Cleanroom shows different characteristics when it is in at-rest and operational states respectively, which is the reflection of its own laws. By further analysis, curve can be drawn with the expression of its particle concentration, through which the influence of every parameter on the air cleanliness level can be shown intuitively. Furthermore, the curve will reveal the law of cleanroom.

12.1 Characteristic of At-Rest State

Figure 12.1, 12.2, 12.3, 12.4, 12.5, and 12.6 can be obtained with the analysis of the steady-state formula when particle concentration is uniformly distributed. During the plot of the curve, suppose $1 - S = 0.3$, according to the test data at home and abroad. Prefilters, placed before the final filter, contain primary filter (often the coarse filter, the efficiency for particles with diameter $\geq 0.5\, \mu m$ is taken as 0.15) and intermediate filter (often the medium-efficiency filter, the efficiency for particles with diameter $\geq 0.5\, \mu m$ is taken as 0.4). Its overall efficiency is about 0.5, which can be calculated through $1 - (1 - 0.15)(1 - 0.4) = 0.49$.

These curves are called as the characteristic curves of turbulence flow cleanroom with uniform particle distribution. These characteristics are called at-rest state characteristics, because it helps people to understand many important characteristics when the particle concentration reaches stable. It has the following characteristics:

1. In a wide range, i.e., $M \leq 10^6 \, \#/L$, the influence of the fluctuation of the atmospheric particle concentration is small on the cleanroom with air cleanliness level equal to or lower than Class 100 where HEPA filters are installed as the final filters (the situation of cleanroom with air cleanliness level higher than Class 100 will be analyzed in the last chapter), which can be negligible.

   It is observed that the characteristic curve is quite flat at the range of $M = 10^6$ to $2 \times 10^6 \, \#/L$, when the efficiency of the final filter whose efficiency is $\eta_3 = 0.99999$, regardless of the orders of magnitude of the particle generation rate $G$ per unit volume.
It is known from Chap. 2 that the value of $10^6$ #/L corresponds to the seriously polluted atmospheric particle concentration, which is two times of that in general industry. Thus, it is acceptable to consider that the present particle concentration in the cleanroom is free of the influence by atmospheric dust concentration.

Fig. 12.1 The curve of at-rest state characteristic in cleanroom (1)
For the cleanroom with medium-efficiency filter as the final filter, the indoor particle concentration fluctuates with the atmospheric particle concentration. It is observed that the characteristic curve is already straight when \( \eta_3/C_2 > 0.9 \). For the room with general particle generation rate, namely, \( G = 10^4 \) to \( 10^5 \) #/(m\(^3\)·min), \( M_2/M_1: N_2/N_1 \approx 1:1 \). Only when \( G \) is larger, \( N_2/N_1 \) will decrease.

The effect of \( M \) on \( N \) is also in between when \( \eta_3 \) is between the values of high- and medium-efficiency filters.

These characteristics have been completely proved by experiments. For example, for a cleanroom with a medium-efficiency air purification system, when the atmospheric particle concentration \( M \) changes from \( 1.7 \times 10^5 \) to \( 2.5 \times 10^5 \) #/L by the increase rate 50 %, the indoor particle concentration \( N \) changes from \( 1.4 \times 10^4 \) to \( 2.1 \times 10^4 \) #/L, correspondingly, which also increases approximately by 50 %.

Fig. 12.2  The curve of at-rest state characteristic in cleanroom (2)
Conversely, when the atmospheric particle concentration $M$ changes from $5.3 \times 10^4$ to $3 \times 10^4$ #/L, decreasing by 40 %, the indoor particle concentration $N$ changes from $0.63 \times 10^4$ to $0.46 \times 10^4$ #/L, correspondingly, also decreasing approximately by 40 %. The change of the indoor particle concentration in the room with this kind of system is simultaneous with that of the atmospheric particle concentration, as shown in Fig. 12.7.

(3) When the indoor particle generation rate $G$ per unit volume changes, it will influence the particle concentration of the cleanroom. The larger the efficiency of the final filter is, the bigger the influence is. For example, when $\eta_3 = 0.5–0.9$ and $G$ increases by 10 times, $N$ only increases by tens of percents. When $\eta_3 > 0.999$, however, $N$ also increases by one time approximately as $G$ increases by one time.
This shows that for cleanroom with high-efficiency air purification system, indoor particle generation rate per unit volume is a significant factor to the indoor particle concentration, which has a greater impact than the atmospheric particle concentration. In this sense, interior management is more important than outdoor environment for this kind of cleanroom.

(4) It is not necessary to install final filter with $\eta_3 \geq 0.99999$ in all cases. When the efficiency of final filter reaches a certain level, the function to increase the air cleanliness level becomes significantly less for cleanroom with air cleanliness level equal to or lower than Class 100. From the perspective of increasing the cleanroom’s air cleanliness level, it has little sense to further increase the efficiency $\eta_3 \geq 0.99999$. In this case, it is much important to solve the leakage problem. From the characteristic curve, final filter that is less efficient but also with lower resistance and lower price will be suitable for the cleanroom where the requirement of the air cleanliness is not high enough, such as sub-HEPA filter. It is beneficial to the development of air cleaning technology. However, for cleanrooms where air cleanliness should be higher than Class 100, it is not enough to install the normal HEPA filter with the efficiency 0.99999 (i.e., 0.3 $\mu$m filter); 0.1 $\mu$m filter must be used.

