Calculation of the dust concentration is the core of the design calculation for cleanroom. The theoretical calculation in this chapter is based on the assumption that particles are uniformly distributed in cleanroom.

**10.1 Three-Stage Filtration System in Cleanroom**

Three-stage filtration system is usually installed for cleanroom, which includes coarse, fine, and HEPA filters (or called primary, intermediate, and final stages). In the system, fine filter is installed in the positively pressurized section downwards of the fan. HEPA filter is installed at the air supply terminal. Fine or coarse filter is installed at return air terminal. It is called high-efficiency air cleaning system when the final stage filter is a HEPA filter, and it is called medium-efficiency air cleaning system when the final stage filter is a fine filter. Figure 10.1 shows the schematic diagram of turbulent flow cleanroom system.

The meanings of each symbol are as follows:

- \( N_t \) is the indoor particle concentration at time \( t \) (min) (#/L);
- \( N \) is the indoor steady-state particle concentration (#/L);
- \( N_0 \) is the indoor original particle concentration, which is the particle concentration at time \( t = 0 \) (#/L);
- \( V \) is the cleanroom volume (m\(^3\));
- \( n \) is the air change rate (h\(^{-1}\));
- \( G \) is the particle generation rate per unit volume [#/\( (m^3 \cdot \text{min}) \)];
- \( M \) is the atmospheric particle concentration (#/L);
- \( S \) is the ratio of return air rate to the supply air rate;
- \( \eta_1 \) is the efficiency of primary filter (or combined with fresh air filter), (particle number concentration, expressed with decimal, this applies for the following symbols);
- \( \eta_2 \) is the efficiency of intermediate filter;
- \( \eta_3 \) is the efficiency of final filter.
In practice, coarse filter is usually placed for filtration of fresh air in the three-stage filtration system. It has been proved that it is the time to update the concept. In 1994 author formally put forward this view [1], and argument was performed on the general air-conditioning system, special air-conditioning system, and air cleaning conditioning systems, respectively [2, 3].

This problem was put forward with the reason that when air-conditioning system is started, both the indoor bacteria concentration and the foul smell increase, which is also reported in foreign country recently [4]. The condensation water left on heat exchange coil, fin, valve, and its surrounding area will provide the high humidity condition near the coil, because water will evaporate slowly with the increase of temperature during the stop of the system. This is suitable for the breeding micro-organism, especially for fungi reproduction. During the startup of the system, a lot of gas will be released suddenly, which is generated by the breeding and becomes the source of foul smell. It is believed that microorganisms are brought in with large amount of dust in fresh air and they settle in these places, and nutritious condition indispensable for microbial growth is provided. The main reason for the generation of foul smell is the reproduction of fungi (for general air-conditioning system, the role of return air is larger).

The efficiency of coarse filter for filtration of fresh air is too low. The atmospheric dust concentration in China is too high (see Chap. 2). So the problem mentioned above will be more serious. The consequences are that not only the fresh air quality declines, but also the high atmospheric dust concentration entering into the system will clog the system components soon, which will greatly reduce the fresh air rate and the indoor oxygen proportion, and result in a vicious circle.

So the new concept of three-stage filtration system should include: three-stage filters for fresh air (coarse, fine and HEPA filters), intermediate preliminary filter (preliminary filter for terminal filter), and terminal HEPA (or sub-high efficiency) filter.
10.2 Instantaneous Particle Concentration in Turbulent Flow Cleanroom

In order to calculate the indoor particle concentration of turbulence cleanroom and the air change rate, we must determine the particle distribution in the cleanroom. Generally there are two types including the uniform distribution and the uneven distribution. In this chapter the calculation theory and method under uniform distribution condition will be discussed (the main content from this chapter to Chap. 13 has been published in the report “Calculation of cleanroom” by HVAC instituted in 1977). In the next chapter, the calculation theory and method for the uneven distribution will be discussed.

For uniform distribution, it is assumed that indoor particles are evenly distributed. If there is any particle source, particles generated will reach the equilibrium state quickly in the room with the diffusional effect of particles and driven force and dilution of air flow.

In order to simplify the calculation, we also need further assumptions: Ventilator flow rate is stable; Particles generated are constant; Atmospheric dust concentration is constant; The influence of particle density both indoors and outdoors and its dispersity variation on the influence of filter efficiency is ignored; Particles by infiltration and the possibility of particle generation by pipeline are ignored; Settlement of particles both inside the pipe and in the room is ignored.

