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Experiment and numerical investigation of inhalable particles and indoor environment with ventilation system

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ABSTRACT

After the outbreak of COVID-19, the indoor environment has become particularly important in closed spaces, being a common concern in environmental science and public health, and of great significance for the building environment. To improve the indoor air quality and control the spread of viruses, the analysis of inhalable particles in indoor environments is critical. In this research, we study standards focused on inhalable particles and indoor environmental quality, as well as analyzing the movement and diffusion of indoor particles. Based on our analysis, we conduct an experimental study to determine the distribution of indoor inhalable particles of different sizes before and after diffusion under the conditions of underfloor air distribution. Furthermore, the mathematical modeling method is adopted to simulate the indoor flow field, particle trajectories, and pollutant dispersion process. The k-ε two-equation model is applied as the turbulence model in the numerical simulation, while the Lagrangian discrete phase model is adopted to trace the motion of particles and analyze the distribution characteristics of indoor particles. The results demonstrate that fine particles (i.e., those with size less than 0.5 μm) have a significant impact on the indoor particle concentration, while coarse particles (i.e., with size above 2.5 μm) have a greater influence on the total mass concentration of indoor particles. Small-sized particles can easily follow the airflow and diffuse to upper parts of the room. Overall, the effects of indoor particles on indoor air quality, including the potential threat of aerosol transmission of respiratory infectious diseases, are non-negligible. Application of the presented research can contribute to improving the health-related aspects of the building environment.

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1. Introduction

In the context of the COVID-19 pandemic, the daily life of human beings has greatly changed, with people having to stay indoors for longer than before. With increases in building airtightness, the circulation of indoor pollutants may increase the risk of airborne viral infection, causing a series of problems in the building environment [1], such as “Sick Building Syndrome” (SBS), “Building Related Illness” (BRI), and “Multi Chemical Sensitivity” (MCS), among others [2]. Therefore, the Indoor Air Quality (IAQ) has a direct impact on the life, work, and health of humans, involving many aspects including medical health, building environmental engineering, and architectural design. The requirements of people for the indoor environment are not only limited to traditional thermal comfort; requirements relating to indoor air quality, closely related to indoor particles, volatile organic matter, and so on, have also become highly important.

Research has shown that viruses can be suspended in the air, in the form of particles, thus realizing air transmission in a confined space. A lack of fresh air and ventilation will, therefore, increase the transmission probability of viruses and pollutants. Ventilation provides an effective method for the dilution and removal of indoor particles [3]. Underfloor air distribution (UFAD) systems, as innovative Heating Ventilation and Air Conditioning (HVAC) technology, when compared with traditional ceiling air condition-
ing, have obvious advantages in terms of energy saving and air quality improvement [4].

Study of the distribution and movement characteristics of indoor particles is of great significance, allowing us to improve the indoor air quality and promote the sustainable and healthy development of indoor environments. To date, scholars have carried out much research in this area, but there still remain areas to be explored. First, almost no complete or detailed theoretical system and method comparison of indoor particles has been presented in the existing literature, and experimental investigations and relevant research results are also very limited. Second, experimental studies on the diffusion of indoor particles have mainly focused on pollution sources at different time points [5–8], while few have considered the movement and diffusion of particles under a specific indoor flow field, especially with respect to the air supply outlet of underground air distribution system, which is set on the floor and can easily cause an increase of particle concentration when the air supply flow is directly sent into rooms from below. Furthermore, few studies have combined experimental analysis with numerical simulation and explored the two methods together, in order to extend the research findings. Therefore, there exists an urgent need to research the distribution characteristics of indoor inhalable particles, as well as the potential threat to the indoor environment posed by the air supply mode, the building design, and the indoor air quality.

Hence, in this paper, we consider the background of the increased demand for indoor environment quality and building ventilation improvement due to the COVID-19 pandemic outbreak. Based on the premise of the UFAD system, we conduct measurement experiments on the indoor particle concentration, as well as using the FLUENT software to carry out numerical simulation of the indoor particle distribution and movement trajectories, the results of which we compare with the experimental results. One of the main purposes of this study is to analyze the characteristics and motion trajectory of indoor particles, in order to determine suitable ways in which we can improve indoor air quality. Another of our aims is determining whether underfloor air supply systems can more efficiently settle or discharge particles to the outdoors, compared with traditional air supply modes, in order to create a cleaner and safer indoor environment, thereby reducing the infection rate of viruses such as COVID-19. Furthermore, a large number of pathogenic bacteria, viruses, and other micro-organisms will breed without air circulation, and people who stay indoors will also release waste gas and carbon dioxide, causing the indoor air quality to decline and potentially become harmful to human health. Thus, in this study, we also consider how to alleviate the harm of aerosols in building environments through creating a hygienic, healthy, and comfortable green indoor air environment.

This paper is organized as follows. Section 1 presents the introduction. Section 2 reviews the theoretical background, and then discusses the distribution and motion mechanism of indoor particles. The experimental study, the mathematical modeling method, and how they are combined to contribute to the research findings are clarified in Section 3. Section 4 details the experimental study, in which the distribution and diffusion characteristics of indoor inhalable particles and their impact on indoor air quality are analyzed. An experiment on the unsteady diffusion process of mosquito-repellent incense is carried out using aerosol spectrometer monitoring before and after implementation of the air supply. Next, the results of the mathematical methods are presented, where the realizable two-equation model and discrete phase model are selected to simulate and track the indoor flow field and particle trajectory. Finally, a comparison between the experimental and numerical simulation results is presented, which are checked to verify the rationality and correctness of simulated results. The main findings and directions for future work are summarized in Section 5. Our conclusions are drawn in Section 6.

2. Theory and research development

2.1. Transmission of aerosol particles

The classification of particulate matter (see Fig. 1) mainly includes: Dust (particle size $\geq 30 \mu m$), which can settle quickly from the air; thoracic particles (PM$_{10}$, GB/3095-1996), which refer to suspended particulate matter that can be inhaled through the mouth and nose; coarse fraction (aerodynamic diameter 2.5–10 $\mu m$), fine particles (PM$_{2.5}$, $<2.5 \mu m$), which can penetrate into the lungs; and ultrafine particles (UFPs, $\leq 0.1 \mu m$).

The description of particulate matter in Fig. 1 above is from research in Science (2005) [9], which reflects the particle size ranging from gas molecules, viruses, and bacteria to pollen and hair. According to the comparison of particles with different sizes, PM$_{10}$, PM$_{2.5}$, PM$_{0.1}$, and so on, reflect particle clusters in the air. Researchers from Tongji University have added the parts to which particles with different sizes can reach in the human body (e.g., pharynx, bronchus, and lung lobe). The toxicity of particles is closely related to their morphology, particle size, composition, and properties. The surfaces of particles can adsorb various harmful pollutants in the air, allowing these toxic substances to more quickly react and dissolve in the human body.

Aerosol particles with an aerodynamic diameter of less than 10 $\mu m$ are called inhalable particles [10]. In recent years, many scholars have found that inhalable particles, such as aerosol particles, which are rich in a large number of bacteria and viruses, can cause various health problems, such as respiratory and nervous diseases, where the incidence rate of carcinogenesis and deformities may be increased [11–13].

