Chapter 13
Design Calculation of Cleanroom

Both the uniform and nonuniform distribution theories of cleanroom have been introduced. In order to meet the need of practical application, the method and procedure of specific analysis calculation will be given in this chapter.

13.1 Determination of Indoor and Outdoor Parameters for Calculation

13.1.1 Atmospheric Dust Concentration

Through the discussion about atmospheric dust in Chap. 2 and the at-rest state characteristics of the cleanroom in Chap. 12, the following two points should be clear:

1. Generally, the corresponding atmospheric dust concentrations for three typical areas at present are $0.75 \times 10^5 \, \#/L$, $10^5 \, \#/L$, and $2 \times 10^5 \, \#/L$, respectively. The highest is about $10^6 \, \#/L$, which is the concentration with the situation of most severe pollution. Since the beginning of this century, the concentration reduces about one third.

2. For the cleanroom with air cleanliness level equal to or lower than Class 100, when the atmospheric dust concentration is under $10^6 \, \#/L$, the effect of the variation of this concentration on the particle concentration in the cleanroom can be ignored.

Therefore, the atmospheric dust concentration for design of cleanroom can be determined as follows:

(1) For HEPA cleaning system with air cleanliness level equal to and higher than Class 5, in order to ensure the safety of the cleanroom in whatever outdoor situations (except the situation with extremely severe pollution), the design value of atmospheric dust concentration ought to be $M = 10^6 \, \#/L$. When three-stage
filtration systems are placed on the passage of fresh air (see Chap. 12), the local specific atmospheric dust concentration can be used for calculation.

As for the atmospheric dust concentration for HEPA cleaning system, there is no single value given explicitly in foreign literatures, and it was pointed out that the variation results in the inconvenience of the design process. However, the single value $10^6$ was suggested in the past by author (see the research report “Calculation of cleanroom” printed in 1977 at Institute of HVAC, China Academy of Building Research), which brings convenience for design calculation and also has high safety coefficient. When the explicit single value of atmospheric dust concentration is given for the HEPA cleaning system, there is no need to search for the data in this aspect.

(2) For a non-HEPA cleaning system, it is not economic to use $M = 10^6 \text{#/L}$ for design since the atmospheric dust concentration affects the concentration of cleanroom a lot. It is better to choose the actual concentration. Of course, filtration of fresh air should be strengthened.

This chapter will not repeat discussing other problems about atmospheric dust.

13.1.2 Particle Generation Rate per Unit Volume of Indoor Air

13.1.2.1 Indoor Particle Source

The main generation sources of indoor particles include humans and building surfaces, equipment surface, and process. But practice has shown that particles are mainly released from human. The particle concentration in the cleanroom can be doubled or more when there is some action from people or when people enter in and out of the cleanroom. Rotating equipment is a particular example which generates a lot of particles. Electromotor (especially the one with carbon brushes), rotating components of gear, components of servo machine, hydraulic and pneumatic starter switch, and manual-controlled equipments will produce particles because of the friction between moving (turning) surfaces. An electromotor (less than 300 W) can produce particles about $2 \times 10^5$ to $5 \times 10^6 \text{#/min}$ for diameter 0.5 μm or bigger in one minute, which equals to the particles generated from an acting human. According to the measurements from Institute of HVAC at China Academy of Building Research, a furnace for phosphorus diffusion used in semiconductor process will increase the indoor particle concentration by six times or more. However, except the special cases, the particle generation rate from process equipment is considered less than that from people. Because in principle the process equipments acting as the particle generation source are not allowed to be placed in the cleanroom, or they only operate under the hood or near the return air opening. But special attention should be paid on the papers, especially the crumpled papers, because they will generate a lot of particles. So in the cleanroom, the usage of paper and the type of paper should be limited. Table 13.1 is the data of the generation rate of papers from foreign study [1]. Table 13.2 is the measured data from domestic study.
Generally, indoor particles in the cleanroom mainly come from people, which accounts for 80–90 %. The second largest particle generation source is building, which accounts for 10–15 %. The proportion from supplied air is much less.

13.1.2.2 Calculation of Indoor Particle Generation Rate Per Unit Volume of Air

Next we will discuss two situations for people in static state (or almost static) and an acting static, respectively.

Situation for People in a Static State (or Basically)

The particle generation rate from people varies a lot with different actions. But it is easy to measure accurately when people are in a static state. After analyzing a large amount of data measured at home and abroad, it is appropriate to use $10^5 \#/\text{(min \cdot person)}$ as the particle generation rate for people in static state. It is shown from the measured data in Table 13.3 [2] that data during the states of “standing” and “sitting” are similar.

### Table 13.1 One example of particle generation rate by paper [#/\text{(min \cdot paper)}]

| Type        | Condition | Move up and down | Tear | Knead broken |
|-------------|-----------|------------------|------|--------------|
|             | Particle size |                   |      |              |
|             | >0.5 µm   | >0.5 µm          | >0.5 µm |
| Art paper   | 0         | 216,800          | 269,500 |
| Sulfuric paper | 0       | 75,600           | 15,400  |
| Graph paper | 15,400    | 491,400          | 1,193,500 |
| Kraft paper | 15,400    | 216,800          | 541,000  |
| Copying paper | 0       | 124,740          | 693,000  |
| Newsprint paper | 15,400 | 604,800          | 3,965,00 |
| Winding paper | 3,850   | 143,600          | 616,000  |

### Table 13.2 Another example of particle generation rate from paper [#/\text{(min \cdot L)}]^a

| Species | Tore half a minute (≥0.3 µm) | Knead half a minute (≥0.3 µm) |
|---------|-------------------------------|-------------------------------|
| Plain paper | 4,410                        | 10,220                       |
| Sulfuric paper | 1,837                        | 523                          |

^aIt is measured at the distance of 0.5 cm from the center of particle generation source

Generally, indoor particles in the cleanroom mainly come from people, which accounts for 80–90 %. The second largest particle generation source is building, which accounts for 10–15 %. The proportion from supplied air is much less.
Particle generation rate from building surface is tenth of that from human. According to the analysis between the measurement data and literature references, it is recommended that the particle generation rate from indoor surface represented by 8 m² floor is equivalent with that of a person in static state. In other words, the particle generation rate of every static-state person corresponds with eight times of that released from unit area of floor. According to dozens of measurement cases, it has been validated by author that the difference between the calculated indoor particle concentration with the above method and the measured concentration is very small. Deviations in most cases are smaller than that with nonuniform distribution method (see Ref. [3]).

The authors have validated tens of results and consider the gap between the dust concentrations measured actually and using the values above is the narrowest. Most examples have a smaller deflection than the inherent deviation of a nonuniform distribution (see details from the author’s book [3]). With the development of processing of materials, the particle generation rate from the envelope structure is much smaller. Calculation with the above principle is much safer.

In order to facilitate the calculation process, the concept of particle generation rate per unit volume is put forward.