In addition, the total efficiency of filter on the fresh air passage is \( \eta_n \). The total efficiency of filter on the return air passage is \( \eta_r \). With Fig. 10.1, we obtain that:

\[
\eta_n = 1 - (1 - \eta_1)(1 - \eta_2)(1 - \eta_3)
\]

or

\[
(1 - \eta_n) = (1 - \eta_1)(1 - \eta_2)(1 - \eta_3) \quad (10.1)
\]

\[
\eta_r = 1 - (1 - \eta_1)(1 - \eta_2)(1 - \eta_3)
\]

or

\[
(1 - \eta_r) = (1 - \eta_1)(1 - \eta_2)(1 - \eta_3) \quad (10.2)
\]

For the combination of fresh air filters, we know

\[
\eta_1 = 1 - (1 - \eta_{10})(1 - \eta_{20})(1 - \eta_{30}) \quad (10.3)
\]

\( \eta_{10}, \eta_{20}, \) and \( \eta_{30} \) are the efficiency of combined coarse, fine, and HEPA filters, respectively.
According to the front schematic diagram and the above hypothesis, it is visible that:

1. Indoor dust particle consists of three parts.

(a) Particles brought in by return air. The flow rate of return air per unit time is $\frac{snV \times 10^3}{60}$ (L/min). With the air filters (air filter at the return air grille, intermediate filter and final filter) on the return air passage, particles number entering indoors per unit time is $\frac{snV \times 10^3}{60}N_t(1 - \eta_r)$ (#/min). Therefore, during $\Delta t$ time period, increase of particle number per liter air indoors by return air is $\frac{snN_t}{60}(1 - \eta_r) \Delta t$ (#/min).

(b) Particles brought in by fresh air. The flow rate of fresh air is $\frac{nV \times 10^3}{60}(1 - s)$ (L/min). After passing through air filters on the fresh air passage, including primary, intermediate, and final stage filters, particle number per unit time entering indoors is $\frac{MnV \times 10^3}{60}(1 - s)(1 - \eta_n)$ (#/min). Therefore, during $\Delta t$ time period, increase of particle number per liter air indoors by fresh air is $\frac{Mn(1 - s)(1 - \eta_n)}{60} \Delta t$ (#/min).

(c) During $\Delta t$ time period, increase of particle number per liter air by particle generation source indoors is $G \times 10^{-3} \Delta t$ (#/min).

2. Particles exhausted from indoors include particles exhausted by organized return air (sometimes exhaust air is included) and particles by disorderly exhaust (discharge) air.

The ventilation rate per unit time is $\frac{nV \times 10^3}{60}$ (L/min). So during $\Delta t$ time period, particle number per liter air exhausted by ventilation system is $\frac{nN_t}{60} \Delta t$ (#/min).

According to above analysis about the particle number in and out of cleanroom, it is known that the variation of particle concentration in the cleanroom during time period $\Delta t$ is

$$\Delta N_r = \left( \text{Particle concentration into the room} \right) - \left( \text{Particle concentration discharged from room} \right)$$

$$= \left[ \frac{N_t n s (1 - \eta_r) \Delta t}{60} + \frac{Mn(1 - s)(1 - \eta_n) \Delta t}{60} + G \times 10^{-3} \Delta t \right] - \frac{N_t n \Delta t}{60}$$

When some items are moved and $\frac{dN_t}{dt}$ is used to replace $\frac{\Delta N_t}{\Delta t}$, we know that

$$\frac{dN_t}{dt} = \frac{60G \times 10^{-3} + Mn(1 - s)(1 - \eta_n)}{60} \times \left\{ \frac{N_t n [1 - s (1 - \eta_r)]}{60G \times 10^{-3} + Mn(1 - s)(1 - \eta_n)} \right\}$$
After integration is performed on the above expression when variables are separated, we obtain:

$$-\frac{60G \times 10^{-3} + Mn(1-s)(1-\eta_n)}{n[1-s(1-\eta_r)]} \ln \left\{ \frac{1 - \frac{N_0 n[1-s(1-\eta_r)]}{60G \times 10^{-3} + Mn(1-s)(1-\eta_n)}}{1 - \frac{N_0 n[1-s(1-\eta_r)]}{60G \times 10^{-3} + Mn(1-s)(1-\eta_n)}} \right\} = \frac{60G \times 10^{-3} + Mn(1-s)(1-\eta_n)}{60} t + C$$

where $C$ is an integral constant, which is determined with the initial condition. When $t = 0$, there are three kinds of situations:

(a) Calculation starts since the startup of the system; indoor particle concentration at time $t = 0$ is the instantaneous particle concentration before the operation of cleanroom. This particle concentration is relatively large due to factors such as leakage.

(b) After a certain period of operation for the system, calculation starts at any time when particle concentration reaches stable. So the indoor particle concentration at the moment $t = 0$ means the steady-state particle concentration. For cleanroom with different cleanliness levels, the values of the concentration are also different.

(c) When calculation starts from any moment during the operation of the system, the indoor particle concentration at the moment $t = 0$ means the indoor particle concentration when the system operates until this moment.

