Chapter 11
Calculation Theory of Nonuniform Distribution in Cleanroom

Due to the nonuniform distributions of airflow and dust particles, particles in cleanroom are actually not evenly distributed. This chapter will focus on the calculation theory of three-zone nonuniform distribution.

11.1 Influence of Nonuniform Distribution

Because of the nonuniform distribution of particles in cleanroom, deviation is inevitable when results are based on the calculation theory of uniform distribution. In general, the larger the nonuniform distributions of indoor airflow and dust particles are, the larger the difference between the measured values and the calculated values according to the uniform distribution theory will be.

For the nonuniform distribution discussed here, it is assumed that the generation of particles is uniform and stable, but the dust particle distribution is not uniform. Even for this nonuniform distribution, it does not mean the nonuniform distribution at every place, but the regional nonuniform distribution. There is regional concentration difference.

In the following sections, we will discuss the factors affecting the nonuniform distribution of indoor particle concentration separately.

11.1.1 Impact of Air Distribution (Including Air Supply Outlet and Its Position)

Different air distribution patterns have an effect on the uniformity of indoor particle concentration field. In general, the difference of existing airflow patterns in this respect is not very significant. The measured results show that the measured particle concentration with side supply mode is generally higher than the calculated value.
according to the uniform distribution calculation method. The measured value will be higher than the calculated value only when the airflow distribution is not uniform, which weakens the dilution effect. Both positive and negative deviations exist between the measured value and the calculated value for local perforated plate, top supply, and diffuser, which indicates that they are slightly better than the side supply mode in terms of uniformity. For the full perforated plate, all the measured values are almost lower than the calculated values, which mean the uniformity may be better.

The effect of the position of air supply outlet is more obvious. For example, for the top air supply outlet with larger air supply velocity, if they are placed on the ceiling where is concentrated at one side of the room, the indoor airflow will become extremely uneven, where several vortex may appear. In this case, the measured particle concentration is much higher than the calculated value, which has been introduced in Chap. 8.

### 11.1.2 Impact of the Number of Air Supply Outlet

The air inlet quantity has significant effect on the uniformity of air distribution. Table 11.1 is based on the experimental results of Kayatawa [1].

| Experimental group | Measured and calculated results | Air change rate (h⁻¹) |
|--------------------|---------------------------------|----------------------|
| 1                  | Measured value with four air supply outlets | 18 18 40 60 70 80 120 140 200 |
|                    | 90 55 23 16 10 7                  |
|                    | Measured value with eight air supply outlets | 70 40 – 20 – 13 8 – 6 |
|                    | 70 48 22 16 10 7                  |
|                    | Calculated value                  | 70 48 22 16 10 7      |
| 2                  | Measured value with eight air supply outlets | 120 110 50 35 26 21 |
|                    | 120 110 50 35 26 21               |
|                    | Measured value with 12 air supply outlets | 150 – 80 – 30 – 27 19 15 |
|                    | 150 – 80 – 30 – 27 19 15          |
|                    | Calculated value                  | 210 110 60 36 28 22   |

### Table 11.1 Indoor particle concentration with different number of air supply outlet (#/L)

It can be seen from Table 11.1 that with the same filters and air change rate, the lesser the number of air supply outlet is, the higher the average indoor particle concentration is, when it is compared with the calculated value by the uniform distribution method. Because when the number of air supply outlets is small, the proportion of turbulent flow and the eddy area become large, and the uniformity becomes poor. When the number of air supply outlets is more, the average particle concentration is gradually lower than the calculated value. Because when the eddy current area becomes small, the velocity field becomes more uniform, and the turbidity is reduced. Moreover, with more air supply outlets, the extrusion effect of airflow increases. In addition, it has been mentioned in the Chap. 6 that with the
same air change rate, when the number of air supply outlets increases, the air velocity reduces, which is helpful to reduce the deposition of particles on the surface of the workpiece.