The viruses are special particles, which may also be called biological aerosols. When patients cough or sneeze, they release a large number of viruses. The virus spreads through aerosols and droplets. Aerosol transmission refers to droplets that are mixed in the air to form aerosols, leading to infection after subsequent inhalation. The main transmission routes of COVID-19 are respiratory droplets and contact transmission, while aerosol and fecal transmission routes remain to be further clarified. (Fig. 2)

The World Health Organization has also pointed out that aerosols usually persist for a long time in a closed environment, while, in a natural environment, under the action of wind and water, aerosol particles easily to combine with other media, accelerating the degradation of the virus nucleic acid. According to the prevention and treatment of influenza virus, if indoor ventilation is maintained, the possibility of aerosol infection can be greatly reduced; hence, more ventilation and maintaining the circulation of indoor air are conducive to reducing aerosol infection.

Thus, it is of great significance to study the distribution characteristics and movement of indoor inhalable particles, in order to determine more effective methods for the control of indoor particles and to improve building environments.

2.2. Distribution characteristics of particles

Many scholars have focused on the diffusion characteristics of particles. Fine [14] has studied the characteristics of particles produced by candle combustion, and pointed out the type of particles depended on the combustion mode of the candle. Lee et al. [15] have studied the impact of different cooking methods on the indoor environment, especially on PM$_{2.5}$ and PM$_{10}$ concentration and particle distribution. Wang et al. [16] have used a high-resolution electrostatic-scanning particle spectrometer to study...
the distribution and attenuation of sub-micron aerosols. They showed that the aerosol produced by a 15-minute mosquito-repellent incense recovered to the initial level after 1–2 h. Li et al. [17] carried out real-time online monitoring on the size and composition of single aerosol particles. Their results showed that the particle range of fresh cigarette smoke is wider than that of aging smoke. Zhou et al. [18] have conducted an experiment, which showed that the PM$_{2.5}$ concentration outdoors can influence the indoor PM$_{2.5}$ concentration. Ahmadzadeh et al. [19] have analyzed the characteristics, distribution, and transmission of COVID-19 virus particles.

2.3. Motion characteristics of indoor inhalable particles

The distribution and movement of indoor particles in a ventilated room are affected by several factors, mainly including particles characteristics, room structures, indoor heat sources, the location of indoor particles, airflow distribution, and so on. The influence of airflow distribution includes the ventilation form, ventilation rate, and layout of air inlet and outlet. The motion characteristics of indoor particles are mainly affected by gravity sedimentation, inertial collision, particle diffusion, particle coagulation, particle attachment, and rebound. Yao and Li have con-
ducted an experiment on the sedimentation characteristics of indoor inhalable particles with an underfloor air distribution system, and proved that the settlement of large particles is mainly determined by gravity, while the settlement of small particles is determined by the Brownian diffusion force [20]. Jin et al. [21] explained the flow and diffusion of suspended particles from outdoors to indoors, and showed that there are differences in the steady-state particle density at different locations in a room under different ventilation conditions. Chang et al. have focused on simulation of the thermal stratification height with underfloor air distribution using EnergyPlus, and obtained influence factors for the thermal stratification height, providing reference for building design [22,23] Table 1.

2.4. Ventilation and its influence on indoor particles

Underfloor air distribution (UFAD), as part of the design of an HVAC system, is used to provide ventilation and space conditioning in buildings. Differing from traditional ceiling air-conditioning systems, it has many distinct characteristics, such as using the air plenum beneath a raised floor to provide conditioned air through diffusers directly to the occupied zone. It has been applied in Nordic countries since as early as the 17th century. Due to its potential advantages of better indoor thermal comfort and indoor air quality, ventilation efficiency, layout flexibility, lower life-cycle cost, and energy saving, it has been increasingly favored by designers and widely used in the past two decades [4,24–27]. As people put forward higher requirements for thermal comfort and the air quality of building environments, research focusing on UFAD systems has been ongoing.

Table 1

| Particle size dp (μm) | $X_{m0}$ (m) | $X_{c}$ (m) | $X_{m0}/X_{c}$ |
|----------------------|--------------|-------------|----------------|
| 0.00037              | $6 \times 10^{-3}$ | $2.4 \times 10^{-6}$ | $2.5 \times 10^{6}$ |
| 0.01                 | $2.6 \times 10^{-4}$ | $6.6 \times 10^{-8}$ | 3900 |
| 0.1                  | $3.0 \times 10^{-5}$ | $8.6 \times 10^{-7}$ | 35 |
| 1.0                  | $5.9 \times 10^{-6}$ | $3.5 \times 10^{-5}$ | 0.17 |
| 10                   | $1.7 \times 10^{-5}$ | $3.0 \times 10^{-3}$ | $5.7 \times 10^{-4}$ |

Equal to the diameter of an air molecule.

Different air-conditioning and ventilation methods lead to different air distribution forms, where the movement and distribution of particles under the various flows are different. According to the experimental results of Zhao and Li et al. [20,28], the sedimentation and concentration of particles are mainly affected by ventilation conditions. The sedimentation of large particles is mainly determined by gravity, while the sedimentation of small particles is determined by the Brownian diffusion force. Meanwhile, increasing the air exchange rate can reduce the concentration of inhalable particles when using an underfloor air distribution system. Therefore, ventilation provides an effective measure to dilute and control the indoor particle concentration.

This section discusses the mechanisms associated with indoor particles, involving the basic concepts, their distribution and movement, and indoor ventilation laying a theoretical foundation for the experimental study and mathematical models for the numerical simulation of the indoor inhalable particle distribution and movement.

3. Research methods

3.1. Experimental study

Experimental measurement is an important and reliable means to study the distribution and movement rules of indoor particles. By using different instruments to measure the concentration and spatial distribution of indoor particles, we can evaluate the indoor air quality. At present, cumulative sampling devices and continuous monitors are mainly used in the research of atmospheric inhalable particles. Current experimental technologies can monitor the overall indoor particle concentration and distribution, as well as the movement of individual particles.

In this experiment, we combine the flow and diffusion characteristics of particles with an indoor airflow field, focusing on the distribution of indoor inhalable particles and exploring potential indoor air quality problems occurring when using an underfloor air distribution system. The GRIMM Model 1.108 aerosol spectrometer was used to monitor the concentration changes for inhalable particles with and without indoor air supply by the underfloor air distribution system, and a mosquito-repellent incense experiment was conducted to analyze the diffusion of particles and impact on indoor air quality, thus providing experimental data that can be used to verify the accuracy of the numerical results.

3.1.1. Experimental site and scheme

The experiment was carried out in an experimental office with an underfloor air distribution and air-conditioning system. The room size was 6 m × 7 m × 2.8 m (length × width × height), where the south–north direction is the depth and the east–west direction is the width, and the floor was composed of 0.6 m × 0.6 m overhead movable plates. The air supply outlet was a circular swirling-floor diffuser. During the experimental test, two computers, four lights, and two testers were present in the room. Fig. 3 shows the layout of the test room, indicating the indoor layout and the position of the air supply outlet.

According to design specifications and standards, the heating capacities of a human body, computer equipment, and lighting are defined as 75 W/person, 100 W/set, and 60 W/lamp, respectively, such that the total heat load was 590 W. The transient heat transfer and solar heat through the south wall were 257 W and 462 W respectively, and the heat gain of other envelope structures was 656 W. According to the load estimation guide provided by York Group, Inc., the distribution ratio of sensible heat load of an underfloor air distribution system in a working area is as follows:
lighting 20%, person 100%, computer equipment 100%, and enclosure structures 60%. Thus, the total heat gain of the working area was 1223 W.

