NUMERICAL ANALYSIS ON PERFORMANCE OF DIFFERENT CEILING COVERAGE OF FAN FILTER UNITS IN SEMICONDUCTOR FABS

Juan Zhao1,2, Xianting Li*, and Wei Xu2

1Department of Building Science, Beijing Key Laboratory of Indoor Air Quality Evaluation and Control, China.
2Institute of Building Environment and Energy, China Academy of Building Research, China.

Abstract. In practical semiconductor fabs engineering, in order to reduce the investment cost, low coverage rate of FFUs is usually adopted and the air supply velocity is high, which brings high resistance to the filter mounted at FFU’s outlet. If a higher ceiling coverage and lower air velocity speed are used, the resistance may be significantly reduced and remarkable energy saving benefits can be obtained. In this study, CFD technology was adopted to simulate airflow in a semiconductor fab and air circulation resistance was obtained by theoretical calculation. Four ceiling coverage of FFUs, 25%, 50%, 75%, 100%, were studied under the condition of same air volume. The particle concentrations and payback period were analysed. The results show that (1) with the increase of the coverage rate, the concentration in most areas decreases significantly while only a small increase in the local area around occupants, and the particle concentration still meets the requirement; (2) adopting high coverage rate for transformation, the initial investment of FFUs increases slightly and the operating cost decreases significantly, and the payback period is only 1.1-2.3 years when 25% coverage rate is transformed into 37.5%-75%.

1 Introduction

Semiconductor fabs are energy-intensive buildings. In order to ensure high cleanliness of the fab, huge circulating air volume is required. Because of the great circulation resistance, the energy consumption of circulation fans is significant, and the annual power consumption can reach 1413 kWh/m² according to the research results of Taiwan fabs [1]. So, how to reduce energy consumption of circulation fans is very important.

FFUs are widely used in semiconductor fabs because of easy installation, which are integrated with high performance filter [2]. In practical engineering, the ceiling coverage of FFUs is usually low and the air supply velocity is high, which brings high resistance to the filter mounted at FFU’s outlet. If a higher ceiling coverage is adopted, the air supply velocity will be lower with the same air volume. In this case, the resistance can be significantly reduced and remarkable energy saving benefits of FFUs can be obtained.

In this study, the particle concentrations and air circulation resistances with different ceiling coverage of FFUs were analysed. The payback period of different schemes was compared to find a better coverage rate.

The research is of great significance for guiding airflow design of semiconductor fabs because both energy efficiency and cleanliness level can be improved significantly. Through this study, we hope to change the current practice that low ceiling coverage is adopted at priority when designing airflow.

2 Methodology

2.1 Physical model

A cleanroom of class ISO 6 was selected as the research object. The design temperature is 23 ± 2 °C and relative humidity is 45 ± 10 %. The dimension is 9.6m × 4.8m × 3.5m and the height of subfab is 1.2 m. The coverage rate of FFUs is 25 % and each size is 1.2m × 0.6m. The supply air velocity is 0.35 m/s. There are five occupants with size of 0.8m × 1.2m × 2.3m and six equipment with size of 0.8 m × 1.2m × 2.3m. Fig. 1 shows a schematic diagram of cleanroom.

Fig. 1. Local schematic diagram of cleanroom.
The heat source of cleanroom is mainly composed of equipment, occupants, lighting, and so on. The heat dissipating capacity of the scene is 310 W/m². The heat generated from each equipment is 1000 W. The heat from each occupant is 100 W. The auxiliary equipment, pipes, lights and other heat source is simplified as uniform background heat source, set to 40 W/m².

The particle source in cleanroom is mainly occupant and the emission rate with overall garment is 56000 pc/(min·p). Other particle source, such as equipment, building materials and so on is accounting for 20% of the total particle emission rate [3]. Those are simplified as background uniform particle source, set as 477 pc/(m³·min).

2.2 Numerical method

The parameter distribution in cleanroom was simulated by CFD. The standard k-ε model can predict the indoor airflow well and consumes less computing resources [4,5]. Hence, it was used to predict the airflow in this study.