In a word, we can call the particle concentration at the moment $t = 0$ as the original particle concentration, which is expressed with $N_0$:

$$t = 0 \quad N = N_0$$

The value of $C$ can be calculated by substituting it into the above formula. The original formula can be rewritten as:

$$1 - \frac{N_0 n[1-s(1-\eta_r)]}{60G \times 10^{-3} + Mn(1-s)(1-\eta_n)} = e^{\frac{n[1-s(1-\eta_r)]}{60}}$$ (10.4)

So the instantaneous particle concentration in the cleanroom is:

$$N_t = \frac{60G \times 10^{-3} + Mn(1-s)(1-\eta_n)}{n[1-s(1-\eta_r)]} \times \left\{ 1 - \left[ 1 - \frac{N_0 n[1-s(1-\eta_r)]}{60G \times 10^{-3} + Mn(1-s)(1-\eta_n)} \right] e^{\frac{n[1-s(1-\eta_r)]}{60}} \right\}$$ (10.5)
10.3 Steady-State Particle Concentration in Turbulent Flow Cleanroom

10.3.1 Steady-State Expression for Single Room

In a stable ventilation condition, although particle source exists in cleanroom, which constantly releases particles, after a certain period of time, it will tend to be stable theoretically when $t \to \infty$. At this time, Eq. (10.5) can be rewritten as

$$N = \frac{60G \times 10^{-3} + Mn(1-s)(1-\eta_n)}{n[1-s(1-\eta_r)]}$$

(10.6)

When Eq. (10.6) is applied, the stable expression for one ventilation system can be easily obtained when it is clear which is the combination efficiency of filters $\eta_n$ and which is $\eta_r$. Taking Fig. 10.2a as an example, we can write:

$$N = \frac{60G \times 10^{-3} + Mn(1-s)(1-\eta_1)(1-\eta_2)(1-\eta_3)}{n[1-s(1-\eta_2)(1-\eta_3)]}$$

It is the same for the rest categories.

Fig. 10.2 Systems with different arrangement of filters
10.3 Steady-State Particle Concentration in Turbulent Flow Cleanroom

10.3.2 Steady-State Expression for Multiroom

The actual air cleaning systems are parallel between multirooms. The steady-state expression for multiroom is different from that of single room. Although foreign literatures [5] have given the steady-state expression, the calculation method for actual multiroom system was not explained. The relationship between two kinds of steady-state expressions was also not given. The parallel case with multirooms shown in Fig. 10.3 will be analyzed. With this parallel condition, calculation becomes very complicated for the particle concentration of each cleanroom.

First, the following expressions can be obtained with the method for single-room steady-state particle concentration:

\[ N_1 = \frac{60G_1 \times 10^{-3} + N_s n_1 (1 - \eta_3)}{n_1} \]  
\[ N_2 = \frac{60G_2 \times 10^{-3} + N_s n_2 (1 - \eta_3)}{n_2} \]

where \( N_s \) means the particle concentration of the mixture air after passing through the intermediate filter (#/L):

\[ N_s = \frac{MQ_n (1 - \eta_1)(1 - \eta_2) + Q_r N_r (1 - \eta_2)}{Q_s} \]

Where

- \( Q_n \) is the flow rate of fresh air (L/h);
- \( Q_r \) is the flow rate of the overall return air (L/h);
- \( Q_s \) is the flow rate of the overall supply air (L/h);
- \( N_r \) is the particle concentration of the overall return air (#/L):

\[ N_r = \frac{s_1 N_1 n_1 V_1 + s_2 N_2 n_2 V_2 + \cdots}{Q_r} \]
where $V_1$ and $V_2$ are the volumes of every room. It is obvious this calculation method is complicated.

The cleanroom shown in Fig. 10.3 will be analyzed. One cleanroom with particle concentration $N_1 = 3 \text{#/L}$ is connected in parallel with another cleanroom where the particle concentration is $N_2 = 3,000 \text{#/L}$. The particle concentration of the return air from multiroom system must be higher than 3 \text{#/L}. If the steady-state expression for single room was used to obtain the particle concentration of Room 1, it is lower for Room 1, which is unsafe. If the unsafe coefficient is too large, the steady-state expression for multiroom must be used to calculate the particle concentration of Room 1. Now how big the difference is will be analyzed.

The particle concentration of the overall return air for the multiroom system is no more than that of the dirtiest cleanroom. In Fig. 10.3, it is less than $N_2$, namely, $3,000 \text{#/L}$. Provided that the particle concentration of the overall return air is $3,000 \text{#/L}$, it is 1,000 times higher than 3 \text{#/L}. So for Room 1 in the multiroom, it is operated under the extreme condition that the particle concentration of the return air for single room is 1,000 times higher.

Under this circumstance, the balance equation of the steady-state particle concentration is:

$$
\frac{10^3 N_1 n S (1 - \eta_r)}{60} + \frac{Mn (1 - s)(1 - \eta_n)}{60} + G \times 10^3 = \frac{N_1 n}{60}
$$

So

$$
N_1 = \frac{60G \times 10^{-3} + Mn(1 - \eta_n)}{n[1 - 10^3 \times s(1 - \eta_r)]}
$$

(10.11)

where $N_1$ means the particle concentration of Room 1 in multiroom system ($\text{#/L}$).

Because HEPA filter is installed in return air passage, its efficiency for particles with diameter $\geq 0.5 \mu \text{m}$ reaches 0.99999 (see Chap. 4), then we know:

$$
(1 - \eta_r) = 0.00001
$$

$$
[1 - 10^3 \times s \times (1 - \eta_r)] \approx [1 - s \times (1 - \eta_r)] \approx 1
$$

So

$$
N_1 \approx N
$$

where $N$ means the particle concentration of Room 1 in single-room system.