We selected a time with stable meteorological conditions and conducted an experiment using an air exchange rate of 740 m$^3$/h for the underfloor air supply. Excluding indoor bookcases, refrigerators, and other objects, the indoor net volume was $V = 7 \, m \times 6 \, m \times 2.8 \, m = 114.1 \, m^3$, and the air supply ventilation rate was 6.5 h$^{-1}$. In the experiment, the measurements were taken at point A (the center of two floor air supply outlets close to office desks and chairs in the depth of the room, 1.1 m away from the ground). The doors and windows were sealed during the test. Referring to the experimental situation, the state in which the fluctuation amplitude of 15 consecutive concentration test data (a total of 15 min) near their mean value does not exceed ±5% is regarded as a stable state, and the arithmetic mean of all test data at the stable state is regarded as the steady-state concentration. After the test value was stable, we placed an ignited disc solid mosquito repellent at indoor point B ($X = 5.5 \, m$, $Y = 0.1 \, m$, $Z = 3.3 \, m$) for the smoke diffusion experiment. The experiment was repeated three times, and typical data were taken for analysis.

### 3.1.2. Experimental equipment

The GRIMM Model 1.108 aerosol spectrometer (Grimm Technologies, Germany) was used for testing. According to the principle of light scattering, the instrument was designed using the right-angle mode, with a range of 0.3–20 μm, where 15 channels were set within the particle range. Online monitoring of the gas sampling, counting, and analysis can be completed automatically through connection of the equipment with a computer. The technical parameters of the Grimm Model 1.108 aerosol spectrometer are provided in Table 2.

### 3.2. Mathematical modeling method

Since the 1970s, with the popularization of computers and the continuous improvement of computing power, Computational Fluid Dynamics (CFD) methods based on numerical calculation have become an important means to study indoor suspended particles. There are two main methods for studying particle motion through numerical simulation: The Euler method, which solves the particle concentration distribution based on Euler coordinates, and the Lagrange method, which solves the particle motion trajectory based on Lagrange coordinates [29].

To this end, we collected, analyzed, and summarized a large number of studies. A detailed comparison of the most recent research methods (i.e., over the past ten years) are listed in Table 3.

It was found that most of the prior articles adopted numerical simulation or experimental measurements to achieve their research purposes. In this paper, experiments and simulations are combined, such that more rigorous conclusions can be drawn through data fitting and comparison. Among them, the mosquito-repellent incense diffusion experiment has been found to be very effective for predicting the indoor air purification process and controlling pollutants through air distribution. Besides, it also further demonstrates the conclusion that fine particles are easily discharged from the upper part of the room. This experiment is also helpful for verifying the accuracy of the numerical model and providing concrete experimental evidence.

The numerical simulation of gas–solid flows has also been successfully applied in various research fields, and scholars have proposed different particle phase models for engineering projects (Table 4) [35]; however, there is no common model yet.

### 3.3. Coordination between the experimental study and mathematical modeling method

In the experimental study, the aerosol spectrometer was used to monitor the change in concentration of inhalable particles before and after applying indoor air supply through the underfloor air supply system, and the corresponding mosquito-repellent incense experiment was conducted to analyze the diffusion characteristics, indoor flow field, and trajectories of particles produced by combustion and their impact on indoor air quality, providing experimental data for verifying the accuracy and rationality of the numerical simulation of the underfloor air supply under the same experimental conditions.

In the modeling approach, the Lagrange discrete phase model was used to simulate the discrete particle phase of the indoor flow using Lagrangian coordinates, and the diffusion and distribution of indoor particles under the UPAD system were analyzed. Based on the previous experimental results, we comprehensively investigated the applicability and reliability of the model. The validity of the mathematical modeling method, which can obtain the same detailed particle distribution or motion trajectory as the experiment, is described in result section.

There are differences among the distribution rules of indoor particles under different conditions. Different ventilation forms, different ventilation times, different wall materials, and indoor disturbances can affect the distribution and motion of indoor particles, thus increasing the complexity in the experimental study. Furthermore, the experimental cycle is longer, the test data are limited, and there are varying degrees of errors in the experiment, due to the accuracy of the instrument, as well as operational and meteorological parameters. Therefore, it is still a lot of work to control and reduce or eliminate interference factors in the experimental study, making it unsuitable for the rapid analysis of particles. In this regard, compared with the experimental study, numerical simulation is convenient, can greatly save costs, and shortens the experimental cycle.

In this study, we verified that the used numerical simulation method is valid for studying the movement of particles and is highly suitable for indoor environmental analysis. Thus, the experimental study and the mathematical modeling method presented a

### Table 2

| Laser | Wavelength: λ = 655 mm Power: P_{max} = 40 mW |
|-------|---------------------------------|
| Particle channel | 15 Particle channels: 0.30/0.40/0.50/0.75/1.0/1.5/2.0/3.0/4.0/5.0/7.5/10/12.5/15/20 μm |
| Particle counting range | 1~2,000,000/L |
| Mass concentration range | 0.1~100,000 μg/m² |
| Accuracy | ±2% |
| Sample flow rate | 1.2 L/min |
| Dust collection | Φ47 mm Polytetrafluoroethylene filter membrane |
| Temperature | 4~45 °C |

The particles in gas–solid phase flow are dispersed phases with varying diameter. The motion characteristics of particles, such as suspension, sedimentation, condensation, and diffusion, are related to their size, shape, and other physical properties. In order to further analyze indoor particles and study their distribution rules, clarifying the characteristics of the particles and the air flow is necessary, which help in understanding the concentration distribution and motion trajectory of the particles in the room.

### Table 3

| Research methods | Number of studies | Comparison |
|------------------|-------------------|------------|
| Over the past ten years | 20 | One-dimensional simulation and two-dimensional simulation |

### Table 4

| Model | Description |
|-------|-------------|
| Euler | Solves the particle concentration distribution based on Euler coordinates |
| Lagrange | Solves the particle motion trajectory based on Lagrange coordinates |
Comparison of different particle phase models.

| Researcher           | Time   | Experiment                                                                 | Method                  | Effect of particles | Interphase sliding | UCS        | Particle transport properties |
|----------------------|--------|----------------------------------------------------------------------------|-------------------------|---------------------|-------------------|-----------|-------------------------------|
| K. Zhong [30]        | 2010   | A full-scale room with two different ventilation methods                   | RNG k-ε turbulent model and the Lagrangian particle tracking method | Neglect             | Yes               | Lagrange  | None                          |
| C. Li [31]           | 2012   | Using particle concentration tester MIEPDR-10000AN and particle counter    | RANS                    | Neglect             | Yes               | Euler     | Yes                           |
| M. Salamanzadeh [32] | 2012   | ——                                                                          | The Euler and Lagrangian computational models & k-ε turbulence model | Partial             | None              | Euler     | Yes (diffusion equilibrium)    |
| C. Zhuang [33]       | 2016   | ——                                                                          | The Euler–Lagrangian approach (DPM) & RNG k-ε model                  | Consideration       | Yes               | Lagrange  | None (orbit determination)Yes (stochastic) |
| Y.M. Fan [5]         | 2017   | Model validation using experimental data from others                       | RNG model               | Consideration       | Yes               | Euler     | Yes                           |
| B. Rahmati [6]       | 2018   | Simulation of UFAD-DDV + system in a typical office                        | RANS                    | Yes                 | Yes               | Lagrange  | None                          |
| A.Morteza [34]       | 2019   | Data from Coelho Leite and Tribess 2005 & Pustelnik and Tribess 2006      | The Eulerian–Lagrangian model & v²-f turbulence model                | Yes                 | Yes               | Euler     | Yes                           |
| T.H. Zhang [7]       | 2021   | ——                                                                          | RANS & RNG k-ε model    | Yes                 | Yes               | Euler     | Yes                           |
| S.M. Liu [8]         | 2022   | Used an environmental chamber to simulate a typical open office            | RANS & RNG k-ε model    | Yes                 | Yes               | Euler     | Yes                           |
| This paper           |        | GRMM Model 1.108 aerosol spectrometer & mosquito-repellent incense experiment | The Euler model, Lagrange discrete phase model, and k-ε two-equation model | Yes                 | Yes               | Euler     | Yes                           |

Table 3
Comparison of the most recent research methods and conclusions.