11.1.3 Impact of the Air Change Rate

The air change rate has great impact on the uniform distribution of indoor airflow and particle concentration. In order to make the airflow and particle concentration fields uniform, there must be sufficient air flow rate to dilute, and the dilution area should be as large as possible, until the whole room. When the air change rate becomes less, the flow rate becomes insufficient, and the corresponding number of air supply outlets would become less, which is likely to cause more big vortex area. Therefore the measured particle concentration is generally bigger than the calculated value, because in fact the effect of uniform dilution is not achieved at all. But when the air change rate is more than 10 h$^{-1}$, the differences are generally not obvious. With the increase of the air change rate, more uniform field will be achieved in full chamber with dilution. The measured value will approach to the calculated value gradually. When the air change rate is about 70 h$^{-1}$, both of them are roughly the same (this will be explained later). When the air change rate continues to increase, opposite situation will occur, where the measured value is generally lower than the calculated value. This is because not only the full uniform dilution has been reached, but also the extrusion effect of the airflow increases because of the increase of the flow rate and the number of air supply outlets (if the number of air supply outlets does not increase, the flow rate of one air supply outlet will be too large, which then causes the opposite result). In this case, the actual particle concentration is still lower than that calculated by uniform dilution method.

In conclusion, there are two main aspects for the influence of the air change rate. For a small number of air change rate, the measured particle concentration is higher than the calculated value. For a large number of air change rate, the measured particle concentration is lower than calculated value. Of course, this is only the general rule, which may not be absolutely true.

11.1.4 Impact of the Type of Air Supply Outlet

Different forms of air supply outlets have obvious effect in the turbulent flow cleanroom. Several main types of air supply outlets are listed in Fig. 11.1.

The following conclusions can be reached with the experiment [3]:

1. Self-purification times area different for various kinds of air supply outlets. Type C with the extrusion airflow is the best, which is slightly better than the theoretical value with the uniform distribution method. Type B with actively mixing
flow is the next, which is close to theoretical value. Type A with common airflow is the worst, which is worse than the theoretical value, which is shown in Fig. 11.2.

2. When there is indoor dust generation source, the indoor particle concentration with Type C is very small.

3. For Type B with actively mixing flow, due to the induction effect of suction, the dust generation near the head may have effect on the top of the table.

4. For the general Type C, the diffusion performance near the head and foot is good. But since the current near the room end is weak and there is updraft, high concentration is prone to appear when particle is generated indoors.

5. When interferences occur when people are walking around, no matter what kind of air supply outlet is, the difference is not large. When the external disturbance is small, the advantage with Type C appears.

Fig. 11.1 Four kinds of air supply outlets: Type A: normal diffusion plate, mainly for direct downward current. Type $B_1$: diffusion plate with outlet at peripheral sides [2], mainly for direct downward current and horizontal current. Type $B_2$: diffuser, mainly for diagonal flow. Type C: hemispherical outlet with the isotropic radial flow

Fig. 11.2 Comparison of the self-purification capacity between four kinds of air supply outlets
To sum up, in order to overcome the problem of deviation of calculated result with assumed uniform distribution method, and to deeply research the characteristic of cleanroom, it becomes an important topic to study the nonuniform distribution calculation method in cleanroom. In 1974, dual zone model was proposed by Kayatawa [1] who tried to solve this problem, but the specific calculation method was not available.

11.2 Three-Zone Nonuniform Distribution Model

The three-zone nonuniform distribution model is shown in Fig. 11.3 [4], which is divided into the mainstream area, the vortex area, and the return air area. The starting point is as follows:

