Study on Self-Cleaning Time and Suspended Particle Distribution in Medical Clean Room

Long Chen¹, Enyan Wang¹, Yang Li², Miaocheng Weng¹,³,⁴,* and Fang Liu¹,³,⁴,*

¹ School of Civil Engineering, Chongqing University, Chongqing 400045, PR China
² Hainan Tianjie Commercial Management Co., LTD, Hainan 570125, PR China
³ Key Laboratory of New Technology for Construction of Cities in Mountain Area of Ministry of Education (Chongqing University), Chongqing 400045, PR China
⁴ Joint International Research Laboratory of Green Buildings & Built Environments, Chongqing 400045, PR China

B Campus, Chongqing University, 83 Shabei Street, Shapingba District, Chongqing.
Email: chlchonglong@qq.com

Abstract. CFD numerical simulation of clean room in Class D medical factory was carried out and compared with the actual measurement to verify the feasibility of the simulation method. On this basis, four typical air flow organizations were simulated and compared by changing air change rate from two directions of self-cleaning time and suspended particle concentration field. According to the simulation results, in order to meet the self-cleaning time within 20 min, the best air change rate should be between 15/h and 25/h. Different air flow organizations have different self-cleaning capacity, and the value of air change rate can be relatively small in the form of single-side supply same-side down return. Different airflow organizations have different suspended particle distribution characteristics, and there are differences in the applicable scenarios, and the applicability of the top supply down return is the best.

Keywords. Clean room; CFD numerical simulation; Self-cleaning time; Suspended particles; Air flow organizations; Air change rate.

1. Introduction

To ensure the quality of drugs, the creation of indoor environment in medical workshop is particularly important, which puts forward a certain test for the design of clean room, not only to meet the requirements of relevant specifications, but also to achieve energy conservation and environmental protection, reasonable air flow organization and air change rate is the key. By comparing relevant domestic and foreign specifications, it can be found from the requirements of air change rate for class D clean rooms and ISO class 8 clean rooms that the span ranges from 3.5/h to 25/h [1][2][3], which brings difficulties to the actual design. Meanwhile, by comparing the changes of the old and new GMP in China and Code for design of pharmaceutical industry clean room, it can be found that the current specifications have removed the specific provisions on air change rate and instead require designers to select appropriate air change rate according to the actual situation to meet the requirements of indoor environment [3][4].

As an important performance indicator of non-unidirectional flow clean room, self-cleaning time is required by current GMP to be within 20 min [4][5]. A lower air change rate can also meet the static standard of Class D clean room, but it may not meet the self-cleaning time requirement. Therefore, an appropriate air change rate is of great significance. Meanwhile, there are a variety of air flow...
organizations for this level of clean room to choose from, and the difference between each air flow organization should also be considered. However, most of the current researches are confined to the analysis and evaluation of the indoor flow field. Some scholars have studied the concentration field of suspended particles, but there is little horizontal comparison between different air flow organizations, and there is a lack of studies on the self-cleaning time of Class D clean room[6][7][8]. In this paper, the single-side supply same-side down return, double-side supply double-side down return, top supply down return and top supply top return the four kinds of typical air flow organizations, use the method of CFD numerical simulation in combination with the measured contrast, change the air change rate to simulate the distribution of suspended particles under self-cleaning process and steady state, and the optimal air change rate to meet the self-cleaning time is given, and the applicable characteristics of different air flow organizations are analyzed.

2. Physical Model Building and CFD Simulation
The pharmaceutical plant is located in Suihua City, Heilongjiang Province. In this paper, a clean room of the fluidized bed granulation process in the plant is selected to simulate the self-cleaning time test under as-built.

2.1. Clean Room Model
One side of the clean room has a local suspended ceiling, two side air supply outlets, a top air supply outlet, and five return air inlets, and two staff members are standing inside. Taking into account factors such as computing resources and computing time, a simplified physical model was set up as shown in figure 1, with the parameters shown in table 1.

![Figure 1. Clean room physical model.](image1)

![Figure 2. Schematic diagram of mesh division.](image2)

| Room size (m) | Room volume (m³) | side air supply outlet (m) | top air supply outlet (m) | return air inlet (m) |
|---------------|------------------|----------------------------|--------------------------|---------------------|
| 7.6×5.5×3.0   | 122.9            | 0.83×0.30                  | 0.50×0.50                | 0.40×0.40           |

2.2. Mesh Division
As shown in figure 2, since the model is composed of regular geometric shapes, it is divided into structured meshes. In addition, the quality of the meshes was checked and it was found that more than 99.5% meshes of the determinant 2×2×2 and determinant 3×3×3 were above 0.95, and no mesh below 0.75 was found, which proved the high quality of the meshing.
2.3. Computational Model Selection

To facilitate the calculation, the following assumptions and simplifications were made based on the characteristics of indoor air flow:

- Indoor air as incompressible Newtonian fluid.
- Indoor air is a viscous fluid, and the air flow is a steady flow.
- Indoor air leakage and outdoor air infiltration are not considered.
- Energy loss caused by air flow is not considered.

