, the office area has the highest I/O$_n$ value at a particle size of 0.29, which is 1.27. The dormitory area also has the highest I/O$_n$ value at a particle size of 0.29, which is 1.31, while the flotation plant has the highest I/O$_n$ value at a particle size of 0.375, which is 4.85. This conclusion is consistent with the literature results [20] and verifies the correctness of this paper.

The average I/O$_n$ value in the flotation plant is much higher than that in the office and dormitory areas. This is because under the same conditions, due to the requirements of equipment and processes, a large amount of particulate matter will be generated during operation in the flotation plant. Some of the fine particulate matter will remain suspended and be discharged outdoors through ventilation, infiltration and other factors, continuously affecting the environmental parameters outdoor the plant [23]. Through testing, it was found that the proportion of fine particles in the flotation plant is extremely high, which increases the health risks to workers and causes damage to surrounding residents and the environment. Compared to office and living areas, there is less impact of equipment dust sources, so the

I/O_n values at different particle size fractions are relatively small. Overall, it is necessary to focus on the treatment of flotation plants in the operating environment, especially the control of indoor pollution sources.

3.4. Mass concentrations of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ indoor and outdoor

The distribution characteristics of particulate matter (PM) mass concentration in measurement locations are shown in Figure 3.

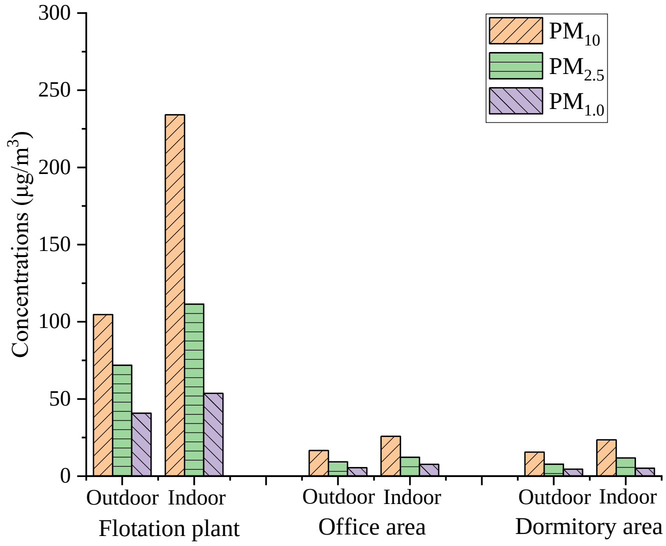

Fig. 3 Changes in particulate matter indoor and outdoor

Figure 3 showed the mass concentrations of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ in measurement locations are higher than those in the outdoor environment of the place. The mass concentrations of PM_{10}, $PM_{2.5}$, $PM_{1.0}$ indoor and outdoor in the flotation plant are 234.12 μg/m³, 111.51 μg/m³, 53.64 μg/m³, and 104.73 μg/m³, 71.94 μg/m³, 40.87 μg/m³, respectively, with differences of 129.39 μg/m³, 39.57 μg/m³, and 12.77 μg/m³. The mass concentrations of PM_{10}, $PM_{2.5}$, $PM_{1.0}$ indoor and outdoor in the office area are 25.75 μg/m³, 12.26 μg/m³, 7.61 μg/m³, and 16.67 μg/m³, 9.21 μg/m³, 5.52 μg/m³, respectively, with differences of 9.08 μg/m³, 3.05 μg/m³, and 2.09 μg/m³. The mass concentrations of PM_{10}, $PM_{2.5}$, $PM_{1.0}$ indoor and outdoor in the dormitory area are 23.48 μg/m³, 11.82 μg/m³, 5.17 μg/m³, and 15.62 μg/m³, 7.79 μg/m³, 4.52 μg/m³, respectively, with differences of 7.86 μg/m³, 4.03 μg/m³, and 0.64 μg/m³. The difference in particle concentration between the indoor and outdoor presents as follows: flotation plant>office area>dormitory area. The differences in PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ indoor and outdoor the flotation plant are higher than those in the office area at 120.31 μg/m³, 36.52 μg/m³, and 10.68 μg/m³, respectively, and higher than those in the dormitory area at 121.53 μg/m³, 35.54 μg/m³, and 12.13 μg/m³. This indicates that there is a significant pollution problem in the air quality in measurement locations, with flotation plants being the most severely polluted. This is related to the function of flotation plants, which are places for preliminary screening and processing of different minerals. Therefore, the concentration is relatively high, and effective measures need to be taken for purification and improvement.