Fig. 12.4 The curve of at-rest state characteristic in cleanroom (4)
(a) In accordance with the theory of uniform distribution, it is a linear relationship between the air change rate \( n \) and the particle concentration \( N \). It can be observed from the characteristic curves above. However, as indicated in last chapter about the influence of nonuniform distribution, with large air change rate, \( N \) changes faster than \( n \) (this will be introduced in detail later). This should be paid attention to during the analysis of the at-rest characteristic curve.

(b) The larger the value \( \eta_3 \) is, the greater the influence of \( n \) will be. Because when the supplied air is clearer, the dilution effect is more efficient. If the air supply volume is larger, the dilution effect will be more efficient.

It should be pointed out that there is a general misconception. It seems that the lower the filter efficiency is and the higher the local atmospheric particle concentration is, it is more likely to increase the air change rate to offset these shortcomings and to increase the air clean effect. But this is not the case. When the value of \( \eta_3 \) is smaller and the value of \( M \) is bigger, the curves with different air change rates \( n \) are almost approaching to a line. Because of the small value of \( \eta_3 \), the particle concentration of the supply air is the equivalent to the indoor particle concentration by the generation source, which has little effect on diluting the indoor particle concentration. So the value of \( n \) has little effect on the cleanroom where medium-efficiency filters are installed as the final filters. On contrary, the larger the value of \( \eta_3 \) is, which reaches up to 0.9999–0.99999, for example, the larger the effect of \( n \) will be.
Fig. 12.6 The curve of at-rest state characteristic in cleanroom (6)
The effect of $n$ increases with the increase of $G$, which means the effect of $n$ will be bigger when the particle generation rate in the cleanroom is large.

For the generation situation, the indoor particle generation rate is $G = 10^4 - 10^5 \text{#/}(\text{m}^3\cdot\text{min})$. If the value of $M$ is not too small (more than $10^5 \text{#/L}$), the curves with $n = 10 - 200 \text{h}^{-1}$ are quite close to each other for medium-efficiency air purification systems. This means in general conditions, the effect of the change of $n$ on $N$ is negligible when $n / C_0 \leq 10 \text{h}^{-1}$ for medium-efficiency air purification systems. In other words, $n = 10 \text{h}^{-1}$ will be practicable for medium-efficiency air purification systems.

In short, it is inappropriate to have the opinion that the larger the value of $n$ is, the better it is, regardless of what situation it is.

Here again, the relationship between the air velocity and the deposit density mentioned in Chap. 6 is emphasized again. If the air velocity above the workpieces increases too much by the increase of the air change rate, especially when the air supply concentration is also large, the consequence is that the probability of contamination on the workpieces will be larger, which is the opposite to the expectation of improving the dilution effect.

For turbulence flow cleanroom with high-efficiency air purification system, the normal air change rate is $\leq 100 \text{h}^{-1}$, and the indoor particle generation rate can be considered as $5 \times 10^4 \text{#/}(\text{m}^3\cdot\text{min})$ (introduced in detail in Chap. 13). From Fig. 12.2, the particle concentration $N$ can reach $50\text{#/L}$ at most when $M = 10^6$, which is equivalent to the circumstance of no-people condition (see Fig. 12.1). When the actual condition with $M = 10^5$ is used, $N$ is also between 6 and 10 $\text{#/L}$. When the air change rate is as large as $150 \text{h}^{-1}$ (it is unlikely to increase in the
turbulent flow cleanroom), \( N \) is close to 100. So generally speaking, it is impossible to reach Class 100 for a turbulent flow cleanroom. It is appropriate to distinguish the unidirectional flow and the turbulent flow with Class 100. The method of unidirectional flow must be taken in cleanroom with air cleanliness level Class 100 or higher. The method of turbulent flow can be used in cleanroom with air cleanliness level lower than Class 100. But according to the theory of nonuniform distribution (Fig. 12.27 and the calculation about the nonuniform distribution in next chapter), if the measuring points are located in the mainstream of the cleanroom with large air change rate, it is possible to obtain the concentration equivalent with Class 100. Of course, this is entirely different from the effect of the Class 100 unidirectional flow. They are not rate interchangeable with each other. So it is not reasonable to replace the unidirectional flow cleanroom with turbulent flow cleanroom with large air change.

In the turbulent flow cleanroom with medium-efficiency air purification system where \( \eta_3 = 0.9 \), air cleanliness level can reach Class 1,000,000 under the premise of \( M = 10^6 \# / \text{L} \). Class 1,000,000 can be realized under the premise of \( M < 3 \times 10^5 \# / \text{L} \) when \( \eta_3 = 0.5 \).