First of all, when the occupant density is only one person per unit square of floor and occupant is the only source of particles, what is the particle generation rate per unit volume of air? Assume the room height is 2.5 m, the particle generation rate per unit volume is:

$$\frac{1 \times 10^5}{2.5 \times 1} = 0.4 \times 10^5 \text{#/}(\text{m}^3 \cdot \text{min})$$

Table 13.3 One example of particle generation from people

| Action                        | Ordinary working clothes | General nylon suit | Full set of nylon suit covering from head to foot |
|-------------------------------|--------------------------|--------------------|-----------------------------------------------|
| Stand                         | 3.39 x 10^5              | 1.13 x 10^5       | 5.58 x 10^4                                  |
| Sit down                      | 3.02 x 10^5              | 1.12 x 10^5       | 7.42 x 10^3                                  |
| Wrist move up and down         | 2.98 x 10^6              | 2.98 x 10^5       | 1.86 x 10^4                                  |
| Upper body anteflexion        | 2.24 x 10^6              | 5.38 x 10^5       | 2.42 x 10^4                                  |
| Wrist free movement           | 2.24 x 10^6              | 2.98 x 10^5       | 2.06 x 10^4                                  |
| Head move around              | 6.31 x 10^5              | 1.51 x 10^5       | 1.10 x 10^4                                  |
| Twisting motion of upper body | 8.50 x 10^5              | 2.66 x 10^5       | 1.49 x 10^4                                  |
| Body bend                     | 3.12 x 10^6              | 6.05 x 10^5       | 3.74 x 10^4                                  |
| Foot movement                 | 2.80 x 10^6              | 8.61 x 10^5       | 4.46 x 10^4                                  |
| Walk                          | 2.92 x 10^6              | 1.01 x 10^6       | 5.60 x 10^4                                  |
Second, convert the particle generation rate from surfaces into that from people. This means the particle generation rate from the indoor surface with the floor area $\beta \, \text{m}^2$ can be considered as that from one person. The whole surface can be thought as a certain number of people. Assuming $P$ as the number of people and $F$ as the area of cleanroom, then the equivalent occupant density is:

$$q^0 = \frac{F}{\beta} + \frac{P}{F}$$

This means the occupant density per square meter of floor is assumed $q^0$. Since the particle generation rate per unit volume of air when the occupant density is one people per square meter is known, the particle generation rate per unit volume for people at static state when the occupant density is $q^0$ is

$$G_m = 0.4 \times 10^5 \times q^0 = 0.4 \times 10^5 \left( \frac{1}{\beta} + \frac{P}{F} \right)$$

(13.1)

where $P/F$ is the actual occupant density, which can be indicated by $q$.

The calculation above is under the condition that the room height is 2.5 m. If the real room height is higher than 2.5 m, the uniform distribution of particles between the upper and lower spaces would be worse. Usually the concentration in the upper space is smaller. So it is unsafe to make correction simply with the inverse relationship between the concentration and the height. If calculating is still performed with the assumed room height 2.5 m, the particle generation rate per unit volume will be larger than the actual value, which is much safer. Although it is a little unsafe when calculation is performed with the assume room height 2.5 m although the actual height is less than 2.5 m, the conditions of room height less than 2.5 m are rare in practice.

According to Eq. (13.1), the straight line can be plotted as shown in Fig. 13.1, so that the value of $G_m$ can be obtained directly with the occupant density $q$. 

---

**Fig. 13.1** Calculation charter of particle generation rate per unit volume in cleanroom
From the figure, when $q = 0$, $G_m$ is equal to the particle generation rate from indoor surface. $G_m$ increases with the increase of $q$ by different ratios, so the indoor particle concentration will increase with the increase of the number of people in a different rate (see details in Chap. 12). When the number of occupants is relatively small and $q$ is relatively small, the increase rate between $G_m$ and $q$ will be small because the particle generation rate from indoor surface as a base (namely, the intercept in the figure) occupies a larger proportion. For example, when $q$ changes from 0.01 to 0.04, which increases four times, $G_m$ only changes from 0.55 to 0.65, which increases less than 20%. When $q$ changes from 0.4 to 0.6, which increases 50%, $G_m$ only changes from 2.1 to 2.9, which increases about 40%. The increase rates between two parameters are very close. For HEPA cleaning system, the relationship between $G_m$ and $q$ can be considered similar as that between $N$ and $q$. This is visible from Figs. 13.2 and 13.3. One figure is from foreign literature (Fig. 13.2 [4]). The dotted line is original. But according to the data points, polygonal line should be plotted (solid line). Figure 13.3 also shows the polygonal line plotted by author with the measured data by No. 10 Design Institute of the

**Fig. 13.2** One example for relationship between the particle concentration and the number of people

**Fig. 13.3** Another example for relationship between the particle concentration and the number of people
former Fourth Ministry of Machinery and Industry. It means that for HEPA cleaning system with few/many persons, the relationship between \( N \) and \( q \) should be the case mentioned above.

Table 13.4 lists the particle generation rate recommended by this book and other related literatures.

According to various numbers of particle generation rates in Table 13.4, the particle concentrations at rest in 46 cases of various cleanrooms were calculated by author (\( G_m \) is considered as 1/5 of \( G_n \) in operational state) with the theory of uniform distribution. Here the specific number will not be presented and only list the comparison result is shown in Table 13.5.

From the above comparison, the particle generation rate for people at rest can be chosen as 10^5 #/(min-person), and the particle generation rate from surfaces represented by each square meter of floor is assumed 1.25 \( \times \) 10^4 #/min, which are suitable for the current management and technical levels in cleanroom. It goes without doubt that the particle generation rate from people is greatly relevant to the types of clothes, and it is even influenced by the ways to treat clothes such as washing and blowing. According to the actual usage and measurement, the particle generation rate from nylon taffeta working clothes is the least. The particle generation rate from both cotton polyester and electro spinning clean working cloth is larger than that from nylon taffeta. And the electro spinning cloth should not be used only. If cotton polyester working cloth is added inside the nylon taffeta cloth, the particle generation rate from nylon taffeta cloth will be further reduced. From the aspect of clothing form, the particle generation rate from the connecting body clean working cloth is much smaller than the split-type clean working cloth. But it is not convenience to wear the connecting body clean working cloth as the split type. Moreover, the type with zipper will generate fewer particles than that with nylon hasp. The clean working cloth should not be kneaded during washing process, and it should be dried in the clean environment after washing.

With the improvement of the management level in cleanroom, the property (such as abrasion resistance and electrostatic elimination) of various materials improves further. In this case, the particle generation rates from people and surface mentioned above will be further reduced, and the above statistical values are not constant.

**Situation When People Move**

The mechanism of particle generation during the action of people is quite complex. But after analyzing various statistic data (such as Table 13.1), the ratio of particle generation rate between the intense activity state and the static state (or basically) is about ten times. In fact, not all indoor activities are intense. If the average value of all the actions is taken, the particle generation rate for the people with activity is considered to be five times the value of the static state (or basically). Then Eq. (13.1) will be changed correspondingly into

\[
G_n = 2 \times 10^5 \left( \frac{1}{\beta} + \frac{P}{F} \right)
\]  

(13.2)
| No. | 1       | 2       | 3       | 4       | 5       | 6       |
|-----|---------|---------|---------|---------|---------|---------|
| No. | 1       | 2       | 3       | 4       | 5       | 6       |
| 13.4| Recommended particle generation rate |
|     | During activity | 10^6 | 10^6 | 10^6 | 3.3 \times 10^6 | 10^5 | 5 \times 10^5 |
|     | At rest (or basically) | – | – | – | – | – | 10^5 |
|     | Particle generation rate from surface | 4.5 \times 10^5 | 4.5 \times 10^5 | Not considered | Not considered | Not considered | 1.25 \times 10^4 |
| Source | Ref. [5] and forum material from Japan electronic industry and measuring instrument exhibition in 1975 | Thematic information about integrated circuit factories in Japan through investigation by No. 10 Design Institute of the former Fourth Ministry of Machinery and Industry | Ref. [6] | Ref. [7] | Ref. [8] | This book |
where $\beta = 40$. This expression is still represented by a straight line similar as that in Fig. 13.1, and the only difference is the vertical axis, which is shown in the right side of the figure. In this way, the value of $G_n$ can be found with $q$.