Meanwhile, the following assumptions and simplifications are made for suspended particles:

- The movement of suspended particles has no influence on indoor air flow field.
- There is no merging and breaking of suspended particles.
- All suspended particles are spherical.

According to the above assumptions and simplifications, the standard k-ε model, which has been verified by most scholars to be feasible, has been chosen for the indoor air turbulence model. k and ε are the basic unknown quantities, and the corresponding equations are as follows:

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + \mu_t \frac{\partial u_i}{\partial x_j} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \rho \varepsilon 
\]  

(1)

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right) - \rho c_2 \frac{\varepsilon^2}{k} + c_1 \frac{\varepsilon}{k} \mu_t \frac{\partial u_i}{\partial x_j} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) 
\]

(2)

For the flow of suspended particles in air, the DPM model was chosen to simulate the discrete phase, which is suitable for situations where the volume fraction of the discrete phase is small, such as in a clean room.

2.4. Boundary Condition Setting

The air change rate in this clean room is 26/h, and the air supply volume is set according to the actual measurement. Table 2 shows the boundary condition settings for the air flow simulation.

| Items               | Boundary conditions | Velocity or pressure |
|---------------------|---------------------|----------------------|
| Side air supply outlet | velocity           | 1.271 m/s            |
| Top air supply outlet   | velocity           | 0.979 m/s            |
| Return air inlet       | pressure            | 0 pa                 |

Table 2. Air flow simulation boundary conditions.

This paper discusses the concentration of suspended particles with a diameter greater than or equal to 0.5μm, which can be approximated by a single particle with a diameter of 0.5μm instead, based on the experience of previous scholars. For the setting of the dust generation, it was determined after comparing the simulation results with the actual measurements based on the review of relevant information [9]. Table 3 shows the relevant boundary condition settings for the DPM model.

| Items       | Dust generation rate | Discrete phase contact type |
|-------------|----------------------|----------------------------|
| Staff       | 2765 pc·(s·person)^{-1} | reflect                   |
| Floor       | 388 pc·(s·m^2)^{-1}    | reflect                   |
| Wall        | 236 pc·(s·m^2)^{-1}    | reflect                   |
| Ceiling     | 0                    | reflect                   |
| Supply/return air outlet | /               | escape                   |

Table 3. DPM model boundary conditions.

2.5. Simulation and Measurement

In order to verify the reliability of the simulation, unsteady-state simulation and steady-state simulation were conducted to compare with the measured data of the self-cleaning process and the
suspended particles after stabilization. The location of the measured suspended particle concentration is shown in figure 3. The height of the arrangement is 0.8m. The specific location of the plane is shown in table 4.

![Figure 3. Layout of measurement points.](image)

**Table 4. Location of measurement points.**

| number | 1       | 2       | 3       | 4       | 5       | 6       |
|--------|---------|---------|---------|---------|---------|---------|
| (x, y) | (1.5, 1.2) | (1.5, 4.3) | (4.0, 1.2) | (4.0, 4.3) | (6.0, 1.2) | (6.0, 4.3) |

Figure 4 shows the comparison between the simulation results and the actual measurement. It can be seen that the simulation of the self-cleaning process has the same trend as the actual measurement, and the data do not differ much, and the simulation of the concentration field of suspended particles after stabilization has the same trend as the measured concentration distribution, so the simulation can be considered reliable.

![Figure 4. Simulated versus measured](image)

Figure 4. Simulated versus measured (a) Variation of suspended particle concentration during self-cleaning process; (b) Post-stabilization suspended particle concentration.

3. CFD Simulation Conditions and Results Analysis

3.1. Clean Room Model

In order to investigate the effect of air change rate on the self-cleaning time, and to compare the characteristics of each air flow organization, this paper conducted unsteady state simulation and steady state simulation for four typical air flow organizations, namely, single-side supply same-side down return, double-side supply double-side down return, top supply down return, top supply top return, and the respective physical models are shown in figure 5. With reference to the design range of air change rate in class D clean rooms, eight types of air change rate were set for each air flow organization, 11/h,
14/h, 17/h, 20/h, 23/h, 26/h, 29/h, 32/h, and the suspended particle concentration at 0.8m height was counted.