1. In the mainstream area, because there is a certain air velocity above the working area, particles will not be dispersed into the whole mainstream area continuously and uniformly against the airflow by the dust source $G_a$. As illustrated in front chapters, the probability of particle dispersion into the whole room with the effect of dispersion, deposition, and mechanical force is very small. They distributed mainly along the airflow. So it is more appropriate to term it as “distribution” instead of “diffusion.” This is why all this book “uniform distribution” and “nonuniform distribution” are used, instead of “uniform diffusion” and “nonuniform diffusion.” Moreover, it is easy to wrongly consider the term “diffusion” as pure molecular dispersion diffusion movement.
2. For particles generated from the dust source in the mainstream area, a part of them is uniformly driven into the boundary layer of the airflow along the eddy upwards and then downwards. According to the simple experiment, when there is a dust source in the air supply flow with enough width, it is unlikely to distribute crosswise to the whole cross section of the flow. When air velocity is 0.5 m/s, the expansion angle behind the dust source is only 5–6° [5]. It has been clear when the lower limit of air velocity was introduced that it is enough to control the lateral spread of pollution with the release velocity of 2 m/s, when the air supply velocity is 0.25 m/s. For pollution with smaller release velocity (such particle generation by occupant), it is less likely for particles to disperse against the airflow. According to the jet flow principle, the cross section of airflow expands, and the flow rate increases, which is mainly from the supplement of side eddy air. Therefore, for particles generated in the mainstream area, they will move along the airstream direction with only slightly extension, and then enter the return air area, where a certain degree of mixture occurs. Part of them is exhausted through the return air grille, and others return to the vortex area. In the vortex area, particles spread out and then go through the whole mainstream area uniformly with the airflow induced by the mainstream area. According to this mechanism, the unidirectional flow and the turbulent flow cleanrooms can be linked together. For the vertical unidirectional flow cleanroom, return outlets are placed on the floor, so the airflow in the entire cross section of the working area is the mainstream, and there is no eddy current area. So below the working area, there is no back vortex in the flow, where basically particle cannot be brought back upwards and then “disperse” again. If there is no eddy current in the upper part of the room, it is the ideal unidirectional flow. Even if dust source exists in the upper part, dust particles will not spread into the entire mainstream area because no eddy current exists in this region. This situation is the basis for the analysis of particle concentration in unidirectional flow cleanroom which is discussed in the previous uniform distribution method. If eddy area exists in the upper part, such as the situation when filters are placed with intervals, the amount of particles entering into the eddy area then the mainstream area will be dependent on the ratio of blowing area, the eddy size, and the size of upper dust source. Generally for the unidirectional flow cleanroom, the upper eddy area is very small, and dust source is also rare. So particles scattered in the mainstream area are few. Therefore, in the unidirectional flow cleanroom, the influence of dust source on the particle concentration is very small. With the increase of eddy area, the particle concentration may be affected when the eddy area increases to a certain extent. In this case, it becomes the turbulent flow cleanroom.

3. There is a return air area where particle concentration is different from that in the mainstream and eddy areas. The actual test has showed [6] that, for a unidirectional flow cleanroom with hundreds of air change rate and air return below both sides, the particle concentration of the working area in the mainstream area is equivalent to about 70% of the average concentration in the return air area (the height of return air outlet is about 0.4 m). The detailed data are shown in Table 11.2.
According to the measurement by No. 10 Design Institute of the former Fourth Ministry of Machinery and Industry, the air change rate in turbulent flow cleanroom reached 128 h\(^{-1}\). The particle concentration at the height between 0.9 and 1 m is about 66 % of the average concentration at the return air area. This is consistent with the results shown in the table above. The measured results also show that, for small value of air change rate, the average ratio is 0.8. From the front analysis, particles generated in the mainstream area are concentrated in the return air area, and this is the important reason why the concentration at the return air area is higher than that in the mainstream area. But the concentrated area of particles should be very small.

The above three points are the main content for three-zone nonuniform distribution model.

### 11.3 Mathematical Model for Three-Zone Nonuniform Distribution

According to the three-zone model, particle concentration \(N_c\) at the return air area is composed of two parts: one is the concentration of the mainstream area, and the other is the concentration of the return air area where particles released from dust source \(G_a\) are mixed with the total air volume \((Q + Q')\), that is,

\[
N_c = \frac{N_a + G_a}{(Q + Q')} \tag{11.1}
\]

Particle concentrations in other two areas should be calculated with the differential equations.

Let

\[
D = \frac{d}{dt}
\]

We know

| Height above ground (m) | 0.4 | 0.8 | 0.9 | 1 |
|------------------------|-----|-----|-----|---|
| Total particle counting concentration for particles \(\geq 0.5\) um (#/L) | 87  | 64  | 61  | 59 |
| Ratio of concentration at the height 0.4 m (%) | –   | 74  | 70  | 67 |
| Total particle counting concentration for particles 0.5 um (#/L) | 41  | 32  | 29  | 28 |
| Ratio of concentration at the height 0.4 m (%) | –   | 78  | 70  | 68 |
\[ DN_a = \frac{N_a Q}{V_a} + \frac{N_b Q'}{V_b} - \frac{N_a (Q + Q')}{V_a} \]  
\[ DN_b = \frac{G_b}{V_b} + \frac{N_b Q'}{V_b} + \frac{G_a Q'}{V_b (Q + Q')} - \frac{N_b Q'}{V_b} \]  

