Scientific and Social Research, 2024, Volume 6, Issue 11
https://ojs.bbwpublisher.com/index.php/SSR
Online ISSN: 2981-9946
Print ISSN: 2661-4332

Operational Strategy of Nonuniform Air Supply in Cleanrooms

Xin Wang[1]*, Minwei Zhang[1], Hao Li[1], Li Wang[1], Jun Li[1], Zhijun Zou[2]

[1]University of Shanghai for Science and Technology, Shanghai 200093, China
[2]Donghua University, Shanghai 201620, China

***Corresponding author:** Xing Wang, wangxinshiyun@126.com

Abstract: To ensure that cleanroom cleanliness requirements are met, the current design and operation of cleanrooms generally necessitate the fan filter unit (FFU) to open. However, deploying an excessive number of FFUs may lead to an air volume redundancy problem, which can reduce air volume. Conversely, reducing FFUs and their airflow might also increase the risk of uneven indoor airflow distribution and particle concentration. This study analyzes the influence of the nonuniform operational strategy of FFUs (including the opening rate, arrangement position, and air velocity of FFUs) on the distribution of airborne particulate matter concentration in the cleanroom using CFD simulation technology. Results showed that opening only the top part of the source FFU can significantly reduce the indoor particulate concentration in the cleanroom and maintain the cleanliness that meets the requirements of cleanrooms. In the case of the same number of air exchanges, increasing the air velocity of the upper FFU of the indoor airborne particulate pollution source has a significant effect on the purification of indoor particulate matter in the cleanroom. These results show that the nonuniform air supply from the upper FFU of the source has good purification performance for airborne particles in a typical cleanroom.

Keywords: Cleanroom; Air supply; Airflow simulation

1. Introduction

A cleanroom is a special artificially controlled environmental space that plays an important role in modern industrial development by controlling air quality, temperature, humidity, and other environmental parameters to create an ultra-clean, dust-free, and sterile environmental space [1–4]. In recent years, cleanrooms have developed rapidly to meet the growing cleanliness requirements of processes and products in the electronics and pharmaceutical industries, as well as in hospital operating rooms [5–6]. An effective airflow organization design is essential for the removal of particles from cleanrooms.

Existing studies have mainly focused on different airflow arrangement forms, equipment coverage, floor openings, and new return air methods, which have enriched the understanding of airflow organization and contamination control in cleanrooms and helped improve the quality of cleanroom environment assurance [11–13]. Yang et al. studied the effects of different ventilation designs in cleanrooms, compared the airflow and particle concentrations of different contaminant sources, and investigated airflow and contaminant control in ventilated spaces to optimize the ventilation design in ISO 5 cleanrooms [7]. Tao et al. analyzed the arrangement of the fan filter unit (FFU) and elevated floor and explained the matching relationship between the arrangement rate of FFU and the opening rate of the elevated floor [10]. They found that by adopting the average arrangement, airflow can be gathered at the inlet of the return air duct, which affects cleanliness, and it should be arranged according to a particular gradient to obtain the optimal solution. Yang et al. analyzed the distribution characteristics of indoor particulate matter concentration in a cleanroom under the coupling conditions of different air return methods and air change times [9]. They found that the number of air change rates or the air supply speed has a significant effect on the inhomogeneity coefficient of indoor particulate matter. Moreover, the floor return method resulted in the lowest inhomogeneity coefficient of particulate matter concentration in cleanrooms, achieving the best uniformity.