12.2 Dynamic Characteristic

The variation process of particle concentration in the cleanroom before the steady state is regular, which includes the “rising curve” and the “decline curve.” The main reason for the variation of the particle concentration is the change of indoor particle generation rate. It can be divided into the following two kinds of circumstances:

12.2.1 To Increase the Particle Generation Rate After Steady State Is Reached by Self-Cleaning Process

This is the major situation. For example, since the system is booted in advance, the indoor particle concentration has reached a lower stable value at the beginning of working time. With the start of the work, people enter in, which increases the particle generation rate. This is the situation:

(1) Particles generate stably (e.g., people stay inside until the end of the working day)

Before working time, point \( b \) in Fig. 12.8 represents the indoor condition. Particle generation rate increases as people enter in (increase from \( G_1 \) to \( G_2 \)), which disturbs the original stable state. As the indoor particle concentration rises, a new stable state appears. Point \( b \) becomes the beginning of a new process. The steady-state concentration \( N_1 \) of the previous process becomes the initial concentration of the
following progress. Since the steady-state concentration of the new progress $N_2 > N_1$, the variation of particle concentration can be written as Eq. (10.12):

$$N_{2t} = N_2 - (N_2 - N_1)e^{-\frac{nt[1 - s(1 - \eta_r)]}{60}}$$

where $N_{2t}$ is the instantaneous particle concentration of the second process. This is a rising progress, as shown the curve $bc$ in Fig. 12.8.

(2) The increased particle generation source disappears at a certain time (e.g., people who enter in will leave the room again midway).

In Fig. 12.8, the indoor particle generation rate increases from the moment of $t_1$. But it disappears suddenly at the moment $t'_1$ (point $c'$ in the figure). Then the indoor particle concentration changes from $b$ to $c'$, and the indoor particle generation rate decreases from $G_2$ to $G_1$. After that, the variation progress of the particle concentration is the same as the previous self-purification process, which decreases along with the curve $c'b'$ (at the moment people leave the room, the particle generation rate increases suddenly because of the activity of people. Otherwise, there is a lag time for the decrease). The particle concentration $N'_{2t}$ at point $c'$ is also the initial concentration of the third progress. Since the increase of the particle generation rate disappears suddenly, the steady-state concentration of this progress should be the original particle concentration $N_1$, and $N_1 < N'_{2t}$. The formula to describe this process can be written as

$$N_{3t} = N_1 + (N'_{2t} - N_1)e^{-\frac{nt[1 - s(1 - \eta_r)]}{60}}$$

where $N_{3t}$ is the instantaneous particle concentration of the third process.
12.2.2 Increase the Particle Generation Rate Before the Steady State of Self-Cleaning Process

(1) Generate particles continuously and stably

In Fig. 12.9, at the moment of \( t_1 \), the indoor particle concentration at point \( b \) increases. Thus, the new process starts from this point with the initial concentration \( N_0 \). Assume the steady-state concentration of this new progress is \( N_2 \). If the increase of the particle generation rate is big enough, it is likely that \( N_2 < N_1' \), which is represented by the rising curve \( bc \). If the increase of the particle generation rate is too small to change the downturn trend of original process, it can just slow down the trend and it will be \( N_2 < N_1' \). But it is apparent that \( N_2 > N_1 \). The process is represented by the declining curve \( bc' \) (as shown in Fig. 12.10).
(2) Sudden disappearance of the increased particle generation rate

As shown in Fig. 12.11, the new increased particle generation rate will increase the indoor particle concentration to point $c'$, and then it disappears. If its original curve is a rising curve $bc'$ (its mathematical expression is the same as the former expression of curve $bc$), the following new process will begin with $N_2'$ as its initial concentration, and $N$ is the steady-state concentration of $c'b'$. If the original curve is the decline curve $cb''$ (as shown in Fig. 12.12), the following new process will begin with $N_2'$ at point $c''$ as its initial concentration, and $N$ is the steady-state concentration of $c''b''$. The mathematical expressions of these processes won’t be repeated here.

Through the analysis above, it is known that the variation progress of the particle concentration in cleanroom can be separated into two basic processes according to the practical measurement. One is the pollution process with indoor particle generation source, which is represented by the rising curve. The other is the
self-purification process, which is represented by the decline curve. This is also the dynamic characteristic of the cleanroom. Figure 12.13 shows the variation of the particle concentration by measurement in cleanroom. It is clearly proved that the above conclusion is suitable for the reality.

According to the characteristic of the variation of particle concentration, the method to plot the curves was proposed by author.