Table 4
Comparison of different particle phase models.

synergistic and complementary relationship and can be used together to enhance the research findings.

4. Research results

4.1. Experimental results

4.1.1. Particle size distribution of indoor inhalable particles

A comparison between the steady-state concentration and initial concentration of inhalable particulate matter in the underfloor air distribution room is shown in Fig. 4. The results showed that fine particles (0.3–2.5 μm) had a great effect on the total particle concentration, where the highest concentration appeared at 0.3 μm (8.91 × 10^4/L); coarse particles (2.5–10 μm) also had a great effect on the total particle mass concentration, where the highest concentration appeared at 3 μm (8.283 μg/m³). It was found that the use of underfloor air distribution significantly reduced the indoor particle concentration, and the larger particles were reduced more significantly. This was mainly caused by the particles being carried by the flow pattern in the wind direction of the underfloor air supply. When the underfloor air distribution was started, the lighter particles may be suspended in a short time, while the large particles can easily to settle or be taken away with the exhaust air, due to their high gravity and settling speed. During continuous ventilation, the particle concentration decreased gradually, as evidenced by a reduction in suspension rate. When the indoor particle concentration reached a stable state, the settlement and discharge of particles were larger than their suspension value.

The 0.3–10 μm particulate matter was divided into four levels for statistical analysis (0.3–0.5 μm, 0.5–1 μm, 1–2.5 μm, and 2.5–10 μm), and we calculated the ratio of the steady-state value to the initial value for each indoor particle concentration. The results are listed in Tables 5 and 6. It can be further seen, from Table 5, that the indoor pollution of 0.3–0.5 μm particles was 152,080/L, accounting for over 90% of the total particles when
Fig. 4. Comparison between stable and initial concentrations of particles under UFAD system.

Table 5
Particle concentration in different particle size range.

| Particle range (μm) | Steady state value of air supply $n$ | Initial value $n_0$ | $n/n_0$ |
|---------------------|-------------------------------------|---------------------|---------|
|                     | No./L  | Cumulative frequencies | No./L  | Cumulative frequencies |         |
| 0.3–0.5             | 94,609 | 94,609                | 142,080| 152,080                | 0.6221  |
| 0.5–1               | 3733   | 98,342                | 7731   | 159,811                | 0.4828  |
| 1–2.5               | 360    | 98,702                | 910    | 160,723                | 0.3955  |
| 2.5–10              | 62     | 98,762                | 209    | 160,930                | 0.2968  |
the office was not ventilated during working hours. Once inhaled, these particles can stay in bronchial terminals and even enter the alveoli. The smaller the particle size, the larger the surface area. The smaller the particle size, the greater the threat of fine particles to human health. It is easier to adsorb some harmful heavy metals and organic substances, which can be seriously harmful to human health. In the case of underfloor air distribution, due to the dilution and exhausting of fresh air, 0.3–0.5 \( \mu m \) particles were reduced to 94,609/L, which was 62.21% of the initial concentration, thus greatly reducing the threat of fine particles to human health.

It can be seen, from Table 6, that when there was no ventilation, the particle mass concentration of the indoor particle sections of size 0.3–0.5 \( \mu m \), 0.5–1 \( \mu m \), 1–2.5 \( \mu m \), and 2.5–10 \( \mu m \) were 14,849 \( \mu g/m^3 \), 8,053 \( \mu g/m^3 \), 10,705 \( \mu g/m^3 \), and 45,755 \( \mu g/m^3 \), respectively. The mass concentration of indoor PM\(_{2.5}\) and PM\(_{10}\) was 33,607 \( \mu g/m^3 \) and 79,362 \( \mu g/m^3 \), respectively. When the underfloor air distribution was kept stable, the particle mass concentrations of the above four particle sections were reduced to 8,442 \( \mu g/m^3 \), 3,900 \( \mu g/m^3 \), 2,823 \( \mu g/m^3 \), and 4,295 \( \mu g/m^3 \), respectively: at this time, the mass concentration of the indoor PM\(_{2.5}\) and PM\(_{10}\) was 15,165 \( \mu g/m^3 \) and 19,460 \( \mu g/m^3 \), respectively. Comparing the indoor PM\(_{2.5}\) and PM\(_{10}\) before and after underfloor air distribution, their concentrations decreased by 54.88% and 75.48%, respectively. Small-sized particles have good follow-up performance, which can be sent to the upper part of the room through the action of the thermal plume and, finally, discharged from the exhaust outlet. For large-size particles, due to their large settling speed, the upward flow from the underfloor air supply was not sufficient to suspend them at the height of the experimental sampling point, such that most of them settled to the ground. Therefore, the air quality in the indoor breathing area was improved when using underfloor air distribution.

According to indoor air quality standard of China (GB/T 18883-2002), the maximum daily mean value of PM\(_{10}\) is 150 \( \mu g/m^3 \), while the second-level standard of American ambient air quality stipulates that the maximum daily average of PM\(_{2.5}\) is 65 \( \mu g/m^3 \). The indoor particle concentrations before and after ventilation did not exceed either standard. This is related to the fact that the indoor doors and windows were closed during the experimental period, the persons in the room were not walking around, and the indoor printers, computers, and other equipment were not running.

In this paper, the particle concentration distribution under the UFAD system was studied experimentally and the distribution characteristics of 0.3–10 \( \mu m \) (i.e., inhaleable) particles were analyzed. The results showed that fine particles—especially those with size below 0.5 \( \mu m \)—had the largest effect on total indoor particle concentration, the coarse particles (>2.5 \( \mu m \)) had the greatest contribution to the total indoor particle concentration, and underfloor air distribution had a significant effect on reducing the indoor particle concentration.

4.1.2. Particle distribution before and after diffusion experiment

As an experimental object, the smoke from mosquito-repellent incense can be used as a source of indoor inhalable particles. Solid mosquito coil incense can produce the carcinogens benzopyrene, CO, and other harmful substances during its combustion, causing deterioration of indoor air quality. Hence, after the indoor particle concentration reached a stable state in the condition of the underfloor air distribution, solid mosquito coil incense was used in a diffusion experiment, in order to explore the effect of diffusion of inhalable particles on indoor air quality.

Fig. 5 shows the comparison of indoor particle concentrations with different particle sizes before and after burning the mosquito-repellent incense. It can be seen, from the figure, that the particle concentration and particle mass concentration of fine particles below 0.5 \( \mu m \) obviously increased, while the concentration of coarse particles above 2.5 \( \mu m \) had little change after burning the mosquito-repellent incense. The peak position of the particle size distribution remained unchanged before and after burning the mosquito-repellent incense, and the distribution of particle number concentration showed an unimodal pattern with peak position at 0.3 \( \mu m \) (from 58,258/L before burning to 81,652/L after burning), while the distribution of particle mass concentration showed a bimodal pattern with peak positions at 0.3 \( \mu m \) and 3 \( \mu m \) (0.3 \( \mu m \) particles rose from 2.039 \( \mu g/m^3 \) before burning up to 3.616 \( \mu g/m^3 \) after burning; while the particle mass concentration of 3 \( \mu m \) particles remained almost unchanged). Based on statistical calculations, the mosquito-repellent incense accounted for about 22.6% of the total indoor particles and the associated particle mass concentration accounted for about 20.5% of the total particle mass concentration. Thus, it can be inferred that the particle concentration may significantly rise when there are indoor dust sources. From the perspective of human health, it is particularly urgent and important to control indoor air pollution and reduce indoor dust.