Figure 5. CFD physical model of typical air flow organization (a) Single-side supply same-side down return;(b) Double-side supply double-side down return;(c) Top supply down return;(d) Top supply top return.

3.2. Evaluation Criteria
The pharmaceutical workshop belongs to class D clean room, according to the GMP[4], the concentration of suspended particles greater than or equal to 0.5 μm does not exceed 3520000 pc·m⁻³ under as-rest, and it is recommended that the self-cleaning time does not exceed 20 min[5], where the self-cleaning time is measured according to 100:1 suspended particle concentration, which means that the clean room in the contaminated state is reduced to 0.01 times the suspended particle concentration after the air conditioning system is turned on[10]. The initial suspended particle concentration in the cleanroom in this simulation was 23135766 pc·m⁻³ and the 100:1 suspended particle concentration was 231358 pc·m⁻³.

3.3. Analysis of Results

3.3.1. Self-cleaning Time. Through CFD simulation, the self-cleaning of each air flow organization with different air change rate is obtained, and the variation of suspended particle concentration with time is shown in figure 6. The specific values and trend of self-cleaning time are shown in table 5 and figure 7 respectively.
Figure 6. Variation of suspended particle concentration with time under different air exchange rate of each airflow organization: (a) Single-side supply same-side down return; (b) Double-side supply double-side down return; (c) Top supply down return; (d) Top supply top return.

As shown in figure 6, the logarithm of the concentration of suspended particles at the beginning of the self-cleaning process under each air flow organization and time is approximately linear, with the increase of time, the greater air change rate, the earlier the concentration of suspended particles into a stable state, and when air change rate is about 25/h or more, increase air change rate the concentration change of suspended particles after stabilization is no longer obvious, indicating that for these types of air flow organizations, simply by increasing the air change rate to improve cleanliness needs to be under a certain air change rate to have a better effect.

Table 5. Self-cleaning time (min) under different air change rate of each air flow organization.

| Air change rate | 11/h | 14/h | 17/h | 20/h | 23/h | 26/h | 29/h | 32/h |
|-----------------|------|------|------|------|------|------|------|------|
| Single-side supply same-side down return | 21.8 | 16.6 | 13.7 | 12.3 | 10.4 | 9.6  | 8.6  | 7.7  |
| Double-side supply double-side down return | 45.1 | 26.2 | 17.6 | 15.7 | 14.3 | 11.6 | 10.6 | 9.6  |
| Top supply down return | 43.8 | 27.4 | 19.6 | 15.7 | 12.3 | 11.4 | 10.6 | 8.3  |
| Top supply top return | 67.2 | 17.4 | 13.4 | 11.9 | 9.6  | 9.1  | 7.4  | 6.6  |
Comparing each air flow organization, combined with table 5 and figure 7, it can be seen that the self-cleaning time of the four types of air flow organizations shows the same trend with the change of the air change rate, and the self-cleaning time of the single-side supply same-side down return and top supply top return is shorter than that of the double-side supply double-side down return and top supply down return with the same air change rate, among which it can be seen from figure 6 that the concentration of suspended particles of the top supply top return decreases more rapidly than other air flow organizations at the early stage of self-cleaning, but the concentration is relatively higher after stabilization. Meanwhile, it can also be seen that increasing the number of air change rate below 23/h has an obvious effect on shortening the self-cleaning time, and when air change rate is above 25/h, the change trend of self-cleaning time becomes smaller, and the difference between the airflow organizations is not big; when air change rate is below 15/h, reducing the air change rate may result in excessive self-cleaning time, in addition, it should be especially noted that even if air change rate in about 10/h, the concentration of suspended particles after stabilization is far below the requirements of the class D clean room (not more than 3520000 pc/m$^3$), but at this time the self-cleaning time has been too large. For these types of air flow organization, to meet the self-cleaning time within 20min, the air change rate in 15/h to 25/h between the best, where single-side supply same-side to the required air change rate can take a smaller value.

### 3.3.2. Suspended Particle Distribution

In order to further compare and analyze the characteristics of each airflow organization, $z=0.8$m and $y=2.75$m cross sections were selected for each air flow organization at 20/h air change rate to analyze the concentration fields of suspended particles after stabilization, as shown in figure 8 and figure 9.
As can be seen from Figure 8, at the working surface height, for the two side supply side return forms, the concentration of suspended particles is high near the return side; for the single-side supply same-side down return, the concentration of suspended particles is lower in the area on the other side of the air outlet; for the double-side supply double-side down return, the concentration of suspended particles is lower in the middle of the room. On the working surface height, for the two top supply forms, the concentration of suspended particles is high near the four sides of the building enclosure, where the top supply top return also has a large area of high concentration of suspended particles on the return side; for the top supply down return, the concentration of suspended particles is low within the area about 1m from the building enclosure; for the top supply top return form, the concentration of suspended particles is low in the area below the air outlet.