Cleanliness is an essential indicator of cleanroom air quality and is one of the most essential evaluation indicators of environmental health, primarily determined by the pollutant emission rate and indoor air supply volume [8, 15–17]. To ensure cleanliness, cleanroom air supply is often over-guaranteed, which can lead to excessive consumption of large amounts of energy in the cleanroom [19, 25]. Energy can be saved by directly reducing the amount of operating air supply, as the volume of recirculated air in the cleanroom presents a substantial opportunity for reducing the air volume. Therefore, how to optimize the design of the number of air changes in a cleanroom has become a research hotspot in the field of air purification. Loomans et al. investigated and simulated two cases to study how to achieve the ideal airflow pattern in a cleanroom to achieve a high level of cleanliness [14]. The results showed that demand-based filtration can reduce the number of air exchange rates from 38/h to 16/h, with the same level of cleanliness, thereby saving considerable energy. Liang et al. studied the FFU arrangement in an electronic cleanroom for personnel in different positions, with a rate of 25% [18]. Their study aimed to reduce the number of air changes in the airflow organization, and they found that reducing air changes from 70/h to 30/h worsened the FFU airflow suppression of the thermal plume effect, increasing the effect of the thermal plume on surrounding FFU airflow significantly. Shao et al. investigated the experimental characterization of particle distribution in electronic clean plants with changes in air supply volume [12]. The results indicated that the particle distribution under non-unidirectional flow shows prominent inhomogeneous characteristics, and the air supply volume significantly affects the particle distribution characteristics. They suggested that deactivating FFUs in partitions farther away from the particle source and maintaining the speed of FFUs in the source partition can be more effective than simply reducing the overall air volume, potentially decreasing the total air volume by 40.6% and reducing air exchanges from 53.2/h to 39.2/h. Zhao et al. developed a theoretical expression for calculating clean air volume in nonuniform cleanrooms, providing a theoretical basis for designing energy-saving nonuniform cleanrooms that reduce air volume [20]. Liu et al. obtained the quantitative descriptive equations for the particulate matter exhaled by human beings in cleanrooms through numerical simulation calculations and statistical analyses of simulated data, providing a theoretical basis for the current study [26].

Results of existing studies have shown the potential of reducing the circulating airflow in cleanrooms [21]. However, the changes in airflow organization, whether the ability to control particle dispersion is weakened, and whether the corresponding cleanliness level of a cleanroom can be maintained at different numbers of air exchanges are the key issues that need to be investigated. Moreover, changes in airflow and particle distribution during airflow reduction have not been adequately investigated in existing studies. Therefore, in this study, a typical ISO 5 cleanroom is taken as an object to simulate and analyze the concentration and distribution of particles in the cleanroom and the feasibility of zonal airflow adjustment from the FFU opening rate and arrangement position. By comparing the uniform and nonuniform arrangements and changing the operational strategy (including FFU opening number, position, and air velocity) to reduce the number of air changes and air supply, this paper provides a scientific basis and reference for the energy-saving operation of cleanrooms.

2. Numerical simulation methods

2.1. Cleanroom physical model

The simulation study in this article focuses on the cleanroom of an electron beam exposure area with dimensions of 7.45 m in length, 6.56 m in width, and 3 m in height. Electronic exposure equipment is the main heat source in the room. The indoor air conditioning form of FFU+DCC+make-up air unit is adopted. The indoor circulating air passes through the elevated floor, returns to the ceiling space through the return air clamping channel and DCC, and then enters indoors through the ceiling space through the FFU. The FFU conveys clean air to remove particulate matter, as shown in **Figure 1**.

Inside the room, two pieces of equipment are situated, each measuring 2.1 m in length, 1.6 m in width, and 2.3 m in height. The room is equipped with a total of 25 FFUs, each sized at 1200 mm x 1200 mm, installed at a height of 3 m, supplying air at a temperature of 18 °C. In addition, eight dry cooling coils (DCCs) sized at 1200 mm x 800 mm, also supply air at 18 °C. Fresh air is sent to the ceiling space, with the air pipe situated 3.7 m above the elevated floor; and air is distributed through two outlets, each measuring 100 mm x 300 mm. The number of people in the room is considered to be two people working at rest. The position of the personnel is shown in the simulation model of the cleanroom in **Figure 2**.