It has shown that for those air cleaning systems with HEPA filter as the final stage filter, the steady-state expression for single-room system can be utilized to calculate the steady-state particle concentration of each room in multiroom system, no matter what system is (multiroom system or single-room system), which makes the calculation more simple.
In the above assumption, \( N_1 = 3 \text{#/L} \) and \( N_2 = 3,000 \text{#/L} \), which can be regarded as the connection of cleanrooms with difference of three classes in parallel. If the difference is less than three classes, there is no problem. If the highest class cleanroom of the high-efficiency air cleaning system and the cleanroom of the medium-efficiency air cleaning system are in parallel, the difference of the concentration indoors is about 10,000 times; then we get:

\[
1 - 10^4 \times s \times (1 - \eta_r) = 0.9 - 1
\]

The less the fresh air is, the bigger the error is. But it wouldn’t be more than 10%. Apparently, if two medium-efficiency cleanrooms are connected in parallel, where filters and recirculation ratio \( s \) are the same, the difference of indoor particle concentration would not be more than one time with different values of \( G \). In this case, the error would be about 10% when the single-room system is used to calculate the situation in multiroom system. But if the difference of filter efficiencies between two cleanrooms is too big, and so is the values of \( s \), the error would be much bigger.

### 10.4 Steady-State Particle Concentration with Local Air Cleaning Equipment

In the turbulent cleanroom, it is common that local cleaning equipment is installed at the same time. Clean bench and self-purifier are used most frequently. For local cleaning equipment working intermittently, although its operation is beneficial for improving the indoor air cleanliness, we do not calculate it separately. Only for local cleaning equipment which operates stably and regularly, the indoor steady-state particle concentration can be calculated for the system including the local cleaning equipment when it is necessary.

Now it is unnecessary to derive as the process for the instantaneous expression above. From the schematic diagram as shown in Fig. 10.4, just like Eq. (10.11), the following equation for the steady-state particle concentration can be obtained directly:

\[
\frac{Nn}{60} [s(1 - \eta_r) + s'(1 - \eta')'] + \frac{Mn(1 - s)(1 - \eta_n)}{60} + G \times 10^{-3} = \frac{Nn}{60} (1 + s')
\]

So

\[
Nn[(1 + s') - s(1 - \eta_r) - s'(1 - \eta')] = 60G \times 10^{-3} + Mn(1 - s)(1 - \eta_n)
\]

where \( s' \) means the ratio of the circulation flow rate through the local cleaning equipment, which is the self-circulation flow rate, to the total flow rate for the whole system;

\( \eta' \) means the total efficiency of each filter in the local cleaning equipment;

Other symbols have the same meanings as Fig. 10.1.
Therefore, the indoor particle concentration can be obtained:

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

(10.12)

Because HEPA filter must be installed in the local cleaning equipment which is used in cleanroom, \( \eta' \approx 1 \), Eq. (10.12) can also be rewritten as:

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

(10.13)

The difference between this equation and Eq. (10.6) is the denominator, where it changes from “1” to “1 + \( s' \).” This means that with the local cleaning equipment, the air change rate increases compared with original room. Since \( s(1 - \eta_r) \) is much smaller than 1, Eq. (10.13) can be simplified as:

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

(10.14)

Therefore, the influence of local cleaning equipment on the particle concentration can be clearly seen.

**10.5 Physical Meaning of Instantaneous and Steady-State Expressions**

From Eqs. (10.5) and (10.6), the instantaneous and steady-state equations of the particle concentration in turbulent flow cleanroom, it is clear that the latter is included in the brace of the former. When the steady-state expression is inserted into Eq. (10.5), we can obtain:
If $N_0 > N$, we get

$$N_t = N + \Delta N e^{-\frac{\eta[1-e^{-\eta t}]}{60}}$$  \hspace{1cm} (10.16)$$

If $N_0 < N$, we get

$$N_t = N - \Delta N e^{-\frac{\eta[1-e^{-\eta t}]}{60}}$$  \hspace{1cm} (10.17)$$

If $N_0 = 0$, we get

$$N_t = N \left\{ 1 - e^{-\frac{\eta[1-e^{-\eta t}]}{60}} \right\}$$  \hspace{1cm} (10.18)$$

Since the case when $N_0 = 0$ can also be included in the situation when $N_0 < N$, the above expression can be simplified as:

$$N_t = N \pm |\Delta N| e^{-\frac{\eta[1-e^{-\eta t}]}{60}}$$  \hspace{1cm} (10.19)$$

where $\Delta N$ means the difference between the original and the steady-state particle concentrations. “+” represents the positive number and “−” the negative number.

From Eq. (10.19), the physical meaning of instantaneous expression is very obvious. For $+\Delta N$, it means that the original particle concentration $N_0$ is higher than the steady-state concentration $N$, which is the decrease process of particle concentration, namely, the cleaning process. It is the decline curve $a$ in Fig. 10.5. Obviously, the particle concentration $N_t$ at any time is higher than $N$, and the differential between $N$ and $N_t$ is a fixed value correlated with $\Delta N$.