When the particle generation rate for the people with activity is five times the value for people at rest, it is $5 \times 10^5 \#/\text{(person-min)}$. According to the measurement performed by No. 10 Design Institute of the former Fourth Ministry of Machinery and Industry, when people wear four types of common clean working clothes, the particle generation rates with common actions are $8.57 \times 10^5 \#/\text{(person-min)}$, $3.63 \times 10^5 \#/\text{(person-min)}$, $3.23 \times 10^5 \#/\text{(person-min)}$, and $1.83 \times 10^5 \#/\text{(person-min)}$, respectively. The average value is $4.3 \times 10^5 \#/\text{(person-min)}$, which is equivalent to the common particle generation rate in electronic industry. It is also close to the value which is five times the value for people at rest. It is of course that five times is considered by average. The magnification ratio will be different with different property of process and the intensity of occupant activity. The two extreme cases for lowest (the intensity of activity is extremely low, or people operate when sitting down and seldom stand up) and highest (the intensity of activity is higher than the ordinary level, or the activity is relative frequent) values are three times and seven times of the particle generation rate during at-rest state, respectively. The corresponding values are $3 \times 10^5 \#/\text{(person-min)}$ and $7 \times 10^5 \#/\text{(person-min)}$, which can be used for calculation. The relationships with three times and seven times of $G_n$ can also be found in Fig. 13.1.

### 13.1.3 Fresh Air Ratio

The function of fresh air in air cleaning system is to meet the hygiene requirement, maintain the positive pressure, supply the local exhaust air volume, and make up the leakage air volume of the system.

From the aspect of sanitation, fresh air is often used to dilute the toxic gas and smell in air. The quantity of diluted air volume in the states of equilibrium is:

$$Q = \frac{L}{(C - C_0) \times 10^{-3}}$$  \hspace{1cm} (13.3)
Where
$L$ is the harmful gas generated indoors ($\text{m}^3/\text{h}$);
$C_0$ is the concentration of harmful gas in the atmosphere ($\text{L}/\text{m}^3$);
$C$ is the controlled concentration of toxic gas ($\text{L}/\text{m}^3$).

For cleanrooms where harmful gases are often generated with a large amount, the air volume of fresh air should be determined with the hygienic standard. For the common cleanroom, it should be determined mainly based on CO2. The USA also specifies the adjustment of fresh air on the basis of CO2 for air-conditioning system after 1980 [9].

According to the research by scholars from the former Soviet Union [10], in the closed room with artificial ventilation system, the oxygen content in air is often lower than normal value, which fluctuates between 17.4 and 20.5 %. It reaches its minimum value at dusk. CO2 content exceeds 1–2 times of the standard value (0.06–0.09 %). It reaches to 0.15 % at dusk.

Tables 13.6, 13.7, and 13.8 show the influence of CO2, O2, and CO contents on human beings. Table 13.9 gives the exhaled carbon dioxide produced by people [11].

In terms of CO2, the value of $C_0$ in Eq. (13.3) is usually taken as 0.3 L/m3, but the data measured in city is often bigger than this value. $C$ is usually taken as 1 L/m3, which is specified in Japanese environmental control standard.

When the value of $L$ is taken in the condition of light labor strength, the essential fresh air per person is:

$$Q = \frac{0.022}{0.0007} \approx 30 \text{ m}^3/\text{h}$$

This value was specified as the lower limit of fresh air volume in both the hygienic standard and the design specification for air-conditioning system. When

| CO2 content/% | Influence on occupant |
|---------------|-----------------------|
| 0.04          | Normal air            |
| 0.5           | Long-term safety limit|
| 1.5           | Physiological limit (metabolic disturbance with Ca and P). Work must be stopped |
| 2.0           | Deep breath is needed. The inspiratory airflow increases by 30 % |
| 3.0           | Work is worsened. Physiological function varies. Respiratory rate increases by 2 times |
| 4.0           | Breath becomes deeper and faster |
| 5.0           | Strong gasp. When it lasts for 30 min continuously, poisoning symptom will appear |
| 7–9           | The allowable tolerant limit. When it lasts for 15 min, people will be unconscious |
| 10–11         | People can adjust normally. When it lasts for 10 min, people will be unconscious |
| 15–20         | People can survive for more than 1 h |
| 25–30         | Breath will disappear. Blood pressure reduces. Coma occurs. Reflection and feeling disappear. People die within hours |
people’s operation is taken into consideration, \( L = 0.03 \text{ m}^3/(\text{person-h}) \) under the light labor strength, then \( Q = 43 \text{ m}^3/\text{h} \). In both the “Code for Design of Clean Room” and the former Soviet Union’s standards for airtight workshop, the fresh air volume per person is set \( 40 \text{ m}^3/\text{h} \) [10]. The value is set as \( 42.5 \text{ m}^3/\text{h} \) in British relevant regulations, and \( 51 \text{ m}^3/\text{h} \) in US Federal Standard 209. There are even specified \( 72–85 \text{ m}^3/\text{h} \) in some standards [11].

As for the standard of fresh air volume, different opinions exist for a long time. Some people consider the fresh air volume as the only factor that influences the

### Table 13.7 Influence of \( O_2 \) contents on human beings

| \( O_2 \) content/\% | Influence on occupant                          |
|----------------------|-----------------------------------------------|
| 21                   | Normal                                        |
| 17                   | Long-term safety limit                        |
| 15                   | Feeling of fatigue                            |
| 10                   | Dizzy with short of breath                    |
| 7                    | Unconsciousness, memory judgment malfunction  |
| 5                    | The lowest limit to maintain life              |
| 2–3                  | People die within several minutes             |

### Table 13.8 Influence of \( CO \) contents on human beings

| CO content | ppm | Influence on occupant                                                                 |
|------------|-----|--------------------------------------------------------------------------------------|
| 0.0002     | 2   | Normal                                                                               |
| 0.0025     | 25  | Visual disorder                                                                       |
| 0.005      | 50  | Long-term safety limit                                                                |
| 0.01       | 100 | With influence when exposed for 6 h                                                  |
| 0.02       | 200 | Headache occurs during 2–3 h. Insomnia by longer time                                 |
| 0.04       | 400 | Deep breath and visual disorder. Headache during 1–2 h. Death by longer time         |
| 0.08       | 800 | Headache, nausea, and dizzy during 45 min. Unconsciousness during 2 h. Die after 4 h |
| 0.64       | 6,400| Headache during 1–2 min. Die after 10–15 min                                          |
| 1.28       | 12,800| Die after 1–3 min                                                                   |

### Table 13.9 Relationship between the male labor intensity and the exhaled \( CO_2 \) quantity

| Labor intensity              | \( CO_2 \) exhalation volume/\( [\text{m}^3/(\text{p-h})] \) | Exhalation volume for calculation/\( [\text{m}^3/(\text{p-h})] \) |
|-----------------------------|------------------------------------------------------------|------------------------------------------------------------|
| Quiet                       | 0.0132                                                     | 0.013                                                     |
| Extreme light labor         | 0.0132–0.0242                                              | 0.022                                                     |
| Light labor                 | 0.0242–0.0352                                              | 0.03                                                       |
| Middle labor                | 0.0352–0.0572                                              | 0.046                                                     |
| Heavy labor                 | 0.0572–0.0902                                              | 0.074                                                     |
indoor sanitary conditions. Although it is surely harmful for people’s health with lack of fresh air, it is not appropriate to attribute the discomforts such as headache, eye ache, fatigue, dizziness, and general debility that appear in the closed workplaces to high concentration levels of CO₂ or insufficiency of fresh air by researches at home and abroad. According to the research [10], the possibility may increase for men to suffer from vegetative nervous disorder symptom and instability of blood pressure when they work in closed workplaces without windows. And there are several possible factors.