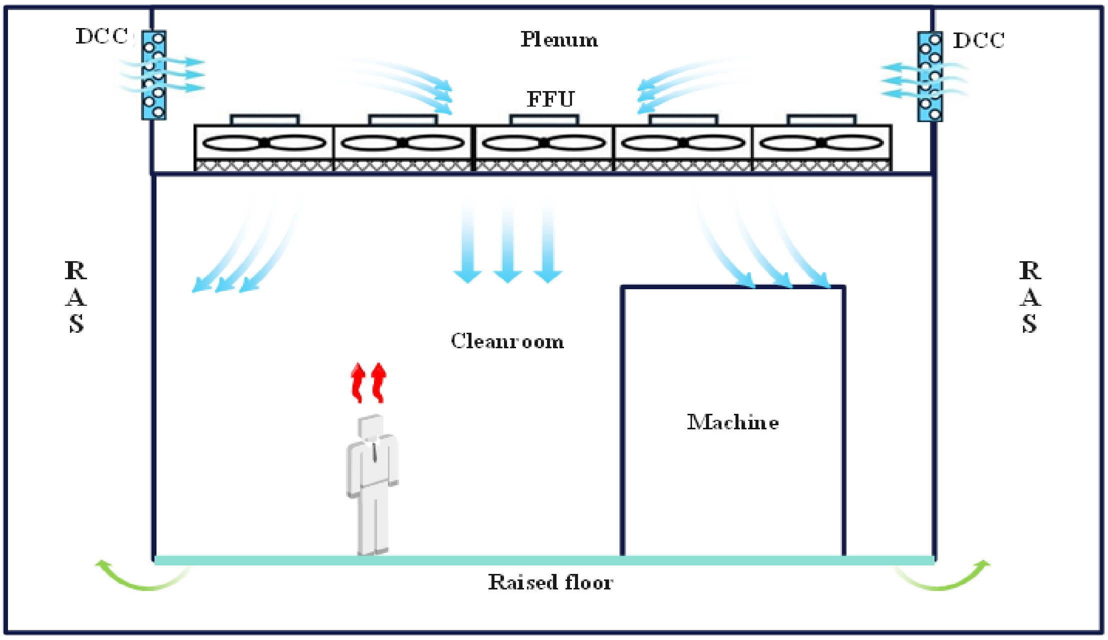


Figure 1. Schematic of the interior elevation of the cleanroom

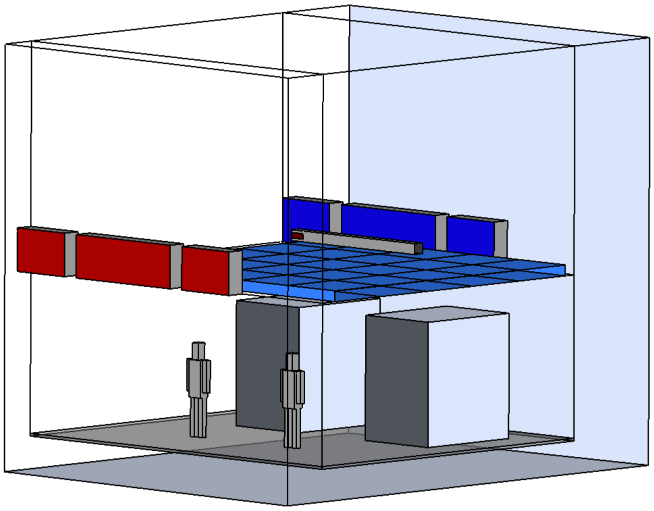


Figure 2. Three-dimensional space simulation model of the cleanroom

2.2. Simulation of working conditions

This study explores different operational strategies by designing seven modes of FFU operation, as shown in **Figure 3**, presenting FFU configurations at 100%, 75%, 50%, and 25% of operation levels in uniform and nonuniform arrangements. A 100% layout rate corresponds to all FFUs being operational, whereas layouts at 75%, 50%, and 25% involve activating 18, 13, and 7 units, respectively. Uniform arrangements are shown in **Figures 3a–3c** and **3g**; whereas nonuniform arrangements, which involve only operating FFUs above the area where the personnel are located, are shown in **Figures 3d–3f**.

This study aims to analyze and simulate the level and spatial distribution of particulate matter in cleanrooms in two cases as follows. The study evaluates the effect of uniformly reducing the number of operational FFUs open and using a nonuniform FFU layout (opening only the FFUs above personnel areas) on maintaining cleanroom cleanliness standards. Both approaches maintain the same FFU air velocity, with details shown in **Table 1**.