For $-\Delta N$, it means the original particle concentration $N_0$ is lower than the steady-state concentration $N$. It is an increasing process of the particle concentration, namely, the polluting process. That is the ascending curve $b$ in Fig. 10.5. Obviously, the particle concentration $N_t$ at any time is lower than $N$, and the differential is also a certain fixed times of $\Delta N$.

If $N_0 = 0$, the particle concentration varies as the ascending curve $c$ in Fig. 10.5. The difference between curve $c$ and curve $b$ is that curve $c$ goes through the zero position of axis.

It also could be deduced from the instantaneous and the steady-state expressions that the instantaneous concentration is relevant to the original concentration $N_0$, while the steady-state concentration has nothing to do with $N_0$, which is only relevant to the characteristic of air cleaning system. It only depends on the balance of the amount of particles in and out of the cleanroom under the steady-state situation. This is an important characteristic of the steady-state particle concentration.
10.6 Other Calculation Methods for Turbulent Flow Cleanroom

Except for the instantaneous and steady-state expressions of particle concentration based on the above three-stage filtration system proposed by author in 1976, both American Air Force Technology Regulation T.O. 00-25-203 (at that time it was mentioned as Austin from the USA; in fact it was Austin who cited this regulation [6]) and Kayatawa [7] from Japan deduced following equations from simplified schematic diagram (Figs. 10.6 and 10.7).

Instantaneous expression in Regulation 203:

$$N_t = \frac{60G}{\eta n V} \left( 1 - e^{-\frac{\eta nt}{60}} \right)$$  \hspace{1cm} (10.20)

Steady-state expression in Regulation 203:

$$N = \frac{60G}{\eta n V}$$  \hspace{1cm} (10.21)

The unit of $G$ in the above two expressions is #/min. It is different from the particle generation rate per unit volume, where $V$ is the room volume. Obviously, Eq. (10.20) is the special case of the previous derivation expression when $N_0 = 0$ and $s = 1$. However, $N_0 = 0$ is impossible in real world, and for most cases $s \neq 1$. So the limitation of this expression is big.

Instantaneous expression by Kayatawa:

$$N_t = N + (N_0 - N)e^{-\frac{nt[1 - s(1 - \eta)]}{60}}$$  \hspace{1cm} (10.22)
For the convenience of comparison, unified symbols are used in this chapter. The steady-state expression similar as Eq. (10.6) can also be deduced. But because the filtration efficiency $\eta$ is the so-called main filtration efficiency according to the single-stage filter, it cannot be used in other circumstances. In other literatures, different steady-state expressions will be deduced from different specific systems, which is also inconvenient for use.

Additionally, in the instantaneous expression of the indoor particle sedimentation proposed by Morrison from the USA, consider the sedimentation rate is uncertain, which makes the expression too complex to be applied. Also some people assume that various kinds of particles were captured when passing through HEPA filter, and then the simplified diagram was made [13]. The error caused is bigger, so it is disadvantageous for the investigation of the characteristic. And also some people proposed to use the method that the particle concentration at air supply outlet was calculated first and then the ventilation rate is calculated [14]. All of them are not systematic calculation and derivation, which will not been introduced in detail here.

Except for the accuracy of expression itself, the agreement between theoretic calculation and practical result also depends on the accurate determination of various parameters. A more practical calculation can be acquired when using the equation in this chapter and the parameter suggested in Chap. 13. The result will be presented in Chap. 13.

### 10.7 Calculation of Dust Concentration in Unidirectional Flow Cleanroom

Since the air cleanliness of unidirectional flow cleanroom can be higher than Class 100, it will mislead people that there is no need of calculation. But the equation of turbulent flow cleanroom mentioned above cannot be used in unidirectional flow
cleanroom. But as the appearance of the unidirectional flow cleanroom with air cleanliness higher than Class 100, and with the need of energy conservation, it is hoped that air cleanliness can still reach Class 100 by decreasing the number of filters originally placed full on the ceiling. Therefore, the calculation of the particle concentration is still necessary for unidirectional flow cleanroom. Author presented oversimplified calculation method based on uniform distribution model in 1976. Fukuda [8] also proposed the similar calculation theory and method based on the assumption that the dust released by people will not disperse in the crosswise direction. This is the first time that foreign countries presented the calculation method of unidirectional flow cleanroom. Fukudan equation ignores the particle generated by filter surface, but takes the particle brought in by return air into account \( N_r \). It can be written as:

\[
N = N_s + N_r
\]

where \( N_s \) is the particle concentration at the air supply outlet.

Actually, \( N_r \) is much smaller than \( N_s \), and the amount of the dust generation on the surface is also much smaller, which can be ignored. If this is the case, \( N \) is just equal to \( N_s \), which is much different from the practical situation.

In order to better calculate the particle concentration of unidirectional flow cleanroom, only the calculation theory of uneven distribution can be used, which will be introduced in detail in the next chapter.