4.2. Mathematical modeling results

4.2.1. Models of particle analysis

(1) Gas-phase governing equation

At present, the High Reynolds number k-\( \varepsilon \) model, corrected by Launder and Spalding, is the most widely used for air flow calculations in air-conditioned rooms. The k-\( \varepsilon \) model is a typical two-equation model. Two parameters, addressing the turbulent flow energy (k) and turbulent dissipation rate (\( \varepsilon \)), are introduced in the calculation process. The ability of the k-\( \varepsilon \) Model to predict strong separated flows, flows with large curvature, and strong pressure gradient flows is weak, due to the need for correction of the turbulent viscosity and laminar velocity fluctuation. In this light, the improved realizable k-\( \varepsilon \) Model is better than the standard one for determining rotating flows, boundary layer flows with strong inverse pressure gradient, flow separation, and secondary flows. This model has better performance and can accurately predict the diffusion of plane and circular jets. Thus, in this paper, the core region of gas-phase turbulence was simulated using the k-\( \varepsilon \) Model, combined with the Boussinesq density hypothesis to calculate the influence of buoyancy on the flow field. The wall function method is used in the wall area; that is, the physical quan-

| Particle range(\( \mu m \)) | Steady state value of air supply m | Initial value m\(_0\) | m/m\(_0\) |
|-----------------------------|-----------------------------------|----------------------|---------|
| 0.3–0.5                     | 8.442                             | 14.849               | 0.5685  |
| 0.5–1                       | 3.900                             | 8.053                | 0.4842  |
| 1–2.5                       | 2.823                             | 10.705               | 0.2637  |
| 2.5–10                      | 4.295                             | 45.755               | 0.0939  |
tivity at the wall is connected with the variables to be solved in the turbulent core area by using a semi-empirical formula, instead of solving in the wall area. The basic equations are as follows.

Continuity equation:
\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0
\]

Momentum equation:
\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu_{\text{eff}} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \rho \beta (T - T_{\infty}) g_i
\]

where \( \mu_{\text{eff}} \) is the effective viscosity coefficient of turbulence \( (\mu_{\text{eff}} = \mu + \mu_t) \).

Energy equation:
\[
\frac{\partial \rho T}{\partial t} + \frac{\partial (\rho u_i T)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \kappa \left( \frac{\partial T}{\partial x_j} \right) \right] - \rho e
\]

where \( \sigma_T = 0.9-1.0 \).

Turbulent kinetic energy equation (k equation):
\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho ku_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] - \rho e
\]

Turbulent energy dissipation rate equation (\( \varepsilon \) equation):

Fig. 5. Distribution of indoor particle concentration before and after mosquito-repellent incense burning.
The force balance equation of particles in Cartesian coordinates is established as

\[
\frac{\partial (\rho e)}{\partial t} + \frac{\partial (\rho e u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \left[ H + \frac{\mu_1}{\sigma_c} \right] \frac{\partial e}{\partial x_i} + \frac{\rho C_L e}{2} \left( \frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_j} \right) \right) - c_2 \times \frac{\rho e^2}{k + \sqrt{\nu e}}
\]

where

\[
\sigma_c = 1, \ \sigma_e = 1.2, \ \delta_2 = 1.9c_1 = \max \left( 0.43 \frac{\eta}{\eta + 5} \right)
\]

\[
\eta = (2E_{ij}^2 - 1)^{1/2} \frac{k}{\nu} \quad E_{ij} = 0.5 \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
\]

\[
\mu_t = c_\mu p \left( \frac{k^2}{\nu} \right)
\]

The governing equation of particle phase

In FLUENT, the trajectories of dissociated particles can be obtained by integrating the differential equation of particle force in Lagrange coordinates. According to Newton’s law of motion, the force balance equation of particles in Cartesian coordinates is established as

\[
\frac{d u_{pi}}{dt} = F_i
\]

where \( u_{pi} \) is the velocity of particles in direction \( i \) (m/s); and \( F_i \) is the unit mass forces applied to particles in direction \( i \) (m/s²):

\[
\frac{d u_{pi}}{dt} = \frac{18}{\rho_p d_p^2} C_D Re \left( u_i - u_{pi} \right) + g_i \left( 1 - \frac{\rho}{\rho_p} \right) + F_{ai}
\]

where \( F_{ai} \) denotes the other external forces received by the unit particle mass, which are related to the flow field conditions and particle properties. With different particle properties and flow fields, the magnitudes of these forces vary with respect to each other. Based on an analysis on the particle force and motion characteristics, for the particle trajectory model in an indoor environment, the pressure gradient force, frictional force, drag force, and Basset force can be ignored, and the fluid drag force, gravity, Brownian force, and Saffman force should be considered. Then, Eq. (7) can be written as

\[
F_i = \frac{18 \mu}{\rho_p d_p^2} C_D Re \left( u_i - u_{pi} \right) + g_i \left( 1 - \frac{\rho}{\rho_p} \right) + F_{bi} + F_{ti}
\]

In order to simplify the simulation processes, the following assumptions were adopted in this study:

- The mass and heat transfer between the particle phase and gas phase are not considered.
- There is no coagulation or splitting of particles (i.e., the particle size remains unchanged in the calculation process).
- All particles are spherical. All particles of any shape can be equivalent to a sphere through use of the “aerodynamic equivalent diameter.”

The boundary conditions of the discrete phase model can be defined separately in each area. The boundary conditions of the granular phase involved in FLUENT mainly include reflect, trap, escape, and interior.

Reflect denotes the reflection boundary condition, where the particles collide with the wall and bounce back, resulting in momentum change. The amount of momentum change is determined by the empirical restitution coefficient \( e_n \) and the tangential restitution coefficient \( e_t \) (see Fig. 6). The former and latter respectively define the momentum change rate of particles in the vertical and tangential directions after collision with the wall; that is,

\[
e_n = \frac{v_{2,n}}{v_{1,n}}
\]

\[
e_t = \frac{v_{2,t}}{v_{1,t}}
\]

where “1” and “2” represent the quantities before and after the collision, respectively. If the normal restitution coefficient is 1.0, the direction of a solid particle changes only after collision with the wall, and the velocity perpendicular to the wall remains unchanged. If the tangential restitution coefficient is 1.0, it means that the tangential velocity direction remains unchanged after the particle collides with the wall. The default value of two recovery coefficients are 1.0; that is, there is no momentum loss and the collision is completely elastic.

Escape denotes an escape boundary condition, where particles escape and terminate the orbit calculation. Escape boundary conditions are generally used on the exit surface.

Interior denotes the internal boundary condition, where particles will pass through the internal flow areas.

In this paper, the boundary condition of the air supply (return) outlet was escape, while the boundary condition of other walls was trap.

The boundary conditions of the air supply (return) outlet were escape, while the boundary condition of other walls was trap.

Phase coupling

In calculations involving fluid and particle phases, the problems of single-phase and two-phase coupling arise. If only the influence of fluid relative to the discrete particle phase is considered, and the influence of particles relative to the fluid phase is not considered, single-phase coupling is used. The orbital calculation in single-phase coupling is based on the flow field calculation results for a continuous fluid phase. When the particle load is relatively high, not only does the influence of the fluid relative to the particles need to be considered, but also the influence of discrete particles relative to fluid phase; that is, bidirectional coupling. Two-phase coupling has higher accuracy than single-phase coupling, but the mathematical model is more complex.