Table 1. Case setup under uniform and nonuniform arrangements

Case	Arrangement	Number of staff	FFU opening rate	FFU wind speed (m/s)	Number of units	ACH (times/h)
a	25% FFU-U	2	25%	0.385	7	95.4
b	50% FFU-U	2	50%	0.385	13	177.3
c	75% FFU-U	2	75%	0.385	18	245.5
d	25% FFU-NU	2	25%	0.385	7	95.4
e	50% FFU-NU	2	50%	0.385	13	177.3
f	75% FFU-NU	2	75%	0.385	18	245.5
g	100% FFU-U	2	100%	0.385	25	341.0

In each case, the FFU air velocity is set to 0.385 m/s. The control group is at 100% FFU operation (0.385 m/s), with uniform arrangements for 75% FFU-U, 50% FFU-U, and 25% FFU-U (**Figures 3a–3c**, respectively);

and nonuniform arrangements for 75% FFU-NU, 50% FFU-NU, and 25% FFU-NU, focusing on areas above personnel (**Figures 3d–3f**, respectively).

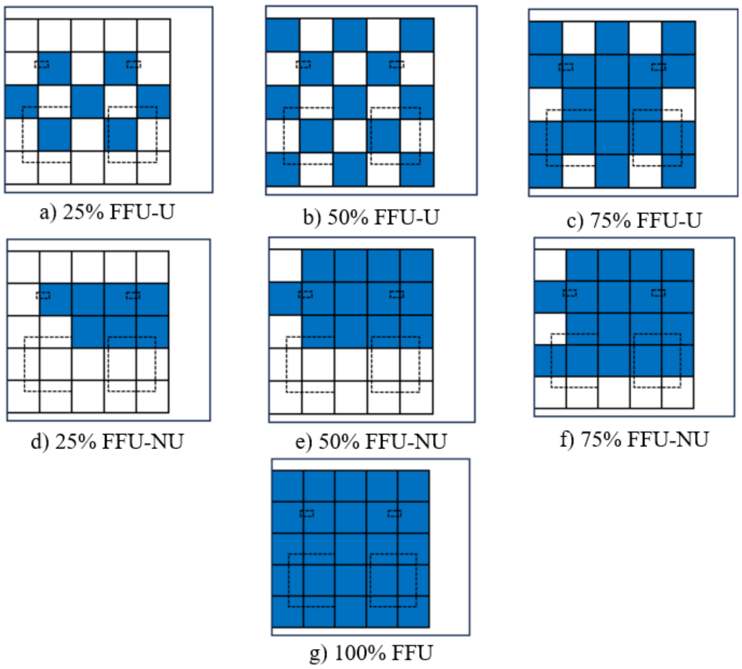


Figure 3. FFU arrangement

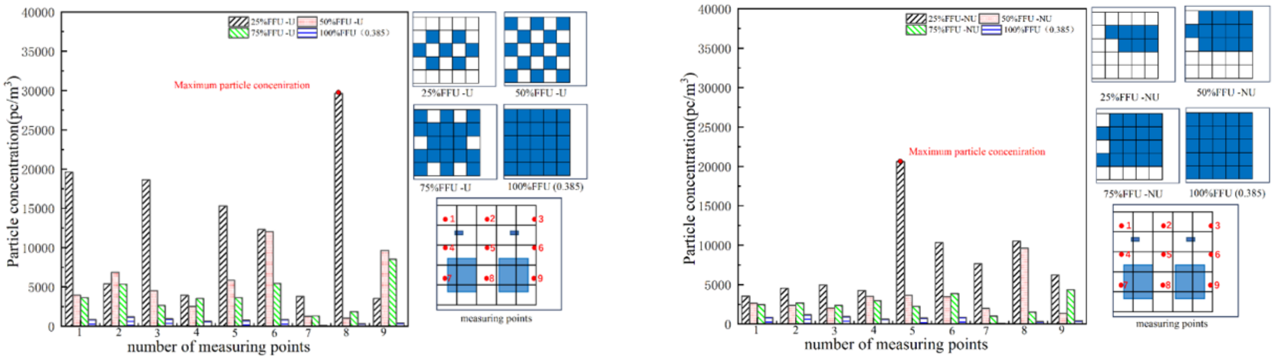
In this paper, the RNG k–ε model is chosen for the simulation process. The RNG k–ε model provides high accuracy, considering that the change in density has a negligible effect on the inertial force term, the pressure difference term, and the viscous force term. Only the effect on the mass force term is considered, enabling the simulation of airflow in the room. The standard wall function is used for the near-wall treatment. The discrete format uses the second-order windward format. The SIMPLE algorithm is used for the solution, and an under-relaxation iterative method is used to ensure convergence [18]. The boundary conditions at the FFU inlets and outlets are designated as the recirculation inlet and outlet, respectively; the fresh air inlet is characterized by the velocity inlet; and the DDC is characterized by pressure outlet boundary conditions [24].