With the instantaneous particle concentration, we obtain:

\[
N_t = N \pm \Delta N e^{-\frac{nt}{60}} \approx N \pm \Delta N e^{-\frac{nt}{60}}
\]

So we obtain

- If \( nt = 60 \), then \( e^{-\frac{60}{60}} = \frac{1}{e} = 0.362 \)
- If \( nt = 120 \), then \( e^{-\frac{120}{60}} = \frac{1}{e^2} = 0.135 \)
- If \( nt = 180 \), then \( e^{-\frac{180}{60}} = \frac{1}{e^3} = 0.050 \)
- If \( nt = 240 \), then \( e^{-\frac{240}{60}} = \frac{1}{e^4} = 0.018 \)
- If \( nt = 300 \), then \( e^{-\frac{300}{60}} = \frac{1}{e^5} = 0.008 \)

and so on.
Then the curve of the variation of the particle concentration can be drawn on the coordinate paper, as shown in Fig. 12.14. Firstly, the self-purification time \( t \) and the steady-state particle concentration \( N_2 \) should be calculated. Secondly, interception \( \frac{60}{n_1} = t_1'' \) is made on the abscissa and interception \( \Delta N \times 1/e = 0.362\Delta N \) is made on the ordinate from \( N_1 \) (the original concentration \( N_0 \) is known). Their intersection point should be the point \( N_1'' \) on the variation curve of particle concentration. Similarly, interception of \( 120/n_1 \) is made on the abscissa of \( t_1'' \) is directly prolonged by one time, namely, \( t_1''' = t_1''' \), and the intersection point with the 0.135 \( \Delta N \) is \( N_1'''' \) and so on. Then, when points \( N_0, N_1', N_1'', N_1''' \), and \( N_1 \) are connected, the variation curve of particle concentration can be obtained. Of course, with the curve connecting points \( N_0, N_1', N_1'', \) and \( N_1''' \), the line parallel with the abscissa and tangential to this curve at point \( N_1 \) can be plotted, so that the self-purification time \( t_1 \) can be obtained in turn.

If the indoor particle generation rate increases from \( G_1 \) to \( G_2 \) after the particle concentration reaches stable, the new steady-state particle concentration can also be obtained with the known value of \( G_2 \). So the curve of pollution process can also be drawn, as shown in Fig. 12.15. Unlike the curve of self-purification, the points \( N_1' \) and \( N_1'' \) are obtained with the interception downwards from point \( N_2 \). When points \( N_1, N_2', N_2'', N_2''' \), and \( N_2 \) are connected, the curve of pollution process can be obtained.
The theoretical calculation results accord well with the actual measurement results. Comparison between the theoretical process and the actual process is shown in Figs. 12.16 and 12.17.

12.3 Characteristic Curve of Nonuniform Distribution

A series of curves can be obtained with Eq. (11.15), as shown in the Figs. 12.18, 12.19, 12.20, 12.21, 12.22, 12.23, 12.24, 12.25, and 12.26. They can reflect the relationship between the nonuniformity coefficient and several characteristic parameters of the cleanroom. They are called as the characteristic curve of the nonuniform distribution in cleanroom [1].
Fig. 12.17 Comparison between the theoretical process and the actual process (2)

Fig. 12.18 Characteristic curve of nonuniform distribution (1)
It can be observed from these characteristic curves:

1. In all conditions, the bigger the value of $\beta$ is, the smaller the nonuniformity coefficient $\psi$ is. That means if the particle generation source can be placed in the mainstream area as possible, the average particle concentration indoors will be smaller.

2. For the turbulent flow cleanroom, $V_b/V$ is usually larger than 0.5. So the bigger the value of $\varphi$ is, the smaller the uniformity coefficient $\psi$ will be, and $\psi$ is approaching 1. This means the air supply outlet with large induction ratio should be installed in the turbulent flow cleanroom, so that the airflow indoors will be well mixed, and uniform dilution effect can be realized as much as possible. Thus the particle concentration is closer to the calculated result with the expression of uniform distribution.
3. For the unidirectional flow cleanroom, \( V_b/V < 0.1 \). The smaller the value of \( \phi \) is, the lesser the uniformity coefficient \( \psi \) will be, which is smaller than 1. This means airflows are already parallel in the unidirectional flow cleanroom; the inducted airflow is expected not to be large, which disturbs the unidirectional parallel flow. On contrary, the smaller the induced airflow is, the more stable the unidirectional parallel flow will be, and the lower the particle concentration will be.

4. For the cleanroom when \( V_b/V \) is between the two above values (usually it is the cleanroom with high air cleanliness level), the value of \( \phi \) should be an intermediate value, so that the uniformity coefficient \( \psi \) can be minimum.
12.4 Inhomogeneity of Concentration Field

12.4.1 Concentration Ratio Between the Mainstream Area and the Return Air Area:

\[
\frac{N_c}{N_a} = \frac{N_a + \frac{G_a}{(Q+Q')}}{N_a} = 1 + \frac{G_a}{N_a(Q+Q')} \frac{G_{so}}{N_sQ+Q'(G_{so}+G_b)}
\]
When the concentration of supplied air $N_s$ is omitted, then:

$$\frac{N_c}{N_a} \approx 1 + \frac{G_a}{Q + Q} \frac{Q}{Q'(G_a' + G_b')} = 1 + \frac{G_a}{Q(1+\phi)} + \frac{G_0 Q'}{Q(1+\phi)} + G_b$$

$$= 1 + \frac{G_a}{1+\phi} \frac{Q(1+\phi)}{Q[G_a \phi + G_b (1+\phi)]}$$

$$= 1 + \frac{\beta G_0}{G_0 (1-\beta)(1+\phi) + G_0 \phi \beta}$$

$$= 1 + \frac{\beta}{(1-\beta)(1+\phi) + \beta \phi}$$

$$= \frac{1 + \phi}{1 + \phi - \beta}$$
So,

\[
\frac{N_a}{N_c} \approx 1 - \frac{\beta}{1 + \varphi}
\]  