where

- \( N_a \) is the concentration of the mainstream area (#/L);
- \( N_s \) is the concentration at the air supply outlet (#/L);
- \( N_b \) is the concentration of the eddy area (#/L);
- \( G_a \) is the particle release rate in the mainstream area (#/min);
- \( G_b \) is the particle release rate in the eddy area (#/min);
- \( Q \) is the air supply flow rate (L/min);
- \( Q' \) is the induced flow rate by the mainstream area (L/min);
- \( V \) is the room volume (L);
- \( V_a \) is the volume of the mainstream area (L);
- \( V_b \) is the volume of the eddy area (L).

Let

\[ \beta = \frac{G_a}{G_0} \]
\[ \frac{\beta G_0}{Q + Q'} = \frac{G_a}{Q + Q'} = G_a' \]
\[ \frac{(1 - \beta) G_0}{Q'} = \frac{G_b}{Q'} = G_b' \]
\[ G_0 = G_a + G_b \]

For Eq. (11.3), we know:

\[ D^2 N_b = \frac{Q'}{V_b} \left\{ \frac{Q}{V_a} N_s + \frac{Q'}{V_a} N_b - \frac{Q + Q'}{V_a} \frac{V_b}{Q'} \left[ DN_b - \frac{G_a Q'}{V_b} - \frac{G_b Q'}{V_b} + \frac{Q'}{V_b} N_b \right] \right\} \]
\[ - \frac{Q'}{V_b} DN_b \]

After reorganization, we know:

\[ \left[ D^2 + \left( \frac{Q + Q'}{V_a} + \frac{Q'}{V_b} \right) D + \left( \frac{Q + Q'}{V_a} \frac{Q'}{V_b} - \frac{Q^2}{V_a V_b} \right) \right] N_b \]
\[ = \frac{Q Q'}{V_a V_b} N_s + \frac{Q'(Q + Q')(G_a' + G_b')}{V_a V_b} \]

(11.4)
So the differential equation can be rewritten as:

\[
\alpha_1 = -\left(\frac{Q + Q'}{V_a} + \frac{Q'}{V_b}\right) - \sqrt{\left(\frac{Q + Q'}{V_a} + \frac{Q'}{V_b}\right)^2 - 4 \frac{QQ'}{V_aV_b}} \tag{11.5}
\]

\[
\alpha_2 = -\left(\frac{Q + Q'}{V_a} + \frac{Q'}{V_b}\right) + \sqrt{\left(\frac{Q + Q'}{V_a} + \frac{Q'}{V_b}\right)^2 - 4 \frac{QQ'}{V_aV_b}} \tag{11.6}
\]

Let

\[
\frac{QQ'}{V_aV_b} A = \frac{QQ'}{V_aV_b} N_s + \frac{Q'(Q + Q')(G_a' + G_b')}{V_aV_b}
\]

so

\[
A = \frac{N_sQ + Q'(G_a' + G_b')}{Q} + G_a' + G_b' \tag{11.7}
\]

We obtain:

\[
N_{bi} = K_1 e^{\alpha_1 t} + K_2 e^{\alpha_2 t} + \frac{N_sQ + Q'(G_a' + G_b')}{Q} + G_a' + G_b' \tag{11.8}
\]

Similarly we can get:

\[
N_{ai} = K_1' e^{\alpha_1' t} + K_2' e^{\alpha_2' t} + \frac{N_sQ + Q'(G_a' + G_b')}{Q} \tag{11.9}
\]

The coefficients of \(K_1, K_2, K_1'\) and \(K_2'\) in above expressions are determined with the initial conditions.