1. With special conditions with no windows, specific affect is posed on staff’s body organisms, which causes unfavorably subjective sensations and psychological abnormality when people is isolated from outside, and decreases the general tension intensity of body organisms and immunologic functions. The total incidence is thus increased.
2. No natural light and lack of fresh air.
3. Negative ion content in the air is insufficient.
4. Trace of other kind of toxic gas is present.
5. Due to the filter media material, the manufacturing process, and the experimentation procedure, filters will have a special smell which emits into the air continuously.
6. Temperature and relative humidity are higher. Especially when the relative humidity increases, people may feel uncomfortable and may fall on the floor in the cleanroom.

Therefore, the conclusion about the issue of fresh air volume can be obtained only when comprehensive study is performed from several aspects.

From the aspect of relative risk for the occurrence of the sick building syndrome, the fresh air volume through experiment is obtained, which is shown in Fig. 13.4 [12]. It is clear that increasing the fresh air volume is beneficial to human health. The effect is obvious and stable only when it reaches more than 90 m³/h (25 L/s) for each person.

Although this conclusion is not based on the cleanroom, it can be still used as the reference for the closed cleanroom. Because the pollutions in the cleanroom are similar as that in the sick buildings, they come from two aspects including people and indoor gaseous pollutants (not only CO₂).

For the convenience of use, especially when the precise number of people is unknown, fresh air volume can be considered as a percentage of the total air volume. The percentages are different according to the ventilation rate and occupational density, which are listed in Table 13.10 (round-off numbers are taken and the story height is taken as 2.5 m).

For general cleanroom, Japanese have claimed that it is acceptable to use 0.25 as the fresh air ratio, but it should be a little higher in view of hygienic standard [13]. However, the revised version of the standard “Code for Design of Clean Room” (GB50073-2001) in China did not present the values of fresh air ratios.
The calculation of the fresh air volume in terms of positive pressure has been introduced in detail in the monograph “Design for the cleanroom” [3], which will not be discussed further here.

The method to determine the calculation parameters inside and outside of the room has been discussed. In Chap. 4, the filtration efficiency of air filter has been introduced in detail, which will not be repeated here.

### 13.2 Calculation of HEPA Cleaning System

This chapter will introduce the specific calculation procedures with the theory of nonuniform distribution theory mentioned in Chap. 11.
13.2.1 Calculation of the Value $N$

Here Eqs. (11.12) and (11.13) are listed again. With the condition of uniform distribution, we obtain:

$$N = N_s + \frac{60G \times 10^{-3}}{n}$$

With the circumstance of nonuniform distribution, we obtain:

$$N_v = N_s + \psi \frac{60G \times 10^{-3}}{n}$$

$$N_s = \frac{N_s n_s (1 - \eta_1) + Mn(1 - s)(1 - \eta_n)}{n} \quad (13.4)$$

where $N_s$ is much smaller than $M$, so in the numerator of the above equation, the left item is much less than the right one. Thus, it can be considered that

$$N_s \approx M(1 - s)(1 - \eta_n) \quad (13.5)$$

where the meanings of each symbol and their determination methods can be referred to previous related chapter.

During the design calculation process, if $N_s$ should be calculated based on parameters such as $s$, $\eta_1$ and $\eta_2$ which are unknown or cannot be fixed (e.g., when a practical project is not measured), a simplified method can be used with the equivalent concentration $M = 2 \times 10^5$–$10^6$ #/L.

For unidirectional flow cleanroom $[(1 - \eta_1)(1 - \eta_2)$ can be assumed as 0.5, and $(1 - \eta_3) = 0.00001]$, we can obtain:

$$N_s = 0.02 - 0.1 \text{ #/L} \quad \text{when} \quad (1 - s) = 0.02$$

$$N_s = 0.04 - 0.2 \text{ #/L} \quad \text{when} \quad (1 - s) = 0.04$$

For turbulent flow cleanroom $[(1 - \eta_1)(1 - \eta_2)$ can be assumed as 0.5, and $(1 - \eta_3) = 0.00001]$, we can obtain:

$$N_s = 0.2 - 1 \text{ #/L} \quad \text{when} \quad (1 - s) = 0.2$$

$$N_s = 0.5 - 2.5 \text{ #/L} \quad \text{when} \quad (1 - s) = 0.5$$

$$N_s = 5 - 5 \text{ #/L} \quad \text{when} \quad (1 - s) = 1.0$$
From these numbers, we can consider that in Eq. (11.14) $N_r$ is much smaller than the right item, so Eq. (11.13) can be approximately written as

$$N_v \approx \psi \left( N_s + \frac{60G \times 10^{-3}}{n} \right) = \psi N \quad (13.6)$$

which is the same form as Eq. (11.15). For high-efficiency air cleaning systems, if certain parameters are unknown, Fig. 13.4 can be used to find the common range of these parameters. The range given by the figure is wide, and the deviation between the valued found in the figure and the calculated value is around 10%.

### 13.2.2 Calculation of the Value $n$

During the calculation of the air change rate with the given indoor particle concentration, the result with nonuniform distribution theory obtained by Eq. (13.4) can be expressed as the following expression, where $n$ is replaced by $n_v$:

$$n_v = \psi \frac{60G \times 10^{-3}}{N_v - N_s} = \psi n \quad (13.7)$$

where

- $N_v$ is the indoor average particle concentration with nonuniform distribution theory required in the cleanroom;
- $n$ is the air change rate calculated by the uniform distribution theory;
- $n_v$ is the air change rate calculated by the nonuniform distribution theory.

Similarly, $n$ can be found from Fig. 13.5 during simplified calculation process.

It should be illustrated that when the air cleanliness level is used to represent the requirement for the design, such as when air cleanroom with air cleanliness level Class 7 is designed, the value of $N_v$ cannot be the maximum particle concentration. The particle concentrations for the cleanroom with a certain air cleanliness level are within a range. For example, it is between 35 and 350 #/L for air cleanliness level Class 7. It is obvious that it is hard to meet the requirement when the value 350 #/L is used. Furthermore, as the reason mentioned for the dynamic-to-static ratio in Chap. 15, the design value of the particle concentration ought to be $1/2$–$1/3$ of the maximum value.

For unidirectional flow cleanroom, no matter what kind of air distribution theories are, $n$ is determined by the air velocity at the cross section of the cleanroom. The air velocity at the cross section should be referred to the section about the lower limit of air velocity.
13.2.3 Calculation of the Value $\Psi$

In order to calculate the uniformity coefficient $\psi$, the property curves in Figs. 12.18–12.26 can be used. When these curves are used, values of $\beta$, $\psi$, and $V_p/V$ are needed. Although it is impossible to determine these coefficients precisely, a reference value can be given.