The solution procedure for two-phase coupling is shown in Fig. 6. When the particles used for calculation contain high mass and momentum loads, the two-phase coupling method must be used in order to calculate the influence of the relative discrete continuous phase.

4.2. CFD numerical model

(1) Physical model

Taking an office with the under-floor air distribution system as the research object, geometric simplification and boundary conditions were carried out. The room size was 6 m × 7 m × 2.8 m, with a diameter of 0.2 m air-returning outlet close to the ceiling of the room, 1.2 m away from the north wall, and 2.5 m away from the east wall. The setting of the air supply outlet was the same as in the experiment. Considering the actual situation during the experimental test, the room was equipped with eight centralized heat sources, including two sitting human bodies, two computers, and four lights. The heat dissipation capacity of the human body was assumed to be 75 W/person, the heat dissipation capacity of the computers was 100 W/set, and that of the lights was 60 W/lamp. The basic structure of the room is shown in Fig. 7.
The internal structure of the actual air-conditioned room was relatively complex. In order to reduce the number of grids in the model, save operation time, and obtain more accurate and reliable simulation results, we simplified the indoor physical model, as detailed in Table 7.

### Table 7

Indoor equipment parameters.

| Name                 | Size(m)  | Number | Notes                                      |
|----------------------|----------|--------|--------------------------------------------|
| Researcher           | 0.4×0.3×1.1 | 2      | Both space obstacle and heat source        |
| Lighting             | 1.2×0.2×0.01 | 4      | Downward single side heat dissipation      |
| Computer             | 0.4×0.4×0.4 | 8      | at the height of desks (0.7 m), of which 2 are in operation |
| Bookcase             | 1.0×0.4×1.8 | 3      | Only as a space obstacle                   |
| Refrigerator         | 0.5×0.5×1.4 | 1      | Only as a space obstacle                   |
| Cabinet air-conditioner | 0.5×0.35×1.25 | 1      | Only as a space obstacle                   |

### (2) Grid Division

When using the gambit software to discretize the physical model in this paper, the tetrahedral unstructured mesh, with high degree of approximation at the wall, was used to complete the overall mesh generation. In order to ensure the accuracy of calculation in the areas near the heat sources, the grid was properly densified near the objects with high temperature and velocity gradient, such as human body, computer, and supply (return) air outlet. Meanwhile, considering the computational time and space, the grid division in other indoor areas with low temperature and velocity gradients were relatively sparse, as the flow mode in these areas had relatively small fluctuation and the physical parameters...
changed little; thus, it was not necessary to use fine grid. Fig. 8 and Table 8 show the grid division results for the underfloor air distribution system simulation.

### 4.2.3. Numerical calculation results and analysis

#### (1) Simulation results of indoor flow field

To a great extent, the air temperature field can reflect the distribution characteristics of indoor temperature. As the temperature is the biggest factor affecting human thermal comfort, studying the temperature field is of great significance, allowing for determination of the optimal arrangement of the air distribution mode to achieve the best thermal comfort effect.

The longitudinal sections \( X = 3.1 \text{ m} \) and \( X = 5.5 \text{ m} \), passing through the center of the air outlet, were selected as bay-direction representative surfaces of the room, while \( Z = 3.3 \text{ m} \) and \( Z = 4.5 \text{ m} \) were taken as depth-direction representative surfaces of the room. Fig. 9 shows the temperature distributions on these four typical planes.

As can be seen from Fig. 9, there was obvious temperature stratification in the vertical direction of the room, while the temperature differences in the horizontal direction were relatively smaller. The temperature around the heat sources, such as human bodies and computers (especially in the top area), increased obviously with an increase in height, forming an updraft in the form of a thermal plume, which was finally discharged from the room through the return air outlet, in order to ensure that an appropriate temperature was maintained in the working area. The temperature near the air supply outlet was lower, while the temperature near the return air outlet is higher, thus not only meeting human thermal comfort requirements, but also achieving an energy saving effect.

#### (2) Simulation results of indoor particle concentration

1) Numerical simulation of ground dust

In the under-floor air distribution room, fresh air is first sent into the indoor working area from the underfloor air supply outlet, in order to dilute pollutants in the working area. Then, it is lifted to the top of the room under the thermal control of the heat source and discharged through the exhaust outlet. However, ground dust—that is, the particles deposited on the ground—as a part of indoor particles, re-enters into the working area due to the action of indoor air flow, resulting in the secondary pollution of the air in the working area. In this section, the distribution characteristics of indoor pollutants, including ground dust, in the UFAD room are analyzed through the numerical simulation method.

According to the particle sizes, the particles used for calculation were divided into \( 0.3 \mu \text{m}, 1 \mu \text{m}, 2.5 \mu \text{m}, 5 \mu \text{m}, \) and \( 10 \mu \text{m} \), for five groups in total, which are in the range of inhalable particles closely related to indoor air quality (PM\(_{10}\)). These particles were evenly arranged on the indoor ground. A total of 200 trajectories were calculated for each group of particles, with particle density of \( 1050 \text{ kg/m}^3 \). The initial conditions are given in Table 9.

Fig. 10 shows the trajectory of a single particle, while Fig. 11 shows the motion trajectories of particles with different sizes. Their initial conditions were the same (i.e., initial position and mass), but there were significant differences in their motion trajectories: the trajectories of smaller particles were more suspended, and were discharged from the air outlet. With an increase in particle size, the number of suspended and discharged particles decreased, while the number of settled particles increased. It can be clearly seen that the desorption of particles mainly occurred near the air supply outlet, as the supplied air flow entrained and mixed with the surrounding air within a certain range. The particles around the air supply outlet were pulled by a large fluid force, resulting in instantaneous suspension of the particles and diffusion in the room along with the air flow. The office areas close to the east and west walls was almost unaffected by indoor particle diffusion, as they were far from the air supply outlet.

The gravity of small-sized particles is less than that of large-sized particles, making them mainly affected by Brownian diffu-
sion. Therefore, they are easily suspended indoors and carried by the air flow to the upper part of the room for discharging at the exhaust outlet, resulting in more suspension and discharge trajectories. Due to their high gravity and sedimentation velocity, the large-sized particles tended to return to the ground before reaching the exhaust outlet in the suspension process, thus forming many sedimentation trajectories.

Table 10 and Fig. 12 show the comparison of discharge, sedimentation, and suspension quantities of particles with different particle sizes. From the above figures, it can be seen that small-sized particles were easier to desorb from the wall and rolled into the fluid, and were also easier to discharge from the air outlet under the action of the upward flow formed by the thermal plume of the floor air supply. Larger particles settled more on the floor.

Fig. 9. Typical plane temperature distribution in room.
and side walls, as they do not easily overcome wall adhesion and their own gravity. With the increase in particle size (at each density) and sedimentation velocity, the slip of particles—which is relative to the fluid—was more obvious and became less easy to move with the fluid.

2) Simulation of pollution diffusion process of mosquito-repellent incense

Next, the unsteady state simulation of the experimental diffusion process of mosquito-repellent incense with UFAD was carried out. The pollution source was set at indoor Point B (X = 5.5 m, Y = 0.1 m, Z = 3.3 m), with mass flow rate of 10⁻⁸ kg/m³, particle size of 0.3 μm (it has been found that burning mosquito-repellent incense mainly emits particles of size 0.3 μm and lower, accounting for more than 85%), and particle density of 1050 kg/m³. Assuming that the indoor initial concentration was 0, the particles were injected into the flow field only at the beginning of the calculation. The concentration fields of the two longitudinal sections passing through Point B (X = 5.5 m, Z = 3.3 m; see Fig. 13) in different periods were calculated, in order to assess the diffusion process of the mosquito-repellent incense, which are shown in Fig. 14.