In addition, according to the first level standard regulations [18], the 24-hour average PM_{10} concentration is 50 μg/m^3, and $PM_{2.5}$ is 35 μg/m^3. The secondary standard stipulates that

PM_{10} is 150 μg/m^3 and $PM_{2.5}$ is 75 μg/m^3. It can be seen that only the concentration in the flotation plant exceeds the standard. At this time, compared with the first level standard, the PM_{10} indoor the flotation plant exceeds the standard by 4.68 times and the $PM_{2.5}$ exceeds the standard by 3.19 times, while the PM_{10} outdoor the flotation plant exceeds the standard by 2.09 times and the $PM_{2.5}$ exceeds the standard by 2.05 times. Compared with the secondary standard, the PM_{10} indoor the flotation plant exceeds the standard by 1.56 times and the $PM_{2.5}$ exceeds the standard by 1.49 times, while the PM_{10} and $PM_{2.5}$ outdoor the flotation plant do not exceed the standard. Currently, there are no emission requirements for $PM_{1.0}$. Therefore, based on the above analysis, further in-depth research is needed on the mass concentrations of PM_{10} and $PM_{2.5}$ indoor and outdoor the flotation plant building.

3.5. Indoor and Outdoor Ratios of PM Fractions

The distribution of the proportion of particulate matter in measurement locations is shown in Table 2.

Table 2 The proportion of PM particles indoor and outdoor

Place	Position	$PM_{1.0}/PM_{2.5}$	$PM_{1.0}/PM_{10}$	$PM_{2.5}/PM_{10}$
Flotation plant	outdoor	56.81	39.02	68.69
	indoor	48.10	22.91	47.63
Office area	outdoor	59.96	33.12	55.24
	indoor	62.06	29.55	47.61
Dormitory area	outdoor	58.05	28.96	49.89
	indoor	43.70	22.01	50.37

From Table 2, it can be seen that $PM_{1.0}$ accounts for about half of $PM_{2.5}$. Among them, it is 8.71% higher outdoor the flotation plant than indoor, 2.10% higher indoor the office area than outdoor, and 14.35% higher outdoor the dormitory than indoor. This indicates that the proportion of $PM_{1.0}$ in $PM_{2.5}$ is relatively high, especially outdoor the flotation plant. The proportion of $PM_{1.0}$ in PM_{10} is relatively small, with no more than 40% in different locations. It is 16.11% higher outdoor the flotation plant than indoor the plant, 3.57% higher outdoor the office area than indoor the office area, and 6.95% higher outdoor the dormitory than indoor the dormitory. This indicates that $PM_{1.0}$ still has a certain proportion in PM_{10}, while the rest are relatively larger particles. More than half of the PM_{10} are $PM_{2.5}$, ranging from 47.61% to 68.69%. The proportion of $PM_{2.5}$ in PM_{10} is 21.06% higher outdoor the flotation plant than indoor the plant, 7.63% higher indoor the office area than outdoor the office area, and 0.48% higher indoor the dormitory than outdoor the dormitory. This indicates that $PM_{2.5}$ accounts for a relatively high proportion, especially outdoor the flotation plant, where the difference in $PM_{2.5}$ proportion is the largest. Therefore, comprehensive analysis shows that the difference between $PM_{2.5}/PM_{10}$ is the largest in the flotation plant and office area, and the difference between $PM_{1.0}/PM_{2.5}$ is the largest in the dormitory. This is related to the use of functional areas in measurement locations, and the results given in relevant literature are consistent with those in this paper [19], which verifies the correctness of this paper. But further efforts are needed to strengthen the monitoring and control of $PM_{1.0}$ and $PM_{2.5}$.

3.6. I/O_c of particulate matter mass in measurement locations

The I/O_c of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ in measurement locations are shown in Figure 4.