Indoor personnel is identified as the source of indoor particulate release, specifically particles of size 0.5 μm, with a release assumed to be 56,000 pc/(person x min) when individuals are walking in a complete set of clean suits [22–23]. The discrete-phase model facilitates the interaction with the continuous phase. The particles are inert, and the material is set to carbon. The forces acting on the particles mainly include mass shear force, effective concentration force, Brownian force, lift force of Saffman, and influence of airflow. The magnitude of the external forces mainly depends on the flow state of the gas-phase fluid and the characteristics of the granular phase particles. For the study of the concentration field in a clean room, only the Saffman lift force and Brownian force caused by gravity and the velocity of the flow field should be considered.

3. Results and discussion

Cases 25% FFU-U, 50% FFU-U, and 75% FFU-U are uniformly operational. The number of FFUs is reduced evenly across the cleanroom occupied by two people. The particulate matter concentration on a 0.8-m horizontal plane at several points is analyzed, as shown in **Figure 4a**. As the number of operating FFUs gradually decreases, the indoor particulate matter concentration increases. With only 25% of FFUs in operation, their effect on controlling the particulate matter is almost negligible. The maximum value of each measuring point is at Measuring Point 8, with a particulate concentration of 29,652 pc/m^3. This result may be due to it being in the middle of the two devices, and pollutants accumulate in the middle. Conversely, in 50% and 75% arrangement rates, the airflow of the FFU above the personnel and the surrounding FFU have difficulty in effectively inhibiting the lateral diffusion of particulate matter emitted by the personnel, which seriously hampers the management of particulates, resulting in notably higher concentrations compared to a fully active FFU setup. However, at 50% and 75% FFU layouts, the FFU still has an inhibitory effect on indoor particulate matter, and the indoor particulate matter concentration at each measuring point can be controlled within 10,000 pc/m3.

Cases 25% FFU-NU, 50% FFU-NU, and 75% FFU-NU are designed to reduce the indoor particulate matter concentration without increasing the number of FFUs by adjusting the FFU arrangement position, such that the number of operating FFUs is arranged above the pollutants. The particulate matter concentration at each point in the cleanroom under the nonuniform arrangement with different numbers of FFUs is shown in **Figure 4b**. From the figure, compared to the uniform arrangement, the nonuniform arrangement of the FFU above the head of the personnel plays a significant role. Specifically, the maximum value of indoor particulate matter concentration from the uniform arrangement reduces from 29,652 pc/m^3 to 20,630 pc/m^3. In the case of 75% of operational FFUs, the nonuniform arrangement of indoor particulate matter concentration can be reduced by 46.3% compared to the uniform arrangement of the average. The indoor particulate matter concentration can be reduced by 49.8% and 67.1% at 50% and 25% operational FFUs, respectively.


a) Uniform arrangement

b) Nonuniform arrangement

Figure 4. Concentration of particle concentration in the cleanroom under uniform and nonuniform FFU arrangements