### 10.8 Calculation of Self-Purification Time and Pollution Time in Turbulent Flow Cleanroom

#### 10.8.1 Concept

After the startup of air cleaning system, the indoor particle concentration of the cleanroom decreases from a high value to a certain stable value (which is measured in the working area or the first working plane in horizontal flow cleanroom), and the time needed is called the self-purification time. The shorter it is, the better the condition is. If the indoor particle concentration increases from a low stable value back to a high one because of pollution, the time needed is the pollution time. The difference is, if the pollution is caused by the halt of the cleanroom, the longer the time is, the better the system and the strictness of the building are. If the indoor particle concentration increases to a new value due to the increase of the particle generation source and the particle generation rate in the operation process of the cleanroom, the time needed is the particle pollution time. And the shorter the time is, the better it is, which means that the clean air current can dilute the pollution quickly. This chapter focuses on the calculation of self-purification time and
10.8 Calculation of Self-Purification Time and Pollution Time in Turbulent Flow

Particle pollution time. Because the pollution time by halt of cleanroom is influenced by both the system and the building, it is too complicated to be calculated.

Figure 10.8 is an example of self-purification curve during the startup of cleanroom and the pollution curve during the halt of the cleanroom in actual situation.

High-efficiency air cleaning system owns the conception of self-purification time and pollution time. The indoor particle concentration with medium-efficiency air cleaning system will change with the change of atmospheric dust concentration (see Chap. 12), so there is no self-purification time and pollution time in this situation.

10.8.2 Calculation of Self-Purification Time

From the instantaneous expression of particle concentration in turbulent flow cleanroom, the particle concentration $N_t$ at any time and time $t$ are unknown, so the self-purification time or the pollution time cannot be solved directly. Author has put forward the following simplified method.

In Eq. (10.5), the item outside of the bracket $\{\}$ is a steady-state expression, so it can be written as:
For cleanroom with high-efficiency air cleaning system, we know $\eta_t > 0.99$. While for the case of $s \leq 1$, $[1 - s (1 - \eta_t)] \approx 1$, so Eq. (10.23) can be simplified as:

$$\frac{N_t}{N} = 1 + \left(\frac{N_0}{N} - 1\right) e^{-\frac{nt}{60}}$$

(10.24)

Further simplification can be made for Eq. (10.24). Let $\frac{N_t}{N}$ is a number a little bigger than 1 (such as 1.01, 1.03, shown in Fig. 10.9), the particle concentration is thought to reach stable, so we can obtain the following expression with Eq. (10.24):

$$1.01 - 1 = \left(\frac{N_0}{N} - 1\right) e^{-\frac{nt}{60}}$$

So we get:

$$nt = 60 \left[ \ln \left(\frac{N_0}{N} - 1\right) - \ln 0.01 \right]$$

(10.25)

This formula will become a straight line in the single-logarithmic paper, which is shown in Fig. 10.10. Because usually $N_0/N >> 1$, so the value of 1 can be omitted during calculation.

In order to obtain the self-purification time, $N_0/N$ must be calculated first. $N_0$ is the original particle concentration in the cleanroom. It should be determined if it is not known in advance. It is shown from practice that, when the system has stopped for several hours just before startup, no matter what system it is in cleanroom, the value of $N_0$ at last tends to outdoor atmospheric dust concentration $M$. It can be seen from Table 10.1 that for cleanroom with the general building envelope, $N_0$ approximately reaches up to 80% of $M$. Because difference of $N_0$ is not large, and its influence on self-cleaning time is also not large, in order to facilitate the calculation, let $N_0 = M$.

The value of $M$ can be determined according to the principle introduced in Chap. 2.

$N$ is the stable particle concentration in cleanroom, which should be determined based on the requirements or calculation. The specific method will be introduced in Chap. 13.
Fig. 10.9 Decline of particle concentration in cleanroom
According to \( N_0/N \), the value of \( nt \) can be obtained from Fig. 10.10, so we get

\[
t = \frac{nt}{n}
\]

As explained in Sect. 10.1, the unit of \( t \) is “min.”

Table 10.2 lists comparison of self-purification time during the startup of the system in 18 cases between the calculation value and the measured value. It is shown that they are closer.

Figure 10.11 is plotted with the foreign experimental data [9]. Because experiment was performed in the same cleanroom with different air change rates, the relationship between the air change and the self-purification time is single, which is more convincing.

Now the self-purification time needed to remove the pollution brought in by the opening of the door introduced in Chap. 8 will be calculated.

It is known that because of the door opening, the indoor concentration ratio increases to \( N_0/N = 3.14 \). The self-purification time should be calculated when \( N_0/N = 1.2 \).