Fig. 13.5 Calculation graph of $N–n$ in high-efficiency air cleaning cleanroom
13.2 Calculation of HEPA Cleaning System

13.2.3.1 $\beta$

This is proportion between the particle generation rate in mainstream area and the total particle generation rate. In practice it is a variable, so it is impossible to propose a fixed value.

If the location of particle generation source cannot be determined, the average method can be used. Let $\beta = 0.5$, or let $\beta < 5$ to ensure the safety, which means that the particle source is considered to be in the mainstream area.

It can also be considered from the aspect of the height covered by airflow. This is related to the area corresponded with filter. According to the flow boundary and the height overlapped with wall, values of $\beta$ are listed in Table 13.11.

13.2.3.2 $\psi$

This is the ratio between the induced airflow rate from the vortex area to the mainstream area and the total air supply volume. For air supply outlet at the side, the equation used in the design manual of air conditioning can be referred to:
Table 13.12  Values of ψ

| Area corresponding with one filter on the ceiling (larger value could be used if air supply outlet is not in the middle/m²) | In unidirectional flow cleanroom, filters are placed in between (the ratio of blowing area is 60 %) | 0.05 |
| In unidirectional flow cleanroom, filters are placed fully (the ratio of blowing area ≥ 80 %) | 0.02 |
| 5–7 | 1.5 | Orifice plate: placed locally | 1 |
| 3–5 | 1.3 | placed fully | 0.65 |
| 2.5–3 | 0.65 | Diffuser Value (ceiling supply mode) × (1.3–1.4) |
| 2–2.5 | 0.3 | HEPA filter air supply with diffuser on ceiling: Good diffusion Value (ceiling supply mode) × (1.3–1.4) |
| 1–2 | 0.2 | In unidirectional flow cleanroom, filters are placed in between (the ratio of blowing area is 40 %) | 0.1 | Poor diffusion Value (ceiling supply mode) × (1.1) |

\[ ψ = 0.5 \sqrt{\frac{F}{d}} - 1 \]  \hspace{1cm} (13.8)

Where

\( F \) is the room’s cross-sectional area corresponding with each air supply outlet (perpendicular to the flow)(m²);

\( d \) is the equivalent diameter of the air supply outlet (m).

\[ d = 1.13 \sqrt{L_1 \times L_2} \]  \hspace{1cm} (13.9)

where \( L_1 \) and \( L_2 \) are two side lengths of the air supply outlet (m).

For HEPA filter air supply outlet at the ceiling, due to the low height of room, the problem of overlapping also exists for flows between neighboring filters. It will be not suitable to use the equation of side air supply mode. Values of \( ψ \) are listed in Table 13.12 when the experimental data about the induction flow rate ratio at different distances from the air supply outlet under the air supply velocity 0.51 m/s, as well as the correction to the perforation ratio on the orifice plate, is referred to [14].

The data in the above table are obtained based on the diffuser air supply outlet with 484 mm × 484 mm HEPA filter, which is about 0.3 m².

The data above are also obtained according to the experimental curves for air supply velocity more than 0.51 m/s. If air velocity is below 0.5 m/s, which is
equivalent to the air change rate $10 \text{ h}^{-1}$ for ordinary condition, the measured particle concentration has an apparent trend of increase compared with the calculated value based on uniform distribution theory. Table 13.13 is the comparison between the two values according to the measured data rearranged by author [15].

If the number of air supply outlets increases although the air supply velocity is very low, several coefficients influencing $\psi$ will vary and opposite results may be obtained, namely, the particle concentration will be decreased greatly.

### 13.2.3.3 $V_b/V$

This is the ratio between the volume of vortex area and the room volume.

The value for top air supply outlet can be obtained with the value of $V_a$ in Table 13.14 (if air supply outlet is not placed in the middle, $V_b/V$ can be multiplied by the coefficient about 1.2).

The performance of top air supply outlets with diffuser plate varies a lot from each other due to the difference of diffusion angle. The value of $V_b/V$ for a good diffusion plate is 0.6 times of the one without diffusion plate, while the value for the poorest one is 0.9 times.

The value of $V_b/V$ for the diffuser can also be considered as 0.6 times of the top air supply outlet without diffuser plate.

| Table 13.13 Relationship between the air change rate (less than 10 h\(^{-1}\)) and the particle concentration |
|---------------------------------------------------------------|
| Air change rate (h\(^{-1}\)) | 12 | 10 | 8 | 6 | 4 | 3 | 2 | 1 |
| Measured value (N) | 1 | 1 | 1 | 2.5 | 7 | 15 | 25 | 70 |
| Calculated value (N) | 1 | 1.2 | 1.5 | 2 | 3 | 4 | 6 | 12 |

| Table 13.14 Value of $V_a$ (m\(^3\)) |
|---------------------------------|
| Room volume (m\(^3\)) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Number of top air supply outlets |
| <5 | 3 | 4 | 5 | 8 | 9 |
| 10 | 7 | 10 | 13 | 16 | 18 |
| 20 | 8 | 12 | 15 | 18 | 20 | 24 | 26 |
| 30 | 9 | 14 | 18 | 20 | 24 | 27 | 28 | 32 | 32 | 35 |
| 40 | 9 | 15 | 18 | 20 | 25 | 28 | 32 | 32 | 36 | 40 |
| 50 | 9 | 16 | 21 | 22 | 25 | 30 | 32 | 36 | 42 |
| 60 | 10 | 17 | 21 | 22 | 28 | 30 | 35 | 38 | 40 | 45 |
| 70 | 10 | 17 | 23 | 28 | 30 | 33 | 35 | 40 | 44 | 46 |
| 80 | 10 | 17 | 23 | 28 | 34 | 36 | 38 | 40 | 45 | 48 |
| 90 | 10 | 17 | 25 | 30 | 35 | 36 | 40 | 44 | 45 | 50 |
| 100 | 10 | 17 | 25 | 30 | 35 | 40 | 42 | 48 | 50 | 52 |

The value of $V_b/V$ for the diffuser can also be considered as 0.6 times of the top air supply outlet without diffuser plate.
For side air supply outlet, it is acceptable to assume $V_b/V = 0.7–0.5$ (Big value can be used when the distance between two vent outlets is larger than 3 m).

For orifice plate, it can be considered with Table 13.15.

For unidirectional flow cleanrooms, let $V_b/V = 0.02$ when filters are fully placed, and let $V_b/V = 0.06$ when the ratio of blowing area is 60 %, and let $V_b/V = 0.12$ when the ratio of blowing area is 40 %.

One thing should be point out that the vortex zone here is caused only by airflow, while equipments and occupants can also form the vortex zone, which is difficult to estimate. So the amount of equipments and occupants need to be controlled.

The determination method of parameters $\beta$, $\psi$, and $V_b/V$ has been introduced above. In case they are not easy to be determined, the coefficient of nonuniformity $\psi$ cannot be calculated. For general situation, the value of $\psi$ can be roughly determined according to the air change rate with Table 13.16 (it is applicable only to top air supply outlet). For example, if the flow rate is 10,000 m$^3$/h for the air change rate 100 h$^{-1}$, ten air supply outlets should be placed, which has the dimension of 484 mm $\times$ 484 mm and the rated airflow 1,000 m$^3$/h. In this case, the value of $\psi$ is shown in the table.