When \(t \to \infty\), we know:

\[
N_b = \frac{N_sQ + Q'(G_a' + G_b')}{Q} + G_a' + G_b' \tag{11.10}
\]

\[
N_a = \frac{N_sQ + Q'(G_a' + G_b')}{Q} \tag{11.11}
\]

Since the range of return air area is smaller, its volume can be ignored. The average concentration of the mainstream area and the eddy area is approximately the average room concentration, that is,
\[ N = N_a \frac{V_a}{V} + N_b \frac{V_b}{V} = N_s + (G_a' + G_b') \left( \frac{Q'}{Q} + \frac{V_b}{V} \right) \]  \hspace{1cm} (11.12)

Let

\[ Q' = \phi Q \]

\[ Q' + Q = \phi Q + Q = Q(1 + \phi) \]

\[ Q = \frac{nV}{60} \]

When they are inserted into the expressions of \( G_a' \) and \( G_b' \), and let \( \frac{G_0}{V} = G \) \([\#/\text{(m}^3\cdot\text{min})]\), Eq. (11.12) can be rewritten as:

\[ N = N_s + \frac{60G \times 10^{-3}}{n} \left( \frac{1}{\phi} - \frac{\beta}{\phi} + \frac{\beta}{1 + \phi} \right) \left( \phi + \frac{V_b}{V} \right) \]  \hspace{1cm} (11.13)

Equation (11.13) can be called the \( N-n \) general formula for cleanroom.

### 11.4 Physical Meaning of \( N-n \) General Formula

1. Obviously, under the condition of uniform distribution:

\[ N = N_s + \frac{60G \times 10^{-3}}{n} \]  \hspace{1cm} (11.14)

Let the coefficient at the right of Eq. (11.13):

\[ \left( \frac{1}{\phi} - \frac{\beta}{\phi} + \frac{\beta}{1 + \phi} \right) \left( \phi + \frac{V_b}{V} \right) = \psi \]  \hspace{1cm} (11.15)

It can be used to express the difference of the particle concentration between uniform and nonuniform distribution conditions.

For the conventional cleanroom with air cleanliness level below Class 100 for particles \( \geq 0.5 \) \( \mu \)m, since the efficiency of HEPA filter can reach above 0.999999(for \( \geq 0.5 \) \( \mu \)m), \( N_s \) is usually about 0.1–0.3 \#/L when circulating air system is used. When full fresh air system is used and \( M \) is about \( 10^5 \) \#/L, \( N_s \) is less than 0.7 \#/L.

For the cleanroom with air cleanliness level higher than Class 10 for particles \( \geq 0.1 \) \( \mu \)m, since the efficiency of HEPA filter can reach above 0.999999
(for $\geq 0.1 \mu m$) and the efficiency of prefilter is also required to be about 0.9, $N_s$ is usually below 0.06#/L when circulating air system is used.

It is clear that $N_s$ in air cleaning system is very small, which can be approximated as:

$$N_v \approx \psi N$$ \hspace{1cm} (11.6)

Where $N$ is the particle concentration with the uniform distribution calculation method; $N_v$ is the particle concentration with the nonuniform distribution calculation method; $\psi$ is the uniformity coefficient.

But for the cleanroom with air cleanliness level Class 100 for particles $\geq 0.5 \mu m$ when the full fresh air system is used, the maximum result of $N_v$ can be added with 1.

2. Equation (11.13) is an $N-n$ general formula for describing both the turbulent flow cleanroom and the unidirectional flow cleanroom. That means no matter it is turbulent flow cleanroom or unidirectional flow cleanroom, when different air supply modes are used in turbulent flow cleanroom or filters are placed fully or partially on the ceiling of the unidirectional flow cleanroom, the $N-n$ general formula can be used to reflect the influence of the number of staff:

(a) For unidirectional flow cleanroom with the ratio of blowing area 100% of filters (there is no border for filter), unidirectional parallel flow exists along the entire height and the cross section in the room, where eddy flow does not exist, so we get:

$$V_b = 0$$

$$Q_s = 0$$

$$\psi = 0$$

So in Eq. (11.13), we know:

$$\left( \varphi + \frac{V_b}{V} \right) = 0$$

Therefore, we obtain:

$$N_v = N_s$$
This is like the situation in the test pipeline for air filter, where the downstream concentration of filter depends only on the inlet concentration. Of course, this is only the ideal situation.

(b) If filters are not fully placed on the ceiling, and there is a certain value of the ratio of blowing area, eddy area will exit. With the decrease of this ratio, both $\psi$ and $V_b$ will increase, and $\beta$ will reduce, so $N_v$ will also increase. This means the particle concentrations are different for the unidirectional flow cleanroom with different values of the ratio of blowing area. Equation (11.13) can be used for calculation. Similarly, the particle concentrations are different for the unidirectional flow cleanroom with different occupational densities. Therefore, the number of occupants in the unidirectional flow cleanroom should be controlled appropriately.