(12.1)

It is clear that for different values of \(\beta\) and \(\varphi\), \(N_a/N_c\) is different. But for the turbulent flow cleanroom where the air change rate is not too big, on average \(\varphi = 1–2\) and \(\beta\) will be about 0.5 (see details in Chap. 13). Inserting them into the equation above obtains:

\[
\frac{N_a}{N_c} = \frac{1.5}{2} - \frac{1.5}{3} \approx 0.8
\]

For cleanroom with large air change rate and several air supply outlets, on average \(\beta = 0.6–0.7\) and \(\varphi = 0.7–1\). Inserting them into the equation above obtains:

\[
\frac{N_a}{N_c} = 0.6 - 0.65
\]

The result is consistent with the measurement data by relevant units mentioned in Chap. 11.

### 12.4.2 Concentration Ratio Between the Mainstream Area and the Vortex Area:

\[
\frac{N_b}{N_a} = \frac{N_a + G_a' + G_b'}{N_a} = 1 + \frac{G_a' + G_b'}{N_a}
\]

When the concentration of supplied air \(N_s\) is also omitted, then:

\[
\frac{N_b}{N_a} \approx 1 + \frac{Q}{\varphi Q} = 1 + \frac{1}{\varphi}
\]  

(12.2)

For common turbulent flow cleanroom, \(\varphi = 1–2\). Inserting them into the equation above obtains:

\[
\frac{N_b}{N_a} = 1.5 - 2
\]

If the number of air supply outlets increases, take \(\varphi = 0.7\), so we obtain:

\[
\frac{N_b}{N_a} = 2.44
\]
In the actual measurement, the measuring points are usually placed in the mainstream area and the vortex area, so \( N_b/N_a \) can reflect the extent of the maximum deviation of the measured concentration field caused by the nonuniform distribution. In the measurement process, it is found that if the measuring points for the working area are placed in the vortex area or on the edge of the mainstream flow region, it is easily influenced by the vortex pulsation. The ratio of the measured concentrations of different measuring points or the values of the same measuring point will be different from about 1.5 times, or even two times as the maximum. For more air supply outlets, it will be more than two times, which is roughly equivalent to the above calculated value of \( N_b/N_a \).

From the above analysis, for a turbulent flow cleanroom, the difference of measured concentrations will be within one time because of the influence of the inherent characteristic of nonuniform distribution, which is allowed. There are also studies abroad \([2]\) that according to the difference of the measured data, the concentration field is nonuniform, and it is suggested that the measurement should be performed at multipoints and multiple times.

### 12.4.3 Concentration Ratio Between the Vortex Area and the Mainstream Area:

\[
\frac{N_b}{N_c} = \frac{N_a + G_a' + G_b'}{N_a + G_a'} = 1 + \frac{G_b'}{N_a + G_a'} \approx 1 + \frac{1 - \beta}{\psi}
\]

The expression shows that \( N_b > N_c \). By substituting specific data, it is easy to find that \( N_b \) is larger than \( N_c \) by 60\% or even 100\%.

### 12.4.4 Concentration Ratio Between Uniform Distribution and Nonuniform Distribution

The nonuniformity coefficient \( \psi \) is defined as the ratio of the particle concentration between the uniform distribution and the nonuniform distribution. For the turbulent flow cleanroom, \( \psi \) is usually within \( \pm 0.5 \), which is shown in Table 13.16. So it is acceptable if the difference between the results calculated by the uniform distribution method and experimentally measured concentration is within a half time, because they are still in the fluctuation range of nonuniform distribution. This is not necessarily the problem of calculation.

It is known from Eq. (11.1) that:
\[ N_c = N_a + \frac{G_a}{Q + Q'} = \frac{\varphi G_a}{Q(1 + \varphi)} + \frac{G_b}{Q} + \frac{G_a}{Q(1 + \varphi)} + N_s = \frac{1}{Q} (G_a + G_b) + N_s = \frac{G_0}{Q} + N_s \]

It is shown that the concentration in the return air area is the average concentration with uniform distribution. However, the real average concentration, i.e., the average concentration with nonuniform distribution, can be larger than that with uniform distribution \((\varphi > 1)\) or smaller than it \((\varphi < 1)\). So the real average concentration can be both bigger and smaller than that in the return air area.

Many actual measurements also show that the indoor average concentration measured in cleanrooms with relatively uniform airflow or multiple air supply outlets is often lower than the concentration in the return air area. In cleanroom with poor air distribution, the measured average concentration is often higher than that in the return air area. This indicates that, the correction coefficient of the calculated results on uniform distribution can be smaller or bigger than 1. When correction is made along the single direction based on the calculated results of uniform distribution will result in the conclusion far from reality.