### Table 13.15 Value of $V_b/V$ for orifice plate

| Airflow overlap height (m) | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
|---------------------------|-----|-----|-----|-----|-----|
| Full orifice plate        | 0.96| 0.92| 0.88| 0.84| 0.8 |
| 1/2 orifice plate         | 0.58| 0.56| 0.54| 0.52| 0.5 |
| 1/3 orifice plate         | 0.46| 0.45| 0.43| 0.42| 0.41|
| 1/4 orifice plate         | 0.42| 0.41| 0.40| 0.39| 0.38|

### Table 13.16 Value of $\psi$ (top air supply outlet)

| Turbulent flow | Unidirectional flow |
|----------------|---------------------|
| Air change rate (484 mm $\times$ 484 mm air filter in the air supply outlet has rated airflow 1,000 m$^3$/h)/h$^{-1}$ | Air supply and return fully placed | Two lower bottom side air return with nonuniform and unequal area |
| 1 2 5 10 20 40 60 | 120 140 | 160 180 200 |
| When air supply outlets are uniformly placed | >6 4.2 2 1.5 1.22 | 0.03 |
| When $n \geq 120$ h$^{-1}$ and air supply outlets are placed centralized, the mainstream area theory can be used for calculation | 0.65 0.51 0.51 | 0.43 0.43 |
13.2.4 Three Principles of Design Calculation

Although it is more realistic to perform calculation on the basis of the nonuniform distribution theory, it needs to point out that there is still considerable discrepancy between the calculated results and the actual values. This is because it is quite difficult to determine the relevant coefficients which change constantly. Taking the parameter $\beta$ as an example, it changes frequently during the movement of people. When it is assume $\beta = 0.8$ during calculation, but in fact or during measurement the particle generation source moves so that the main particle source is located in the vortex area, the calculated results will obviously different, which maybe deviate further from the one obtained based on the uniform distribution theory. Regarding these facts, different principles can be used during the design calculation process for three kinds of situations.

1. Calculation according to the average indoor concentration, that is, with Eq. (11.13) or Eq. (11.16).

2. According to the specific condition, when it can be ensured that the mainstream area is relatively larger, or when the operation is conducted within the mainstream area, calculation can be performed with the particle concentration in the mainstream area. With Eqs. (12.1) and (12.4), we can obtain:

$$N_a \approx \left(1 - \frac{\beta}{1 + \varphi}\right) \left(N_s + \frac{60G \times 10^{-3}}{n}\right)$$  \hspace{1cm} (13.10)

In brackets on the right side of the above formula, the value $N$ is calculated with uniform distribution theory, which can also be approximately found out according to Fig. 13.4.

3. For cleanroom with strict requirement of air cleanliness or for the workpiece with frequent movement indoors, which should be prevented from pollution, or for cleanroom with large space or for operation with fixed location within the vortex zone, the particle concentration in the vortex area can be used for calculation. With Eqs. (12.3) and (12.4), we can obtain:

$$N_b \approx \left(1 + \frac{1 - \beta}{\varphi}\right) \left(N_s + \frac{60G \times 10^{-3}}{n}\right)$$ \hspace{1cm} (13.11)

13.2.5 Examples

Example 13.1. There is a turbulent flow cleanroom with a high-efficiency air cleaning system. This cleanroom is 28 m$^2$ in area (5.6 m in width and 5 m in length), and 2.5 m in height. It is equipped with two side air supply outlets with the size 0.3 m $\times$ 0.2 m. The air change rate is 28 h$^{-1}$. The fresh air ratio is 25%. When
there are three people working inside, please calculate how much is the particle concentration inside the cleanroom.

**Ans:**

\[ q = \frac{3}{28} = 0.104 \text{ people/m}^2 \]

According to Fig. 13.1 (using the vertical axis with five times, which is the same below), \( G_n = 2.7 \times 10^4 \text{ #/}(\text{m}^3 \cdot \text{min}) \). With the values of \( G_n \) and \( n \) in Fig. 13.4, we can get that \( N = 60 \text{ #/L} \).

\[ \therefore \text{Distance between the two side air supply outlets approximates 3 m.} \]

\[ \therefore \text{We can have } \beta = 0.6, \text{ and } V/V = 0.6. \]

\[ \therefore \text{According to Eq. (13.8), we can obtain:} \]

\[ \varphi = 0.5 \sqrt{5.5 \times \frac{2.5}{2}} - 1 = 4.6 - 1 = 3.6 \]

According to Eq. (11.15), we know:

\[ \psi = 1.013 \]

\[ N_v = \psi N = 1.013 \times 60 = 61 \text{ #/L} \]

**Example 13.2.** The condition is the same as Example 13.1. When the indoor particle concentration is required to be 61 #/L, what is the required air change rate?

**Ans:**

With 61 #/L and \( G_n = 2.7 \times 10^4 \text{ #/}(\text{m}^3 \cdot \text{min}) \), the air change rate can be found from Fig. 13.4 that \( n = 26 \text{ h}^{-1} \).

With the same method above, \( \psi = 1.013 \). According to Eq. (13.7), we can obtain

\[ n_v = \psi n = 1.013 \times 26 = 26.3 \text{ h}^{-1} \text{ (approximately } 27 \text{ h}^{-1}) \]

**Example 13.3.** There is a turbulent flow cleanroom with a high-efficiency air cleaning system. This cleanroom is 14 m\(^2\) in area and 2.5 m in height. It is equipped with one top air supply outlet. There are two people working in the room. When the indoor particle concentration is required to be less than or equal to 84 #/L, what is the required air change rate?

**Ans:**

\[ \therefore \text{Occupant density is:} \]

\[ q = \frac{2}{14} = 0.144 \text{ people/m}^2 \]
According to Fig. 13.1, \( G_n = 3.3 \times 10^4 \) #/(m\(^3\)-min). With \( G_n \) and 84 #/L, the air change rate for uniform distribution can be found from Fig. 13.4 that \( n = 24 \) h\(^{-1}\). Since the area corresponding with one air supply outlet is larger than 10 m\(^2\), we can get \( \beta = 0.6 \) and \( \psi = 1.5 \).

∴ Volume of the cleanroom is \( V = 35 \) m\(^3\); according to Table 13.14, we get \( V_b = 8 \) m\(^3\).

∴ \( V_b/V = 0.73 \) and then \( \psi = 1.24 \).

∴ According to Eq. (13.7), we get:

\[
   n_v = \psi n = 1.24 \times 24 = 30 \text{ h}^{-1}
\]

If the above calculation is not performed and instead Table 13.16 is used, we can obtain \( \psi \approx 1.21 \), so \( n_v \approx 1.21 \times 24 = 29 \text{ h}^{-1} \). So the discrepancy is acceptable.

**Example 13.4.** The condition is the same as Example 13.3. When the air change rate is 30 h\(^{-1}\), what is the indoor particle concentration?

**Ans:**

According to Fig. 13.4 with the given values of 30 h\(^{-1}\) and \( G_n \), we can get \( N = 67 \) #/L. With the same method above, we get \( \psi = 1.24 \), then:

\[
   N_v = \psi N = 1.24 \times 67 = 83 \text{ #/L}
\]

**Example 13.5.** There is a cleanroom with a high-efficiency cleaning system. When the particle generation rate \( G_m \) at static state is \( 2 \times 10^4 \) #/(m\(^3\)-min), and the fresh air ratio is 0.5, what is the required air change rate for air cleanliness level Class 7?