For the particles, previous studies pointed out that the diffusion and transport properties of particles of size less than 2 μm are similar to that of a passive gas [6,7]. Therefore, in this study, particles were regarded as gaseous pollutants being transported passively. The control equation used to calculate the concentration of particles is as follows

\[
\frac{\partial}{\partial t} (C_p) + \nabla \cdot (C_p u_i) = S_p
\]

where \( C_p \) is particle concentration (particles/m³); \( u_i \) is the velocity of the air (m/s); \( S_p \) is the emission rate per unit volume of the particle source (particles/(m³·s)).

The above equation was discretized into algebraic equations using the finite volume method (FVM), with a second-order upwind scheme. The SIMPLE algorithm was adopted to solve the continuity and momentum equations. The Boussinesq model was employed to evaluate the buoyancy effect. The details of the numerical method can be found in Ref. [8–10].

The coverage rate of FFU will significantly affect the initial investment and operating costs. So, the payback period should be evaluated. When the 25% coverage rate is transformed into the 37.5% - 75%, there will be an increase in initial investment and a decrease in operating costs. The payback period can be calculated by the following equation

\[
T = \frac{P_{\text{initial}} - P_{\text{initial}}}{P_{\text{operating}} - P_{\text{operating}}}
\]

where \( T \) is payback period (year); \( P_{\text{initial}} \) is initial investment of FFU (¥); \( P_{\text{operating}} \) is operating costs (¥); \( P_{\text{initial}} \) is initial investment of 25% coverage rate (¥); \( P_{\text{operating}} \) is operating costs of 25% coverage rate (¥).

The initial investment is mainly determined by the number of FFUs used and the initial investment can be expressed as

\[
P_{\text{initial}} = n \times P_i
\]

where \( n \) is the number of FFUs (/); \( P_i \) is unit price of FFU (¥), here is 1000 ¥.

The operating costs is mainly determined by the power of FFUs and the operating costs can be expressed as

\[
P_{\text{operating}} = N \times 8760 \times P_2
\]

where \( P_2 \) is electricity price (¥/kWh), here is 0.8 ¥/kWh; \( N \) is the power of FFU (kW).

The power of FFUs (N) should be determined by the air volume and circulation resistance, where the resistance is composed of filter resistance and other resistance. The filter resistance will be affected by the supply air velocity, that is, the coverage rate of FFUs. Thus, the power of FFUs can be calculated by the following equations

\[
N = Q^*H/(3600*1000*\eta)
\]

\[
H = H_1 + H_2
\]

\[
H_1 = C^*V^{1.2}
\]

where \( Q \) is total air volume (m³/s); \( H \) is total circulation resistance (Pa); \( \eta \) is efficiency of FFUs (/), here is 0.35; \( H_1 \) is filter resistance (Pa); \( H_1 \) is the rest of resistance (Pa), here is 60 Pa; \( C \) is resistance coefficient of filter, here is 845 [11]; \( V \) is supply air velocity (m/s).

2.3 Case design

For the traditional airflow design in the cleanroom, the low coverage rate of FFUs is adopted. It results high supply air velocity and high filter resistance. If higher coverage rates are used, from 25% to 75%, the resistance and power of FFUs can be reduced, which means lower operating costs. However, the number and investment of FFUs will increase. The payback period should be evaluated.

![Fig. 2. Arrangement of FFUs in cleanroom.](image)

Table 1. Setting of different coverage rate

| Coverage rate | FFU arrangement | Supply velocity |
|---------------|----------------|----------------|
| 25%           | FFU arrangement | Supply velocity |
| 37.5%         | FFU arrangement | Supply velocity |
| 50%           | FFU arrangement | Supply velocity |
| 75%           | FFU arrangement | Supply velocity |
3 Results

3.1 Particle concentration

First of all, the particle concentration should be analyzed when increasing the coverage rate of FFUs. Because the particle release intensity from occupant is large, the concentration around occupant is higher than the other areas.

Thus, the particle concentration in cleanroom is evaluated in two parts: the concentration within 0.2m of occupant and the concentration in the other areas. The calculation results with different coverage rate of FFUs are shown in Table 2.

From the result we can see, when increasing the coverage rate of FFUs, the particle concentration in most areas of cleanroom decrease significantly, from 1130 pc/m³ to 242 pc/m³, and the concentration are increased only in a small area around occupant, from 8810 pc/m³ to 15400 pc/m³. In a word, all the average particle concentration with different coverage rates is lower than the standard value, 35200 pc/m³.