According to Eq. (10.24), we know

\[
\begin{align*}
nt &= 60 \left[ \ln \left( \frac{N_0}{N} - 1 \right) - \ln \left( \frac{N_t}{N} - 1 \right) \right] = 60 \left( \ln \frac{2.14}{0.2} \right) = 60 \times 2.37 = 142.2
\end{align*}
\]
Table 10.1  Indoor particle concentration after stop of the system

| Cleanroom                                      | Stable particle concentration after shutdown $N_0$ (#/L) | Atmospheric dust concentration at the same time $M$ (#/L) | $N_0/M$ |
|------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|---------|
| The envelop structure is the welded steel plate, sealed doors, pipes, seams, plus welding | $1.4 \times 10^4$                                        | $2.5 \times 10^4$                                        | 0.56    |
| General civil engineering clean room           | $12 \times 10^4$                                         | $17 \times 10^4$                                         | 0.70    |
| General assembly clean room                    | $9.8 \times 10^4$                                         | $10.5 \times 10^4$                                       | 0.93    |

Table 10.2  Comparison of self-purification time between the calculation value and the measured value

| No. | $n$ (h$^{-1}$) | $N_0$ (test value) (#/L) | $N$ (calculated value) (#/L) | $N_0/N$ | $nt$ | $t$(calculated value) min | $t$(test value) min |
|-----|---------------|--------------------------|-------------------------------|---------|------|--------------------------|---------------------|
| 1   | 28.1          | $2.6 \times 10^4$        | 22                            | $1.18 \times 10^3$ | 765  | 27                       | 26                  |
| 2   | 29            | $1 \times 10^4$          | 16                            | $6.3 \times 10^2$ | 670  | 23                       | 24                  |
| 3   | 67            | $5.4 \times 10^4$        | 14                            | $3.85 \times 10^3$ | 775  | 12                       | 18-20               |
| 4   | 59            | $4.5 \times 10^3$        | 16                            | $2.8 \times 10^3$ | 750  | 13                       | 15-27               |
| 5   | 21            | $2 \times 10^4$          | 22                            | $9 \times 10^2$   | 680  | 33                       | 33-38               |
| 6   | 21            | $6 \times 10^3$          | 22                            | $270$             | 620  | 30                       | 30-35               |
| 7   | 70            | $9 \times 10^4$          | 9.5                            | $9.5 \times 10^3$ | 830  | 12                       | 8-15                |
| 8   | 185           | $5.8 \times 10^4$        | 3.8                            | $1.5 \times 10^4$ | 850  | 4.6                      | 19                  |
| 9   | 36            | $7 \times 10^4$          | 28                            | $2.5 \times 10^3$ | 748  | 21                       | 14                  |
| 10  | 72            | $7 \times 10^4$          | 14                            | $5 \times 10^3$   | 780  | 11                       | 11.5                |
| 11  | 120           | $7 \times 10^4$          | 9.8                            | $7.2 \times 10^3$ | 810  | 6.7                      | 6.5                 |
| 12  | 150           | $7 \times 10^4$          | 8                             | $8.7 \times 10^3$ | 820  | 5.5                      | 5.5                 |
| 13  | 180           | $7 \times 10^4$          | 6.8                            | $1.1 \times 10^4$ | 830  | 4.7                      | 3                   |
| 14  | 230           | $7 \times 10^4$          | 5.4                            | $1.3 \times 10^4$ | 850  | 3.6                      | 3                   |
| 15  | 25            | $1.1 \times 10^3$        | 10                            | $1.1 \times 10^2$ | 560  | 22                       | 16                  |
| 16  | 50            | $8.5 \times 10^2$        | 10                            | $0.85 \times 10^2$ | 540  | 11                       | 10                  |
| 17  | 40            | $10^3$                   | 200                            | $5 \times 10^2$   | 650  | 16                       | 30                  |
| 18  | 29            | $1.06 \times 10^5$       | 15                            | $7 \times 10^3$   | 810  | 28                       | 30                  |

Fig. 10.11  Relationship between self-purification time and the air change rate
If the air cleanliness of cleanroom is Class 1,000, and \( n \) is 60 h\(^{-1}\), we can get the following expression from the above expression:

\[
t = \frac{142.2}{60} = 2.37 \text{ min}
\]

The pollution brought in not only increases the particle concentration but also brings in the foreign particles (such as different bacteria, dust sources with opposite natures). The self-purification time is expected to be within 2 min. Since it is less than 2 min for general unidirectional flow, the limit is set with 2 min. So the results above show that the pollution by opening of the door is dangerous. In this case, the buffer room should be set, as already discussed in Chap. 8.

From a series of calculation above, it is clear that the particle concentration in turbulent flow cleanroom reaches to a stable state in very short time. Under the extreme serious pollution condition after the stop of the system, namely, \( N_0 \to 10^6 \times N \) and \( nt \to 1,100 \), when the air change rate reaches 20 h\(^{-1}\), the self-purification time after the startup of the system does not exceed 1 h. When the air change rate reaches 30 h\(^{-1}\), it is less than 40 min. When the air change rate reaches 50 h\(^{-1}\), it is less than 22 min. But such a serious pollution is extremely rare, and usually \( N_0 \approx 10,000N \). According to the above air change rates, the self-purification times correspond to 41, 28, and 17 min. In the past there was no measurement on system; the effect of turbulent flow cleanroom was underestimated. So regardless of the ratio between the indoor original particle concentration and the stable concentration, as well as the air change rate, it was generally put forward that the self-purification time needed for turbulent flow cleanroom should be 1 h [10], and the duty fan must be set. Now it has been proved from both theory and practice that the self-purification time for turbulent flow cleanroom is not long. This means that, unless the product cannot be collected to avoid pollution after the stop of the system, usually the duty fan could not be set, as long as the system starts up half an hour before the operation of the cleanroom.