Figure 5 shows the concentration distribution of uniform and nonuniform arrangements at 0.8 m horizontal height. In the case of uniform arrangement (**Figures 5a–5c**), as the number of operational FFUs decreases, the diffusion capacity of particles increases in the case of 75% FFUs, and a small amount of buildup is found in the rear of the equipment area. In the case of 50% operational units, a large amount of particulate matter accumulation is observed in the non-FFU air supply area. In the case of 25% operational units, the influence range is further expanded, and the lateral diffusion of particulate matter emitted by the personnel in the FFU airflow is difficult to effectively control, and the deterioration of the airflow organization performance is severe. Therefore, as the FFU arrangement rate decreases, the performance of the airflow organization to inhibit the lateral diffusion of particulate matter deteriorates, and the scope of influence of particles increases.

When using a nonuniform arrangement (**Figures 5d–5f**), in the case of 75% of FFUs, the FFU arranged above the head of the personnel plays a significant role. It can still control particles around the contamination source. However, in the non-FFU air supply area, the contaminant source releases particles by the indoor vortex, and particles tend to agglomerate. Equipment located far from the FFU air supply remains largely unaffected, thereby maintaining cleanliness in those areas. At 50% operation, despite FFU being arranged above the pollutant source and less so above the equipment, it still manages to confine most of the particles near the pollutant source. However, due to the relatively small number of FFUs, the airflow organization to inhibit the lateral diffusion of particles deteriorates, and the particles diffuse into the equipment between the particles to expand the effect of the particulate matter. In the case of 25% FFU and pollutants on the top side, the FFU is only arranged above the head of the personnel, and the range of the effect of the particulate matter is further expanded. At this time, the personnel above the FFU and the surrounding FFU airflow have difficulty effectively inhibiting the lateral diffusion of particulate matter emitted by the personnel. The deterioration of the suppression ability of the airflow organization is severe, and the influence range of the particulate matter expands. It is concentrated near the equipment area, and signs of accumulation are present in the area away from the equipment and the air supply area of the FFU.