(c) For different turbulent flow cleanrooms, the size of the mainstream area, the size of the eddy area, and the volume of induced airflow are different.

| No. | Air supply mode                                | $\bar{N}$ | $N$  | $N_v$                  |
|-----|------------------------------------------------|-----------|------|------------------------|
| 1   | Side supply                                    | 26        | 21   | 23                     |
| 2   | 1/3 local perforated plate                     | 13        | 10   | 12                     |
| 3   | 2/3 local perforated plate                     | 26        | 22   | 26                     |
| 4   | Ceiling supply                                 | 5         | 14   | 6                      |
| 5   | Ceiling supply                                | 30        | 26   | 32                     |
| 6   | Ceiling supply (Japan Oshitari Lab)            | 1         | 7    | 2.3                    |
| 7   | Ceiling supply with air diffuser plate         | 30        | 26   | 29                     |
| 8   | Air diffuser                                   | 19        | 25   | 21.5                   |
| 9   | Full perforated plate                          | 1         | 3.8  | 1.6 (with mainstream area) |
| 10  | Full perforated plate                          | 2.8       | 8.4  | 3.6 (with mainstream area) |
| 11  | Full perforated plate                          | 8.3       | 12   | 5 (with mainstream area) |
| 12  | Air supply with filters fully placed on the ceiling (the ratio of blowing area 80 %), air return with grid-type floor | 0.25 (room average) | 0.042 | 0.23 (with mainstream area) |
|     |                                                | 0.14 (mainstream area) | 0.16 |                           |
| 13  | Two HEPA filters are placed. Air supply with filters fully placed on the ceiling (the ratio of blowing area 80 %), air return on single bottom side | 0.026 | 0.05 | 0.042 (with mainstream area) |
| 14  | Two HEPA filters are placed. Air supply with filters fully placed on the ceiling (the ratio of blowing area 80 %), air return on both bottom sides | 0.033 | 0.04 | 0.044 (with mainstream area) |
For example, the diffusion angle of diffuser is a little larger than HEPA filter air supply outlet, so $V_b$ is smaller and $\psi$ is larger. So the difference of particle concentrations in different turbulent flow cleanrooms is shown.

### 11.5 Comparison Between Uniform Distribution and Nonuniform Distribution

In Table 11.3, results with different air supply modes are shown. In the table, $\bar{N}$ represents the mean value of measured concentration. $N$ is the calculated results according to the uniform distribution theory. $N_v$ is the calculated value according to the nonuniform distribution theory. It is shown that compared with the calculated results with uniform distribution theory, the calculated results with nonuniform distribution theory are generally closer to the actual value. The final three examples in table correspond to the unidirectional flow cleanroom. Although the difference of the calculated results is not large in the final two cases between the uniform distribution calculation method and the nonuniform distribution method, the calculated results are only related to the air change rate, which has been illustrated in the uniform distribution calculation method for unidirectional flow in Chap. 10. Other factors are not reflected in these two cases. So the calculated results among the final three cases are basically the same. But it is obvious that in the 12th case, the calculated result is much different from the actual value. Although in general the calculated results with the nonuniform distribution calculation method are more accurate than the uniform distribution calculation method, in some circumstances, opposite results may appear, which will be illustrated later.

### References

1. Hayakawa K, Aoki H (1974) Study of cleanroom (2). J SHASE Jpn 48(2):13–88 (In Japanese)
2. Xu ZL, Shen JM (1989) Application of air cleaning technology. China Architecture & Building Press, Beijing, p 99 (In Chinese)
3. Suzuki K (1988) Study of characteristics of air supply outlet in conventional cleanroom. In Proceeding of the 7th international symposium on contamination control, Paris, France, pp 97–102 (In Japanese)
4. Xu ZL (1979) Calculation method for the non-uniform distribution in cleanroom. J HV&AC 4:15–21 (In Chinese)
5. Hayakawa K et al (1974) Air conditioning and air cleaning. Soft Science Co. Ltd., Tokyo, Japan (In Japanese)
6. Кочерин ИД (1978) Air cleaning technology in production of semiconductor and integrated circuits. Translated by the 10th Design Research Institute of the Former Fourth Machinery Industry Department (In Chinese)