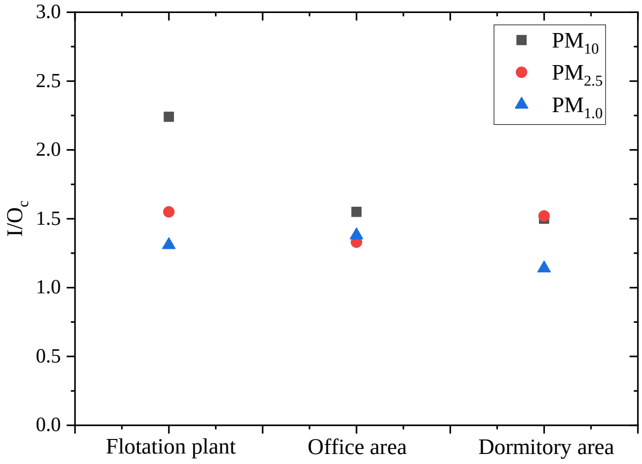

Fig. 4 I/O_c changes of particulate matter indoor and outdoor

Figure 4 showed the average I/O_c values of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ in the flotation plant are 2.24, 1.55, and 1.31, respectively. The average I/O_c values of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ in the office area are 1.55, 1.38, and 1.33, respectively. The average I/O_c values of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ in the dormitory area are 1.50, 1.52, and 1.14, respectively. The I/O_c values in measurement locations are all greater than 1, indicating that indoor particulate matter concentration is higher than outdoor particulate matter concentration, and outdoor particulate matter concentration is mainly affected by indoor particulate matter. At the same time, it also indicates that there is a significant difference in mass concentration between indoor particulate matter and outdoor environment. Regarding the average I/O_c value of PM_{10}, it shows that the flotation plant>office area>dormitory area, with differences of 0.69 and 0.73 between the flotation plant and the office and dormitory areas, respectively. The average I/O_c value of $PM_{2.5}$ shows that flotation plant>dormitory area>office area, with differences of 0.03 and 0.22 between flotation plant, dormitory area, and office area, respectively. This is because a large amount of dust is generated during the flotation process in the flotation plant, which affects the particle concentration outdoor the flotation plant. The office area and dormitory area are relatively far away from the workplace, so the overall environment is relatively good. The average I/O_c value of $PM_{1.0}$ shows that the office area>flotation plant>dormitory area, with differences of 0.07 and 0.24 between the office area, flotation plant, and dormitory area, respectively. It can be seen that due to the relatively high number of small particles such as personnel movement in the office area, but not much different from the flotation plant [24], overall, it is still necessary to strengthen the management and control of dust in the plant to improve the air quality and working environment for work and life. The correlation coefficient (r) between indoor and outdoor PM mass concentrations can also be used as an indicator of the contribution of outdoor particulate matter to indoor infiltration, and relevant literature has verified the correctness of this conclusion [25-26]. Therefore, the correlation between indoor and outdoor pollutants needs to be studied from multiple perspectives in order to clarify the control pathways of pollutants.

In addition, this paper studies the distribution characteristics of indoor and outdoor particulate matter mass concentration and particle number concentration in three different locations. Based on the diffusion distribution characteristics of pollutants, targeted improvements can be made to ventilation systems, dust suppression technologies, or workplace safety measures, especially in deep mining [27-29], so as to improve the production and living environment of mining locations and contributing to the safe construction of mining environments.

However, this paper still has certain limitations. Due to the influence of factors such as work progress and personnel on the mining environment, future research in this paper should continue to strengthen long-term monitoring and consider the subjective evaluation of personnel. From a subjective to objective perspective, the distribution of pollutants in the mining environment should be comprehensively provided, it provides reference for the construction of mining environment in China and even the world.

4. Conclusion

This paper takes a case study mine to test and study the distribution of indoor and outdoor particulate matter mass concentration and particle number concentration in three measurement locations. The conclusions are as follows: In measurement locations, the concentration of particle size less than 0.3 μm is higher, and the concentration of particles with different diameters is higher indoor than outdoor. The particle size with the largest difference in particle number concentration is 0.3~0.5 μm. Particle size of 0-2.5 μm account for about 99.62% indoor the flotation plant, while those outdoor the flotation plant account for about 99.73%. Particle size of 0-2.5 μm account for about 99.76% in the office area, while those outdoor the office area account for about 99.55%. Particle size of 0-2.5 μm account for about 99.71% in the dormitory area, while those outdoor the dormitory area account for about 99.63%. The office area has the highest I/O_n value of 1.27 at a particle size of 0.29, the dormitory area also has the highest I/O_n value of 1.31 at a particle size of 0.29, and the flotation plant has the highest I/O_n value of 4.85 at a particle size of 0.375. The mass concentration of indoor and outdoor particulate matter in the flotation plant is higher than that in the office area and dormitory area, with only the concentration in the flotation plant exceeding the standard. The I/O_c values in measurement locations are all greater than 1, the outdoor particulate matter concentration is mainly affected by indoor particulate matter.

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