It can be observed from Fig. 12.27 that line A is the calculated results with as-built and at-rest states with the theory of uniform distribution. Polyline B corresponds with the measured values with as-built and at-rest states. Polyline C is an example of the calculated particle concentration with the theory of nonuniform distribution in a common cleanroom. In this kind of cleanroom, when the air change rate exceeds 120 h\(^{-1}\), the number of air supply outlets should be increased correspondingly. The mainstream area will extend to the whole working area, so the indoor average concentration can be calculated with the concentration of the mainstream area. The calculated concentrations can be plotted as the polyline D, which is closer to the actual measurement. It is worthy to point out that the turning points exit in the measured data in the studies at home and abroad [3]. And the air change rates at the turning point are close to each other, which has not been paid attention to and analyzed. This phenomenon that appeared in the actual measurement has not been explained and proved by theory. Now with the above analysis and theoretical calculation, the turning point on the calculated polyline is close to that of the measured polyline, so it has been illustrated from theory.

It is indicated that in the real circumstance, which is under the nonuniform distribution condition, there is a polyline relationship between the particle concentration in the working area and the air change rate of the cleanroom. It is not an ideal linear relationship with the uniform distribution condition. This \(N–n\) polyline relationship has been the basic rule of the cleanroom.
12.5 Particle Load Characteristic of Fresh Air

According to the concept of three-stage air filtration on the fresh air passage, the particle load characteristic of fresh air should be understood for further application of this concept.

12.5.1 Effect of Three-Stage Air Filtration for Fresh Air

For places with HEPA filter as the final filter, it can be observed from Fig. 12.2 that when three-stage air filtration is used for fresh air so that the comprehensive efficiency can be increased by an order of magnitude, it is equivalent to the condition that the atmospheric particle concentration will be lowered by an order of magnitude. In this case, its influence on the indoor particle concentration can be ignored. In other words, for a common cleanroom, the feature of three-stage air filtration is not to reduce the indoor particle concentration.
For places with sub-HEPA filter as the final filter, it can be shown from curves 2–3 in the figure that, when the comprehensive efficiency can be increased by an order of magnitude, it is equivalent to the condition that the atmospheric particle concentration will be lowered by an order of magnitude. In this case, the indoor particle concentration can be lowered by an order of magnitude.

For places with medium-efficiency filter as the final filter such as $0 < \eta_3 < 0.5$, the indoor particle concentration will reduce inversely by more than one order of magnitude after three-stage air filtration for fresh air is used.

The above conclusion is shown with the following examples. Table 12.1 shows an example of a cleaning air-conditioning system.

Table 12.2 is an example of a common air-conditioning system, as shown in Fig. 12.28.

The results indicate that, in order to reduce the particle concentration by a half in a room with a common air-conditioning system, where final filter is not installed, air filter with efficiency $\eta_3 = 0.3$ should be installed at every air supply outlet. In this specific system, there are ten air filters with the same airflow rates. If air filters are not installed at the air supply outlets and combined filters are only installed for fresh air (e.g., one coarse filter and one medium-efficiency filter, or one coarse filter and one high- and medium-efficiency filter, are combined in the air handling unit of fresh air) with the comprehensive efficiency $\eta_0 = 0.62$, the effect of lowering the indoor particle concentration will be the same as the measures to install air filters on every air supply outlet, but the ratio of the number (assuming the rated air volumes are the same) of filters is 2:10. Meanwhile, the efficiency of bacterial filtration is about 80–90%. If three-stage air filtration with sub-HEPA filter is used, $\eta_0 = 0.97$. Not only the indoor particle concentration can decrease to 1/10, but also the efficiency of bacterial filtration can reach up to 99.9%.

### 12.5.2 Particle Load Ratio of Fresh Air

In order to quantitatively study the economic effects of three-stage filtration of fresh air, the concept of “particle load ratio of fresh air” is proposed [4]. It can be expressed with $\alpha$, then we obtain:

$$
\alpha = \frac{\text{Particles deposited on various components brought by fresh air}}{\text{Total quantity of particles deposited on various components}}
$$

For the system shown in Fig. 12.29, coarse filter is installed on the return air passage (in some cases, return air does not go through the coarse filter, as shown with the dotted line in Fig. 12.28). The following calculation is performed ($\eta_0'$ in the picture is neglected first):