Table 2. Particle concentration with different coverage rate of FFUs (pc/m³)

| Coverage rate | 25% | 37.5% | 50% | 75% |
|---------------|-----|-------|-----|-----|
| Occupant 1    | 9390| 11700 | 13600| 15900|
| Occupant 2    | 12500| 11500 | 13600| 16700|
| Occupant 3    | 10700| 11200 | 15100| 17400|
| Occupant 4    | 7350| 12500 | 15500| 16700|
| Occupant 5    | 4160| 8970  | 9400 | 10700|
| Average concentration within 0.2 m of occupant | 8810| 11200 | 13500| 15400|
| Average concentration in the rest area | 1130| 431   | 275  | 242  |

3.2 Payback period

All coverage rates can well meet the requirements of particle concentration, but the costs of different schemes vary a lot. With the increase of coverage rate, from 25% to 75%, although the circulation resistance and power of FFUs can be significantly reduced, the initial investment of FFUs will also increase. The payback period should be calculated to compare the different schemes.

Table 3 shows the calculation results of payback period with different schemes. With the increase of the coverage rate, more FFUs are needed, and the initial investment increases significantly, from 16000 yuan to 48000 yuan. However, due to the decrease of the air supply velocity and filter resistance, the power consumption of the FFUs is reduced, and the operating cost is significantly reduced, from 24199 yuan to 10041 yuan. The payback period is only 1.1-2.3 years when the 25% coverage rate is transformed into the 37.5% - 75%.

It shows that increasing coverage rate is a feasible scheme. The remarkable energy saving and economic benefits can be achieved.

Table 3. Payback period of different coverage rates

| Coverage rate | Initial investment (¥) | Operation costs (¥/year) | Payback period (year) |
|---------------|------------------------|--------------------------|-----------------------|
| 25%           | 16000                  | 24199                    | Baseline              |
| 37.5%         | 24000                  | 16722                    | 1.1                   |
| 50%           | 32000                  | 13269                    | 1.5                   |
| 75%           | 48000                  | 10041                    | 2.3                   |

4 Conclusion

In practical engineering, the ceiling coverage of FFUs in cleanroom is usually low and the air supply velocity is high, which brings high resistance and high energy consumption. In order to achieve the goal of energy saving, the method that adopting high coverage rate is studied.

In this study, the model with a coverage rate of 25% was established as a baseline. The particle concentration, initial investment, operating costs and payback period with coverage rates 37.5%, 50% and 75% were compared with that of 25%. The main conclusions are as follows:

(1) Under the same air volume, the high coverage of FFUs can decrease the particle concentration in most areas of cleanroom significantly except only a small increase in the local area around occupant. The concentration still meets the requirement.

(2) With the increase of the coverage rate, the initial investment of FFUs increases slightly and the operating cost decreases significantly. The payback period is only 1.1-2.3 years when the 25% coverage rate is transformed into the 37.5% - 75%.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (Grant No. 51908313)
References

1. S.C. Hu, Y.K. Chuah, Energy. 28, 895-907 (2003)
2. S.C. Hu, Y.K. Chuah, S.C. Huang, ASHRAE Trans. 108, 1014–1022 (2002)
3. A.E. Fedotova, Cleanroom - Topics, theory, practice, (2004) (in Russia)
4. B.E. Launder, D.B. Spalding, Comput. Methods Appl. Mech. Eng. 3, 269–289 (1974).
5. P.V. Nielsen, ASHRAE Trans. 104, 1119–1127 (1998)
6. F. Chen, S.C.M. Yu, A.C.K. Lai, Atmos. Environ. 40, 357–367 (2006)
7. S. Murakami, S. Kato, S. Nagano, Y. ASHRAE Trans. 98, 82–97 (1992)
8. S.V. Patankar, Numerical heat transfer and fluid flow, (1980)
9. J.D. Anderson, Computational fluid dynamics: the basics with applications, (1995)
10. H.A. Khawaja, Int. J. Multiphys. 5, 89–99 (2011)
11. Z. Xu, B. Zhou, Fundamentals of Air Cleaning Technology and Its Application in Cleanrooms, (2014)