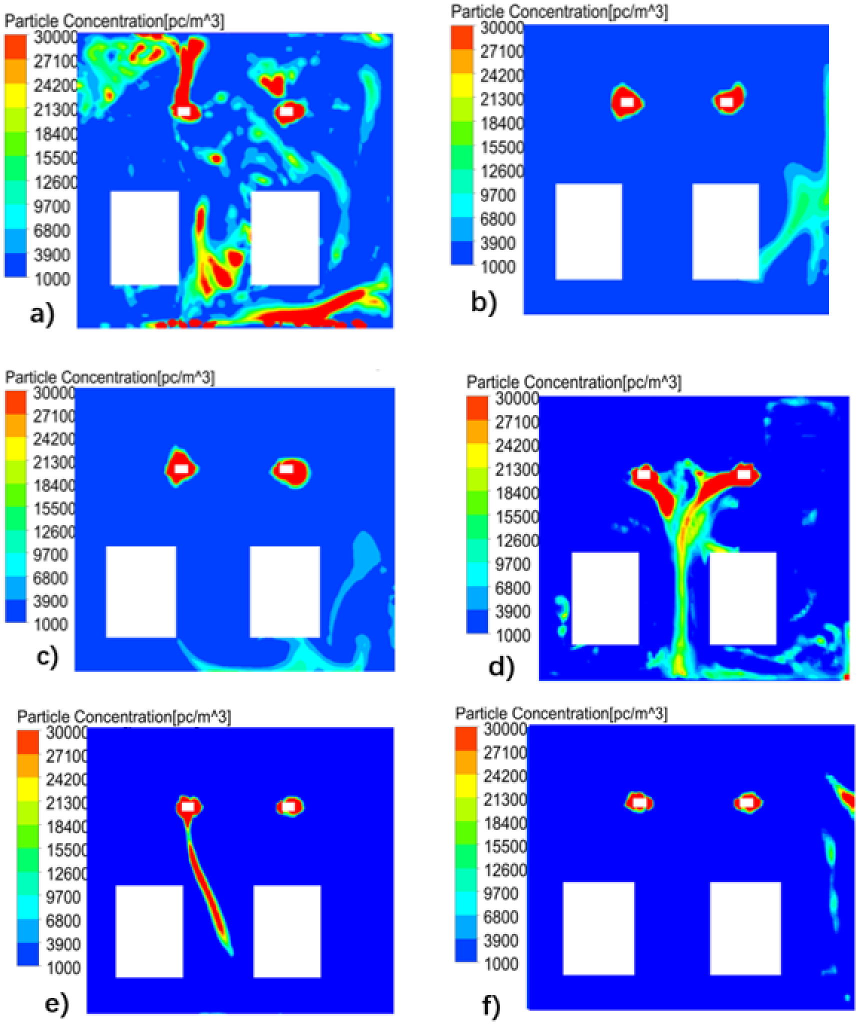


Figure 5. Distribution of particle concentration in uniform and nonuniform arrangements; a) 25% FFU-U, b) 50% FFU-U, c) 75% FFU-U, d) 25% FFU-NU, e) 50% FFU-NU, f) 75% FFU-NU

The detailed characteristics of particle concentration at each measurement point for indoor particles at each arrangement rate for the uniform and nonuniform arrangements are shown in **Figure 4**. The results are further processed using box plots to reflect the discrete state of particle concentration, as shown in **Figure 6**. A significant difference exists in the indoor particle concentration between the nonuniform and uniform arrangements. By uniformly reducing the number of FFUs, the number of air exchanges can be reduced by 7 FFUs from the original 341/h to 245.5/h while maintaining the ISO 5 cleanroom rating. By contrast, through a nonuniform reduction strategy that scales down by 12 FFUs, the number of air changes can be reduced from 341/h to 177.3/h. With the increase of the FFU arrangement rate, the particle concentration between each position becomes concentrated. When a uniform arrangement is used, the indoor particle concentration tends to increase compared to the nonuniform arrangement, whereas the particle concentration between the measurement points becomes discrete. Nonuniform arrangements can effectively reduce particulate retention and deposition in space by optimizing airflow and mixing effects. This arrangement is expected to provide improved particulate control performance in the cleanroom while saving energy and maintenance costs.

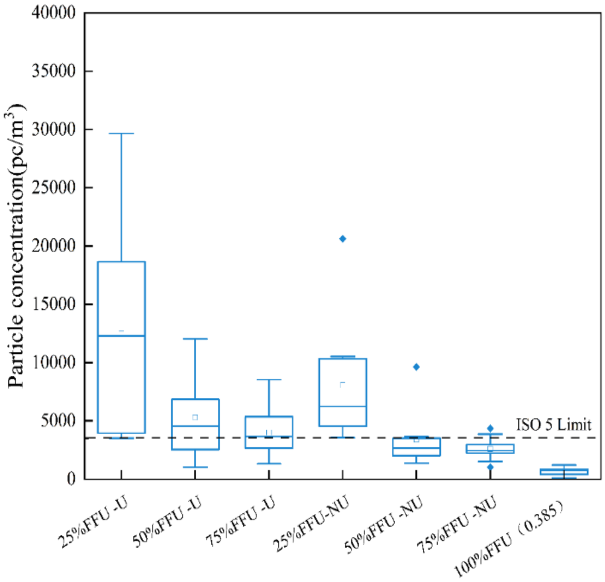


Figure 6. Box plot of particle concentration for uniform and non-uniform arrangements

4. Conclusion

Through the numerical simulation calculation method, this study analyzes cleanroom particle concentration and distribution by changing the number and arrangement of operational FFUs while maintaining the same air speed and air change rates.

When comparing uniform and nonuniform FFU arrangements with the same surface and velocity, the nonuniform arrangement, which places FFUs directly above the pollutant sources, significantly reduces the indoor particle concentration. Specifically, the average particle concentration can be reduced by about 46.3% to 67.1%, and the number of air change rates can be reduced from 341/h to 177.3/h. Changing the air speed in different areas has a more striking effect on particle management compared to a uniform distribution strategy when the air change rate remains constant.

Disclosure statement

The authors declare no conflict of interest.

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