The atmospheric dust weighing method is used during calculation. In the figure, $M'$ is the weighing concentration of atmospheric dust, mg/m$^3$; $\eta_1'$ denotes the
Table 12.1 Relationship between the indoor particle concentration (#/L) and the concentration of fresh air for the cleaning air-conditioning system under different conditions

| Condition | Operational state ($G_m = 0.65 \times 10^5$) | At-rest state ($G_m = 0.17 \times 10^5$) | Operational state, as left | At-rest state, as left |
|-----------|-----------------------------------------------|------------------------------------------|---------------------------|------------------------|
| Final HEPA filter | 157 | 42 | – | – |
| Final sub-HEPA filter ($\eta = 0.97$) | 5,384 | 4,398 | 1,714 | 1,599 |
| Final sub-HEPA filter ($\eta = 0.97$) | 384 | 268 | 225 | 109 |
| Three-stage filters for fresh air, comprehensive efficiency 0.97 | 612 | 12 | Characteristics of Cleanroom |
arrestance of the first-stage coarse filter; \( \eta_1 \) represents the “arrestance” of the cooler in air-conditioning system (If there are four rows of coils in the cooler or heater in air-conditioning system, the resistance can reach 100 Pa, which is even higher than that of a medium-efficiency filter. The particle deposition rate is large. This is why it is easily blocked as mentioned before. So we assume that it also has certain “arrestance” for the deposited particles.); \( \eta_2 \) denotes the arrestance of the medium-efficiency filter; \( \eta_3 \) refers to the arrestance of HEPA filter; \( S \) and \( S' \) denote the proportions of the return air volume and the fresh air volume in the total air volume, respectively, and \( S' = 1 - S \); and \( N' \) indicates the weighing concentration of indoor particles.

The particle load ratio in fresh air through the first-stage coarse filter is:

\[
\alpha_1 = \frac{M'S'\eta_1'}{M'S'\eta_1' + N'S_1} = \frac{M'S'}{M'S' + N'S}
\]
For the particle load ratio through the cooler, since the upstream concentration changes from $M_0$ to $\frac{M_0}{C_0\eta_1}$, and from $N_0$ to $\frac{N_0}{C_0\eta_1}$, so we can obtain

$$\alpha_c = \frac{M_0 S_0}{M_0 S_0 + N_0 S}$$

Likewise, for other medium-efficiency filters and HEPA filters:

$$\alpha_2 = \alpha_3 = \alpha_1 = \alpha_c = \alpha = \frac{M' S'}{M' S' + N' S} \quad (12.6)$$

Final filters are rarely used in simple air-conditioning systems, but the value of $\alpha$ does not changed.

This means the proportions of particles brought in by fresh are the same in the total amount of deposited particles on various components. Specific values are shown in Table 12.3. It can be seen that since the particle concentration of return air is relatively high, the value of $\alpha$ is relatively lower, which is about 0.3. Therefore, filtration should be strengthened not only for fresh air, but also for return air.

Since the value of $N'$ in a cleaning air-conditioning system ranges from 0.01 to 0.00001 mg/m$^3$, it can be assumed 0.001 mg/m$^3$ and the calculated results are shown in Table 12.4. It is obvious that in cleaning air-conditioning systems, $\alpha$ is more than 0.9, namely, more than 90% of the deposited particles on various components come from fresh air. In all, apparent technological and economic effects will be generated in any systems when $\alpha$ is lowered.

**Table 12.3** Particle load ratio $\alpha$ of fresh air in air-conditioning systems

| $S'$ | $M'$ (mg/m$^3$) | $N'$ (mg/m$^3$) |
|------|----------------|-----------------|
|      | 0.1            | 0.15            | 0.20            | 0.25 |
| 0.1  | 0.2            | 0.18            | 0.13            | 0.10 | 0.08 |
| 0.1  | 0.3            | 0.25            | 0.18            | 0.14 | 0.12 |
| 0.1  | 0.4            | 0.31            | 0.23            | 0.18 | 0.15 |
| 0.1  | 0.5            | 0.36            | 0.27            | 0.22 | 0.18 |
| 0.1  | 0.6            | 0.40            | 0.31            | 0.25 | 0.21 |

**Table 12.4** Particle load ratio $\alpha$ of fresh air in air-conditioning systems

| $S'$ | $M'$ (mg/m$^3$) |
|------|----------------|
|      | 0.1            | 0.15            | 0.20            | 0.25 |
| 0.1  | 0.2            | 0.18            | 0.13            | 0.10 | 0.08 |
| 0.1  | 0.3            | 0.25            | 0.18            | 0.14 | 0.12 |
| 0.1  | 0.4            | 0.31            | 0.23            | 0.18 | 0.15 |
| 0.1  | 0.5            | 0.36            | 0.27            | 0.22 | 0.18 |
| 0.1  | 0.6            | 0.40            | 0.31            | 0.25 | 0.21 |
12.5.3 Relationship Between Particle Load Ratio of Fresh Air and Lifetime of Component

When the efficiency of air filters for fresh air increases, the indoor particle concentration can be lowered, and the lifetime of all components in the system can be prolonged.

With the particle load ratio \( \alpha \), the relative change of components’ lifetime (time period to reach the standard dust holding capacity) can be calculated quantitatively. Suppose the change rate of the particle concentration in fresh air is denoted by \( \beta \), which is

\[
\beta = \frac{\Delta K}{K}
\]

where \( K \) is the original penetration of the components;
\( \Delta K \) is absolute value of the increment or decrement of the penetration.