As shown in Figure 9, in the middle of the room, for the two side supply side return forms, the concentration of suspended particles is high near the return side, while the phenomenon of suspended particles gathering near the floor; for the top supply down return, the concentration of suspended particles is more uniform in most areas, and the phenomenon of high concentration of suspended particles appears in the lower area between the air supply outlets; for the top supply top return, the phenomenon of high concentration of suspended particles appears in a large area in the upper part of the room on the return side.
3.3.3. **Summary.** In a comprehensive analysis, the top supply down return is applicable to most cases, while the side supply and top supply top return form are applicable to the case where only part of the room is used as the working area, among which the side supply form should try to avoid the dust on the floor caused by indoor activities, while the top supply top return is best to stay away from the return side during production activities because of the obvious gathering of suspended particles in the space above the working height on the return side.

4. **Conclusion**

CFD method was used to perform unsteady-state simulation and steady-state simulation for a pharmaceutical plant of class D cleanliness, and compared with the measured data, and then four typical air flow organizations were simulated and compared, and the following main conclusions were drawn.

To meet the requirements of self-cleaning time within 20 min, according to different forms of air flow organization can be designed for different air change rate, but generally in 15 / h to 25 / h for the best, where the single-side supply same-side down return can be relatively small value. For the top supply top return, although the concentration of suspended particles in the early stage of the self-cleaning process decreases more quickly, air change rate above 15/h, the self-cleaning time is relatively shorter than other forms, but also faster to enter the steady state, while the concentration of suspended particles is relatively higher, it is not appropriate to take a lower air change rate.

When air change rate is below 15/h, reducing the air change rate will increase the self-cleaning time and the concentration of suspended particles after stabilization; when air change rate is above 25/h, increasing air change rate will not reduce the self-cleaning time significantly, and the concentration of suspended particles after stabilization will not change significantly. Therefore, when air change rate is lower than 15/h, the appropriate increase in air change rate can bring a greater improvement to the cleaning effect; when the air change rate is higher than 25/h, the increase in air change rate will not improve the cleaning effect much, but increase the energy consumption in vain.

Different forms of air flow organization have different characteristics of suspended particle distribution, the top supply down return does not have a particularly concentrated area of suspended particles, and is applicable to most scenes; the side supply form is applicable in part of the area for the work area, and when setting up the work area as far as possible in the middle of the room, which for the room length is relatively small room, single side supply same side down return than double side double side down return better performance, this is because The former in most of the space can form a similar one-way flow of parallel airflow and the latter will form more turbulent area; the top supply top return will form suspended particles gathering above the working height of the air return side, workbench arrangement should be far from the return side, applicable to workshops with low dust generation and low cleanliness requirements.

**References**

[1] European Committee for Standardization ISO 14644-4. 2001 *Cleanrooms and Associated Controlled Environments* Part 4: Design, construction and start up. p 18.

[2] Domestic - National standard - State Administration for Market Regulation CN-GB. GB 50073-2013 *Code for Design of Clean Room*. p 21.

[3] Domestic - National standard - State Administration for Market Regulation CN-GB. GB 50457-2019 *Standard for Design of Pharmaceutical Industry Clean Room*. pp 30–38.

[4] State Food and Drug Administration. 2011 *Good Manufacture Practice of Medical Products*.2010. Beijing: China Medical Science Press. p 74.

[5] Xu Z L. 2011 *Pharmaceutical Clean Room Design, Operation and GMP Certification*. Version 2. Tongji University Press. pp 23–24.

[6] Huang W H, Wei Q, Lu Q M. 2006 *Application of CFD in Airflow Design for Cleanroom* (Contamination Control & Air-conditioning Technology (02)) pp 7–11.
[7] Khoo C Y, Lee C C, Hu S C. 2012 An Experimental Study on the Influences of Air Change Rate and Free Area Ratio of Raised-floor on Cleanroom Particle Concentrations (Building & Environment, 2012, 48(Feb.) pp 84–88.

[8] Zhao J N, Zhang X S. 2008 Clean Down Capability Prediction in Clean Operation Room Based on Technology of CFD and Reliability Test (Journal of Harbin University of Commerce(Natural Sciences Edition), 2008(02)) pp 227–232.

[9] Xu Z L. 2014 Fundamentals of Air Cleaning Technology And Its Application In Cleanrooms. Version 4. Science Press. pp 385–390.

[10] European Committee for Standardization ISO 14644-3. 2019 Cleanrooms and associated controlled environments Part 3: Test methods. pp 34–38.