Considering the concentration cloud diagram of the mosquito-repellent incense diffusion process (X = 5.5 m), it can be seen, from Fig. 14, that the particles from the pollution source gradually diffused near the ground under the conditions of UFAD. Some particles diffused to the upper area of the room after about 5 s, while almost all particles were concentrated in the upper area of the room after

| Particle size/μm | Mass of particles per trajectory/μg | Trajectory number | Particles number of per trajectory |
|------------------|----------------------------------|-------------------|----------------------------------|
| 0.3              | 1.2 × 10⁻¹                        | 200               | 8.084 × 10⁵                      |
| 1                | 1.2 × 10⁻¹                        | 200               | 2.183 × 10⁵                      |
| 2.5              | 1.2 × 10⁻¹                        | 200               | 1.397 × 10⁴                      |
| 5                | 1.2 × 10⁻¹                        | 200               | 1.746 × 10⁴                      |
| 10               | 1.2 × 10⁻¹                        | 200               | 2.183 × 10⁴                      |

| Particle size/μm | Discharge trajectory | Sedimentation trajectory | Suspended trajectory |
|------------------|----------------------|--------------------------|----------------------|
| 0.3              | 123                  | 23                       | 54                   |
| 1                | 98                   | 56                       | 46                   |
| 2.5              | 43                   | 122                      | 35                   |
| 5                | 26                   | 148                      | 26                   |
| 10               | 9                    | 172                      | 19                   |

Table 9
Initial conditions of particles.

Table 10
Comparison of orbital numbers of particles with different sizes.
about 2 min. Some gathered at the top exhaust outlet, resulting in an increased particle concentration in the upper area of the room. After 10 min, most particles had been discharged from the exhaust outlet. The change of particle concentration in the $Z = 3.3$ m plane had a similar trend as that in Fig. 14. Therefore, with underfloor air supply, it can be seen that small-sized particles gradually diffuse to the upper area of the room and can be discharged from the exhaust outlet, thus creating a cleaner indoor air quality in the working area. Combined with the above analysis of the flow field in the underfloor air supply room, it is not difficult to determine the reason for this: the air distribution at the floor forms a cold-air lake in the lower area of the room, where the flow direction is horizontal and the flow velocity is relatively low. Therefore, more particles are sent to upper part of the room through the thermal plume. Small particles more easily move with the fluid, and the air quality in the working area is enhanced.

4.3. Comparison between experimental results and mathematical modeling results

In the numerical simulation, the discrete phase model of FLUENT was used to consider the force and inter-phase coupling of particles, such as the fluid resistance, gravity, Brownian force, and Saffman lift. In the following, we provide a comparison of the numerical simulation results with the experimental measurement results.

4.3.1. Experimental test

Temperature test: An Agilent 34970A was used. The thermocouple measuring points were arranged at indoor Point C ($X = 5.5$ m, $Z = 2.7$ m) at heights of 0.1 m, 0.3 m, 0.5 m, 1.1 m, 1.5 m, 1.8 m, and 2.5 m, in order to measure the temperature distribution in the vertical direction.

Wind speed test: A KIMO-MT4 anemometer was used to measure the axial wind speed at the outlet (or tuyere).

Particle concentration test: A Grimm Model 1.108 aerosol spectrometer was adopted, and the measuring points were arranged every 0.5 m along the depth direction in the plane $Y = 1.1$ m (height of human sitting breathing area). See Fig. 15 for the layout of measuring points.

4.3.2. Results comparison and discussion

The simulated values of temperature and air jet attenuation were in good agreement with the measured values. In the simulation, the swirl tuyere model is described by defining the tangential, radial, and axial velocities of the supply air, which can accurately reflect the induction and attenuation characteristics of the tuyere. The wind speed decays rapidly in the axial direction of the tuyere, by more than 60% at a height of 0.5 m. The simulated and test val-
Fig. 14. Concentration cloud diagram of mosquito-repellent incense diffusion process (X = 5.5 m).

Fig. 15. Layout of particle concentration measurement points.

Fig. 16. Comparison of velocity attenuation of air supply jet.

Fig. 17. Temperature comparison at the measurement points (X = 5.5 m, Z = 2.7 m).

Fig. 18. Particle concentration comparison at the measured points (X = 4.3 m, Y = 1.1 m).
ues at the height of 1.1 m were 0.135 m/s and 0.1 m/s, respectively. The temperature at test points was obviously layered in the height direction of the room, and there was a large temperature jump near the floor. The temperature rose with each layer from 0.1 m to 1.5 m. The temperature increases for the simulated and test values in this area were 2.96 °C and 2.73 °C, respectively. The increase in temperature at the top of the room was not obvious (Figs. 16–18).

From the experimental comparison between the simulated and measured values of particle concentration, it was found that the simulated value was generally lower, for which four main reasons can be noted. First, only the ground dust was considered in the numerical simulation and the influence of wall surfaces was ignored. Second, the amount of dust caused by the testers was not included in the calculation. Third, the setting of no-slip and capturing boundary conditions for the solid-wall velocity simplified the complex behavior of particles and the flow field on the side wall (e.g., partial slip, rebound, and so on), such that the random disturbance in the calculation results was weak. Fourth, due to the limitations of the particle concentration measurement instrument (multi-point measurement cannot be synchronized), as well as those of the test conditions, the few measurement sample points and single-point sampling times, the measured data cannot fully meet the accuracy needs. However, considering the rules and trend changes reflected by the simulation and test values, the test was relatively successful and can meet research needs, to a certain extent.

5. Discussion

5.1. Findings

In this study, we took the inhalable particles in an indoor environment with an underfloor air distribution (UFAD) system as the research object, in order to establish mathematical models. Based on the analysis of numerical models, the realizable \( k - \varepsilon \) two-equation model and discrete phase model in the Lagrange method were used to simulate the indoor turbulence and particle phase. Simulation of the interior airflow field, particle trajectories, and particle diffusion is useful for predicting the floor air supply purification process and controlling pollutants through air distribution methods. Finally, the numerical simulation results were compared with experimental results, in terms of the temperature distribution in the vertical dimension of the room, the axial velocity of the tuyere, and the indoor particle concentration when the air supply reached a stable state, which verified the feasibility and correctness of the numerical models.

Based on the theoretical review, experimental measures, and numerical simulation, our main findings are as follows:

(1) The experimental study demonstrated that fine particles, with size below 0.5 \( \mu m \), are mainly affected by Brownian forces and have a great impact on the indoor particle concentration. Meanwhile, the coarse particles, with size above 2.5 \( \mu m \), are greatly affected by gravity and have an obvious impact on the total mass concentration of indoor particles. Viruses can be transmitted by particles, while the UFAD can significantly reduce the indoor particle concentration and create a cleaner indoor environment.

(2) Experimental analysis of the indoor flow field found that the small-sized particles gradually diffused to the upper area of the room and were discharged from the exhaust outlet under the action of the UFAD. We also found that the air distribution with the UFAD formed a cold-air lake in the lower area of the room, with horizontal flow direction and relatively low flow velocity. Therefore, more particles are sent to upper part of the room through the thermal plume, which more easily move with the fluid, leading to better air quality in the working area.