**Ans:**

∴ The fresh air ratio = 0.5. According to the data given before, we can get:

\[
   N_s = 2.5 \text{ #/L}
\]

Assume for Class 7 it is designed with the concentration of 100 #/L. According to Eq. (13.7), we can obtain the value of \( n \):

\[
   n = \frac{60 \times 2 \times 10^4 \times 10^{-3}}{100 - 2.5} = 12.3 \text{ h}^{-1}
\]

From Table 13.16 with the value of \( n \), we can interpolate and obtain \( \psi = 1.4 \). Then we get:

\[
   n_v = 1.4 \times 12.3 = 17.2
\]

∴ \( n_v = 18 \text{ h}^{-1} \).
Example 13.6. With the same condition as the former example, when the air change rate is 18 h\(^{-1}\), and the fresh air ratio is 0.25, which air cleanliness level can be reached in the at-rest state?

Ans:
\[
\therefore \text{ Fresh air ratio } = 0.25. \text{ According to Fig. 13.4 with the air change rate } 18 \text{ h}\(^{-1}\) \text{ and } G_m = 2 \times 10^4 \text{ #/L, we can obtain } N = 68\text{#/L. }
\]
According to Table 13.6, we can obtain \(\psi = 1.27\) with the air change rate is 18 h\(^{-1}\). With Eq. (13.6), we can obtain:
\[
N_v = 1.27 \times 68 = 86.4 \text{#/L}
\]
\[
\therefore \text{ Air cleanliness level Class 7 can be reached during at-rest state. If the air cleanliness level at operational state should be estimated, the dynamic-to-static ratio should be assumed.}
\]
If the dynamic-to-static ratio is set to be 3, then:
\[
N_v \approx 260 \text{#/L}
\]
It’s still Class 7.
If the dynamic-to-static ratio is set to be 5, then:
\[
N_v \approx 432 \text{#/L}
\]
It’s beyond the range of Class 7. Only when the air change rate is increased, the particle concentration can be lowered.

Example 13.7. There is a turbulent flow cleanroom with a high-efficiency air cleaning system. This cleanroom is 7 m\(^2\) in area and 2.5 m in height. It is equipped with five top air supply outlets placed on one side. The fresh air ratio is 20 % and there is one person working in the room. Because the area is small, and the number of air supply outlets is large, the workspace is almost within the mainstream area, and it can be designed with the particle concentration in the mainstream area. When the indoor particle concentration is 7 #/L, what is the required air change rate?

Ans:
\[
\therefore \text{ Occupant density is:}
\]
\[
q = 17 = 0.14 \text{ persons/m}^2
\]
According to Fig. 13.1 when the dynamic-to-static ratio is assumed to be 5, \(G_n = 3.3 \times 10^4 \text{#/}(\text{m}^3\cdot\text{min})\), which is beyond the available range of Fig. 13.4.
So Eq. (13.7) can be used for calculation. As \((1 - s) = 0.2\), \(N_s = 1 \text{#/L. \ Then we can obtain:}
\]
\[ n = \frac{60 G \times 10^{-3}}{N - N_s} = \frac{60 \times 3.3 \times 10}{7 - 1} = \frac{1980}{6} = 330 \text{ h}^{-1} \]

Because one air supply outlet corresponds with the area larger than 1 m\(^2\), and the air supply outlets are located on one side, with Table 13.11 we can get \( \beta = 0.8–0.9 \), and \( \psi = 0.2 \).

\[ \therefore \text{According to Eq. (13.10), we can obtain the following expression when the particle concentration in the mainstream area is used:} \]

\[ \psi = 1 - \frac{\beta}{1 + \varphi} = 1 - \frac{0.8 \sim 0.9}{1 + 0.2} = 0.25 \sim 0.33 \]

\[ \therefore n_v = \psi n = 0.33 \times 330 = 108 \text{ h}^{-1}, \text{ or } n = 0.25 \times 330 = 82.5 \text{ h}^{-1}. \]

When the dynamic-to-static ratio is assumed to be 3, we can obtain \( n = 210 \text{ h}^{-1} \) and \( n_v = 52.5–69.3 \text{ h}^{-1}. \)

**Example 13.8.** There is a cleanroom with air supply outlets mounted at the whole ceiling and return air openings on two lower sides. One HEPA filter has been installed in series in the fresh air passage. The cleanroom is 20 m\(^2\) in area, and the air change rate is 617 h\(^{-1}\). When there are two people for measurement, what is the particle concentration under at-rest state?

**Ans:**

\[ \therefore \text{We know} \]

\[ N_v = N_s + \psi \frac{60 G_m \times 10^{-3}}{n} \]

During calculation with the mainstream theory

\[ \psi = 1 - \frac{\beta}{1 + \varphi} \]

\[ \therefore \text{HEPA filter has been installed in series in the fresh air passage.} \]

\[ \therefore N_s \approx 0. \]

Because air supply outlets are mounted on the whole ceiling, we get \( \varphi = 0.02 \). Because return air openings are installed on two lower sides, we get \( \beta = 0.97 \). So \( \psi = 0.05 \). Because the occupant density is \( q = 0.1 \text{ people/m}^2 \), we get:

\[ G_m = 0.9 \times 10^4 \#/(\text{m}^3 \cdot \text{min}) \]

\[ \therefore \text{The particle concentration is obtained:} \]

\[ N_v = 0.05 \times \frac{60 \times 0.9 \times 10^4 \times 10^{-3}}{617} = 0.044 \#/L \]
The measured results showed that among 84 times of measurement, the average concentration is 0.033#/L. Because of the insufficient measuring points and measuring times, the measurement result can be relatively lower. (Refer to the section about cleanroom in Chap. 17.)

**Example 13.9.** There is a cleanroom with air supply outlet mounted on the ceiling (covering slightly over 80% of the whole ceiling area) and return air openings are placed on one lower side. One HEPA filter has been installed in series in the fresh air passage. The cleanroom is 5.5 m² in area, and the air change rate is 500 h⁻¹. When there is one person for measurement, what is the particle concentration under the at-rest state?

**Ans:**
As the former example, we know \( N_s \approx 0 \) and \( \varphi = 0.02 \). Since the ratio of blowing area is slightly larger than 80%, we can choose \( \beta = 0.99 \). Since \( q = 0.1 \) people/m², we get:

\[
G_m = 0.9 \times 10^4 \text{#/}(m^3 \cdot \text{min})
\]

On the basis of mainstream area theory, we can get \( \psi = 0.03 \).

Since \( n = 500 \) h⁻¹, we get:

\[
N_v = 0.03 \times \frac{60 \times 0.9 \times 10^4 \times 10^{-3}}{500} = 0.042 \text{#/L}
\]

The measured results showed that the average concentration is 0.026#/L. Because of the insufficient measuring points and measuring times, the measurement result can be relatively lower.

### 13.3 Calculation for Applications with Local Filtration Device

In some applications such as computer rooms or program-controlled rooms, special air-conditioning systems are always used due to special requirements for the parameters, in order to circulate and clean indoor air. These special air-conditioning systems are equipped with filters. This is equivalent with the case where local air cleaning equipment is used. Under these circumstances, filtration measures are usually supplemented for fresh air, whose efficiency is equivalent to that of medium-efficiency air cleaning system. For example, in large- and medium-scale computer rooms, it is required that the concentration should be \( \leq 18,000 \)#/L for particles with diameter \( \geq 0.5 \) μm, which is even lower than the lowest air cleanliness level Class 9. But even so, the requirements can be met only with feasible calculation. Taking the computer rooms as an example, calculations will be performed with different types [16].
### 13.3.1 Computer Room with Both Central Air-Conditioning System and Special Air Conditioner

The use of special air conditioner is equivalent to installing local air cleaning equipment in the cleanroom, as shown in Fig. 13.6.