If the original particle load ratio is \( \alpha \), and the decrement rate of fresh air is \( \beta \), the decrease of particle deposition by fresh air is \( \beta \alpha \). The total quantity of deposited particles on the component during the original lifetime period decreases to \( 1 - \beta \alpha \). If particles continue to deposit by \( \beta \alpha \), under the fixed air volume when the standard dust holding capacity reaches 100 %, the ratio between the prolonged time and the original lifetime is \( \Delta t = \beta \alpha / (1 - \beta \alpha) \). So the lifetime can be prolonged by \( t = (1 + \Delta t) \) times. Also, suppose the particle concentration in fresh air increases by \( \beta \), then the quantity of deposited particles by fresh air increases by \( \beta \alpha \), and the total quantity of deposited particles during the original lifetime period increases to \( 1 + \beta \alpha \). When the standard dust holding capacity achieves 100 %, the quantity of deposited particles will decrease by \( \beta \alpha \). Accordingly, if particles continue to deposit by \( \beta \alpha \), the ratio between the extended time and the original lifetime is \( \Delta t = \beta \alpha / (1 + \beta \alpha) \), and the lifetime will be reduced by \( t = (1 - \Delta t) \) times.

For an air-conditioning system, suppose the standard dust holding capacity is 100 g, 30 g of which are brought by fresh air; then \( \alpha = 0.3 \). If the particle concentration of fresh air reduces by half, which means \( \beta = 0.5 \), the deposited particles brought by fresh air during the period of original lifetime are only 15 g, and the total quantity of deposited particles becomes: 70 g (dust from return air) + 15 g (dust from fresh air) = 85 g. Since there can be 15 g more dust deposited within the lifetime, it is equivalent with the time \( 15/85 = 0.176 \) of the original lifetime. We can obtain:

\[
\Delta t = \frac{\beta \alpha}{1 - \beta \alpha} = \frac{0.5 \times 0.3}{1 - 0.5 \times 0.3} = \frac{0.15}{0.85} = 0.176
\]

So, the prolonged lifetime is 1.176 times of the original lifetime \( (t = 1 + \Delta t = 1 + 0.176 = 1.176) \).
As it is calculated above, the standard dust holding capacity is 85 g, 15 g of which is brought by fresh air, and $\alpha = 0.176$. When the change rate of the particle concentration increases by 100 %, $\beta = 1$ (change from 15 to 30 g), there will be 100 g particles deposited during the original lifetime. However, if the lifetime is calculated with the standard dust holding capacity, the deposited particles will be less by 15 g, which occupies 15 % of the original value 100 g, so the lifetime will also be reduced by 15 %.

With the above expression, we obtain:

$$\Delta t = \frac{\beta \alpha}{1 + \beta \alpha} = \frac{1 \times 0.176}{1 + 1 \times 0.176} = \frac{0.176}{1.176} = 0.15$$

Therefore, the shortened lifetime is 0.85 times of the original one ($t = 1 - \Delta t = 1 - 0.15 = 0.85$).

For the system mentioned above, if combined filters with arrestance 0.99 are installed (its particle counting efficiency is more than 70 %) at the entrance of fresh air opening, the particle concentration in the fresh air will decrease by $\beta = 1 - 0.01/1 = 0.99/1$ for each original component, as shown Fig. 12.29 with the dot line. Thus, the prolonged lifetime of the original components, including the coarse filter at the mixing section of the fresh air and return air, air cooler, and medium-efficiency filter, becomes:

$$\Delta t = \frac{0.99}{1} \times 0.3 = \frac{0.297}{0.703} = 0.42$$

It means that the lifetime becomes 1.42 times of the original one ($1 + 0.42 = 1.42$), which is rather remarkable.

For the air cleaning system, it is known from the first row of Table 12.4 that $\alpha_2 = \alpha_3 = \alpha = 0.934$, and from the next row that $\alpha = 0.96$. If air filter with efficiency $\eta_0'$ is not installed in the system, instead the efficiency $\eta_1'$ of the original fresh air filter increases from 0.7 to 0.99, the prolonged lifetime for air cooler, medium-efficiency filter, and HEPA filter will be:

$$\Delta t = \frac{0.3 - 0.01}{0.3 - 0.01} \times 0.934 = 9.3$$

$$\Delta t = \frac{0.3 - 0.01}{0.3 - 0.01} \times 0.96 = 12.9$$

That means the lifetimes are extended to 10.3 times and 13.9 times of the original value, respectively.
By economic comparison [4], the scheme of three-stage filtration is cost-saving (cost of installation and operation) and energy-saving compared with the scheme where the efficiency of air filters at the air supply outlet increases only.

With the combined scheme in Table 12.2 as an example, the result is as follows (see details from Ref. [4]):

\[
\frac{\text{Expense of scheme 4}}{\text{Expense of scheme 2}} = 0.78 - 0.85 \\
\frac{\text{Electrical energy consumption of scheme 4}}{\text{Electrical energy consumption of scheme 2}} = 0.83
\]

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