(3) The smoke diffusion experiment using mosquito-repellent incense revealed that the number and mass concentration of fine particles below 0.5 \( \mu m \) obviously increased; however, the indoor air quality can meet the design requirements using the underfloor air distribution. The results of numerical simulation were consistent with those of the experimental measurements, proving that the Lagrange method is an effective means to simulate the steady-state and dynamic distribution of indoor particles, and has applicability and reliability for the improvement of building environments.

(4) The trajectory simulation of indoor particles showed that the small-sized particles had a relatively high number of suspension and discharge trajectories. As the particle size became bigger, the number of suspended and discharged particles reduced, while the settled particles increased.

(5) Simulation of the unsteady diffusion process of the mosquito-repellent incense smoke further proved that small-sized particles easily diffuse to the upper area through the thermal plume and are mostly discharged from the exhaust outlet. Meanwhile, large-sized particles tend to settle on the ground, due to their high gravity and sedimentation speed.

(6) We discussed the powerful diffusion and movement forces of particles, which seem to imply that the potential threat of aerosol transmission of respiratory infectious diseases cannot be ignored in relatively enclosed indoor environment. The experiment indicated that, once particles form aerosols—especially in narrow and confined spaces, such as enclosed offices, elevators, carriages, cinemas, and so on—a greater risk of infection is posed. Therefore, it is necessary to conduct indoor ventilation research, in order to reduce the aerosol concentration and, consequently, the virus density.

5.2. Limitations and future directions

Based on our results, there are several limitations to be noted, which also provide directions for future research.

(1) Complementing the theoretical study on particle suspension from wall to turbulence, the mechanism of particle desorption can be further analyzed and a particle desorption model can be established.

(2) Establishing an experimental system that can be precisely controlled to eliminate more interference factors, such as the dust raised by the testers, the particles infiltrating from outdoors into indoors, and multiple working conditions and measuring points, in order to comprehensively analyze the influence of ventilation, indoor heat sources, particle source locations, and other factors on the distribution of the indoor particle concentration.

(3) Due to the limitations of computing in numerical simulation, some settings were simplified in this research. In order to simulate the motion distribution of indoor particles more accurately, more particle tracks can be set while considering the turbulent diffusion of particles and monitoring the deposition of particles on the wall, in order to obtain more applicable motion rules.
6. Conclusion

In order to improve the indoor environment more effectively, we focused on distribution characteristics and motion trajectories of the particles through a combination of experimental measurement and mathematical modeling. By using theoretical methods, experimental tests, numerical simulation analysis, and physical modeling, several revealing conclusions can be drawn from this study.

In the scientific research fields, this study attempts to fill some research gaps in the main following aspects. First, there is a lack of detailed theoretical system and method comparisons in prior studies on indoor particles, the experimental studies have also been very limited. Second, there exist almost no previous studies focusing on the indoor particles on the ground which re-enter the room due to the action of the indoor air flow, resulting in the secondary pollution of the indoor air. Experiments on the motion and diffusion characteristics of particles under indoor flow fields are also rare. In this study, the distribution and motion characteristics of indoor pollutants in a floor air supply system considering the secondary pollution of ground dust were analyzed. Experiments on the particles with indoor flow fields are also discussed. Third, most research has not specifically studied through any medium, while this study analyzed the diffusion experiment of the mosquito-repellent incense. Through this experiment, it can be demonstrated again that the particles below 0.5 μm in the conclusion can be affected by Brownian force and can be easily discharged directly from the exhaust outlet. Moreover, the simulation analysis in this study provides theoretical guidance and numerical basis for predicting the purification process with a floor air supply and for controlling pollutants through a reasonable air distribution method.

In the practical fields, the results of the current study contribute to addressing factors associated with the climate change, indoor environment and human health in the background of the global energy crisis and CO₂ drainage reduction around the world. The main motivation behind this study reveals to evaluate and control indoor environment, particularly in terms of reducing the harm of air pollution to human health and reduce the harm of air pollution to human health. We also considered the comfort needs of indoor environment and addressed the lack of research on indoor air flow considering the secondary pollution of ground dust. In the future, it will be necessary to further analyze the correlation between the aerosols and indoor environment in order to propose methods for improving the air quality in closed spaces.

Based on the findings and conclusions of this study, the following recommendations can be proposed:

(1) From the perspective of government, environmental protection departments and health inspection departments should monitor the environment in densely populated areas, reduce the impact of outdoor pollution on indoor pollution. Meanwhile, the government should keep the supervision and management of indoor environment.

(2) From the perspective of controlling pollution particles, the ventilation environment should be optimized in order to realize the circulation between indoor and outdoor air. Indoor air self-purification, the air flow distribution and indoor air exchange design should be improved [36], which are also essential ways to improve the air exchange frequency, the quality of the fresh air, the air distribution and the indoor air flow. Physical adsorption and indoor greening can also regulate indoor temperature and humidity.

(3) From the perspective of building design, we should consider the general planning, improvement of the urban microclimate, building materials and application of renewable energy in buildings. A strong biological climate regulation and a virtuous cycle of ecological environment system among people, buildings and natural environment are necessary.

(4) From the perspective of energy conservation, we should avoid to reduce the fresh air rate to cut down the energy consumption of ventilation. The energy conservation of green buildings should be based on ensuring indoor ventilation, geothermal energy, solar photothermal technology, photovoltaic and wind power technology can also be used.

(5) From the perspective of people themselves, we should strengthen the awareness of indoor environmental protection and create a better green indoor environment.

Hence, the green indoor environment, which is essential for human health, can be achieved by reducing indoor air pollution. Research on particles in the indoor environment has become a common concern of environmental science and public healthy communities, which is of great significance for improvement of the building environment [37]. Building energy conservation and indoor environment quality have become two major themes for the optimization of building environments. Faced with global issues involving the resources shortage and environmental pollution, the green and low-carbon development, the energy conservation and emissions reduction, the resource-saving production and green energy-saving buildings are effective measures to get out of the dilemma and achieve sustainable development.

CRediT authorship contribution statement

Xinyu Zhuang: Conceptualization, Supervision, Formal analysis, Writing – original draft, Writing – review & editing. Yisong Xu: Methodology, Software, Writing – review & editing. Li Zhang: Supervision, Methodology, Formal analysis. Xin Li: Validation. Jie Lu: Validation.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The work was supported by the 2021 Research Project of Shandong Social Science Planning(grant number 21LYJ17), We would like to thank the editors and reviewers for their constructive feedback and help in improving the quality of the manuscript.

References

[1] Y. Guo, N. Zhang, T.R. Hu, Z.Y. Wang, Y.P. Zhang, Optimization of energy efficiency and COVID-19 pandemic control in different indoor environments, Energy and Buildings 261 (2022), https://doi.org/10.1016/j.enbuild.2022.111954 111954.
[2] N. Suzuki, Y. Nakayama, H. Nakaoka, K. Takaguchi, K. Tsumura, M. Hanazato, T. Hayashi, C. Mori, Risk factors for the onset of sick building syndrome: A cross-sectional survey of housing and health in Japan, Building and Environment 202 (2021) 107976.
[3] Z. Noorimotlagh, N. Jaafarzadeh, S.S. Martínez, S.A. Mirzaee, A systematic review of possible airborne transmission of the COVID-19 virus (SARS-CoV-2) in the indoor air environment, Environmental Research. 193 (2021) 110612.
[4] K. Zhang, X. Zhang, S. Li, X. Jin, Review of underfloor air distribution technology, Energy and Buildings. 85 (2014) 160–186.