Central air-conditioning system is usually targeted for thermal comfort indoors. However, places with large amount of computers will generate a lot of heat, which needs the dedicated air conditioner to solve this problem. In this case, the indoor particle concentration should be calculated with Eq. (10.10) when local air cleaning equipment is used, i.e.,

\[
N = \frac{60G \times 10^{-3} + Mn(1 - S)(1 - \eta_n)}{n[(1 + \eta'S') - S(1 - \eta_n)]}
\]

where \(\eta'_n\) is the filtration efficiency of the local air cleaning equipment. Here it is the efficiency of filters in the special air conditioner, which is generally equivalent to 0.3; \(S'\) is the ration between the circulation airflow rate and the total air volume through the local air cleaning equipment.

Other parameters are shown as follows: assuming \(q = 0.1\) preson/m², then \(G_n = 1.07 \times 10^5\) #/(m³·min); let \(M = 3 \times 10^5\) #/L; \(n\) is the air change rate of the computer room, which can be considered 10 h⁻¹ as a normal air-conditioning room; \(S\) is the ratio of the circulated airflow, which can be chosen as \(S = 0\) when the air change rate for positive pressure indoors is considered and the fresh air flow rate can be assumed 2 h⁻¹ at least; \(\eta_n\) is the overall efficiency of the filters in the fresh air passage (for particles with diameter \(\geq 0.5\) μm) and \(\eta_n = 0.829\); \(\eta_r\) is the overall efficiency of the filters along the return air passage (for particles with diameter \(\geq 0.5\) μm), and from Fig. 13.6 we know \(\eta_r = \eta_n = 0.829\).

According to the “Design Code for Electronic Computer Room” (GB50174-93), the large- and medium-scale computer rooms are those with area larger than 140 m². When the story height is 3 m, the room volume is 420 m³, where one or two special air conditioners can be usually placed. When one air conditioner is used, the airflow rate is 10,000 m³/h. When two air conditioners are used, the
The airflow rate is 20,000 m³/h. This means the air change rate of self circulation indoors is 25–50 h⁻¹, which is 2.5–5 times as that of the central air-conditioning system (10 h⁻¹). It means $S'$ is equivalent to 250–500 %. Suppose 400 % is used as an average, which is four times, we can obtain that $N = 5,285 \#/L$.

### 13.3.2 Computer Room with Special Air Conditioner and Air Handling Unit for Fresh Air

At present, central air-conditioning systems are not installed in most of the existing computer rooms, and it is aimed to solve the problem of heat generation from computers. The special air conditioner is used to deliver the cold air into the plenum box. On part of the cold air enters the computer from bottom to up, and the other part is sent indoors from the floor air supply outlets. In order to meet the hygienic standard, another fresh air supply outlet is set in another place inside the computer room, so that the treated outdoor air is sent into the room, as shown in Fig. 13.7.

There are several situations:

1. At present, the most commonly used computer room is that equipped with special air conditioner and fresh air handling unit with medium-high-efficiency filters (Fig. 13.7a).
Since there is no air supply system, it is equivalent to the straight flow system. So the total airflow rate is the same as the fresh airflow rate. The circulation ratio is $S = 0$.

It is not allowed for a special air conditioner to have a large proportion of fresh air, which is usually about 5%. That means for the air conditioner, the fresh air ratio is $(1 - S) = 0.05$. So the proportion of circulating airflow rate of the special air conditioner to the indoor total airflow rate is $S' = 1/0.05 = 20$.

According to Fig. 13.7a, the efficiency of the combined filters is:

$$
\eta_n = 1 - (1 - 0.05)(1 - 0.1) = 0.145
$$

The filter efficiency in special air conditioner $\eta'$ is equivalent to 0.3 (for particles with diameter $\geq 0.5 \mu m$). It is known from the above introduction that the chosen value of $n$ has little effect on the indoor particle concentration $N$. If $n = 50$, we can obtain $N = 36,661 \#/L$ according to the equation above. So the requirement can hardly be met in this kind of the computer room, where special air conditioner is commonly used and fresh air handling unit with medium-high-efficiency filters are installed.

(2) When the efficiency of filter installed in the special air conditioner is increased to 0.8 (for particles with diameter $\geq 0.5 \mu m$) (Fig. 13.7b), and substitute $\eta' = 0.8$ to the above equation, we can obtain $N = 15,096 \# /L$. It only basically meets the requirements since the number is quite close to the upper limit of the specified concentration.

(3) In the computer room where the efficiency of filter installed in the fresh air passage is increased to 0.8 (for particles with diameter $\geq 0.5 \mu m$) (Fig. 13.7c).

Because $\eta_n = 1 - (1 - 0.05)(1 - 0.8) = 0.81$, we can obtain $N = 8,161 \# /L$. It is obvious that this method can meet the requirement.

(4) In the computer room where the efficiencies of both filters used for fresh air and special air conditioner are increased to 80% (Fig. 13.7d).

We can get $\eta_n = 0.81$. When other conditions are the same, we can obtain $N = 3,360 \# /L$. It is obvious that this method can not only meet the requirement but can also reach the upper limit of air cleanliness level Class 8.

References

1. Shigeharu H (1967) Local dust collection for the environment in clean sterile workshop. Mag Building Equip 2:46–57 (In Japanese)
2. Shiobin K (1971) Selection method of air cleaning devices for different application. Jpn Air Cond Heat Refrig News 11(9):103–110 (In Japanese)
3. Xu ZL (1994) Design of cleanroom. Seismological Press, Beijing, pp 12–125 (In Chinese)
4. Schütz H, Raüme R (1969) Staubfreie Arbeitsplätze für die Feiwerktechnik. Feinwerktechnik, Oktober, pp 444–449 (In German)
5. Kosuke H (1973) Planning and design of cleanroom. Jpn Air Cond Heat Refrig News 13(1):75–88 (In Japanese)
6. Humikura A (1967) Design and construction of cleanroom. Jpn Air Cond Heat Refrig News 13(17):20–29 (In Japanese)
7. Нонезов РТ, Знаменский РЕ (1973) Обеспыливание воздушной среды в "Чесмых комнатах". Водоснабжение и Санитарная Техника 3:29–32 (In Russian)
8. Schichir HH (1973) Clean room technology-principles and applications. Sulzer Techn Rev 1:3–15
9. Wang SG (1997) Fresh air and control of fresh air systems. J HV&AC 1:23–28 (In Chinese)
10. Кокорев НП (1972) Гигиеническая оценка без оконных и бесфонарных промышленных зданий. Гигиена и Санитария 6:25–28 (In Russian)
11. Kanzi S, Keiji K (1979) Design basis of air cleaning system indoors. Jpn Air Cond Heat Refrig News 19(9):68–76 (In Japanese)
12. Fanger PO (2000) IAQ in the 21st century: search for excellence (trans: Yu Xiaoming). J HV&AC 30(3):32–35. (In Chinese)
13. Kazuya H et al. (1974) Air conditioning and air cleaning. (In Japanese)
14. Tuve GL (1953) Air velocity in ventilating jets (Heating, Piping and Air Conditioning, No.6360). Special Science and Technology Information Collection (HVAC). (In Chinese)
15. Shunzou B, Tora B (1973) Design of cleanroom. Jpn Air Cond Heat Refrig News 13(1):89–95 (In Japanese)
16. Xu ZL (1996) Essential measures to insure cleanliness in computer rooms. J HV&AC 26(6):65–69 (In Chinese)