### 10.8.3 Calculation of Pollution Time

With particle generation pollution, the stable concentration before pollution becomes the original concentration \( N_0 \), and the new stable concentration is \( N \) after pollution. So \( N_0/N < 1 \). Equation (10.23) can be rewritten into:

\[
1 - \frac{N_t}{N} = \left(1 - \frac{N_0}{N}\right) e^{-\frac{nt[1-s(1-\eta_r)]}{60}} \approx \left(1 - \frac{N_0}{N}\right) e^{-\frac{nt}{60}} \quad (10.26)
\]
\( N_0/N \) can be assumed slightly less than 1, such as 0.99 (or 0.98). The particle concentration at this time can be regarded as stable. With Eq. (10.26), we know:

\[
nt = 60 \ln \left( 1 - \frac{N_0}{N} \right) - \ln 0.01
\]  

(10.27)

It is also a linear line on a single-logarithmic paper with this expression. It is equivalent to the extension of the line for self-purification, but with the abscissa \( N_0/N \) changes into \( 1 - N_0/N \).

### 10.9 Calculation of Self-Purification Time in Unidirectional Flow Cleanroom

The self-purification time in unidirectional flow cleanroom is extremely short. In principle, according to the piston flow theory, the ideal of self-purification time should be obtained with the room height divided with the velocity at the cross section. However, due to the uneven distribution of indoor particulate matter (see Chap. 11), the airflow in unidirectional flow cleanroom is actually the gradually varied flow, and reverse flow appears near the wall and overlap of airflow occurs beneath the air filters (see Fig. 8.23). Therefore, some particles cannot be discharged along with air for one time. They may be discharged after two times or even more than two times of circulation. This kind of circulation may also occur in local area with only a very small distance. This prolongs the self-purification time of the cleanroom. Therefore, the self-purification time in unidirectional flow cleanroom from practical measurement is generally longer than 30 s, and for vertical unidirectional flow cleanroom it is about 1 min, and for horizontal unidirectional flow cleanroom it is slightly longer, up to 2 min. This number is very important. If it is claimed that the self-purification time in unidirectional flow cleanroom reaches up to 5 min or even up to 10 min, the indoor velocity field may be not uniform. The turbidity of airflow will be greater, and the risk of leakage may be present, which lost the due function of unidirectional flow cleanroom.

Author thinks that, because the particle concentration in unidirectional flow cleanroom is very low, and the difference of measured results may be large (e.g., difference between 0.3 and 0.5 #/L is 70 %), it is inappropriate to judge the extent of unidirectional flow only with the particle concentration value. Since the self-purification time is closely related to the uniformity of velocity and the parallelization of streamline, it is much convenient and intuitive to judge with the characteristics of the flow field. Based on this view, author has collected some test cases with complete data of the velocity field in vertical unidirectional flow cleanroom, and the deviation of average velocity and the turbidity were calculated, which are listed in Table 10.3. From the table it is visible that: (a) except No. 7, with the increase of the turbidity and the average deviation of average velocity, the self-purification time is also lengthened;
(b) from the functional requirement of unidirectional flow cleanroom, the self-purification time is hoped to be less than 1 min. This is also suggested in the acceptance measurement about cleanroom in foreign country [12], and $\beta_u$ is about less than 0.25; and (c) if $\beta_u$ is between 0.25 and 0.35, and the self-purification time is not more than 2 min, which is 10 times less than the ideal self-purification time, it is feasible to regard it as the unidirectional flow cleanroom, and of course its performance was slightly worse.

For horizontal unidirectional flow cleanroom, the actual cases are rare which are consistent between the measuring point for the self-purification time and the measured velocity field plane, so it is not analyzed above. But the relationship between the self-purification time and the velocity field should also be the case.

### Table 10.3 Relationship between the self-purification time and the velocity field in vertical flow cleanroom

| No. | Average velocity (m/s) | Maximum deviation with average velocity | Turbidity ($\beta_u$) | Actual self-purification time | Ratio between actual and ideal self-purification times | Investigator |
|-----|------------------------|-----------------------------------------|----------------------|-------------------------------|--------------------------------------------------------|-------------|
| 1   | 0.44                   | 9.1, 6.8, 8                            | 0.045                | 28                            | 4.4                                                    | Kamishima Ya [11] |
| 2   | 0.4                    | 32, 42, 37                             | 0.17                 | 50                            | 8                                                      |             |
| 3   | 0.295                  | 59, 52, 56                             | 0.227                | 52                            | 6                                                      |             |
| 4   | 0.329                  | 73, 51, 62                             | 0.31                 | 90                            | 15                                                     |             |
| 5   | 0.234                  | 84, 66, 75                             | 0.34                 | 90                            | 10.6                                                   |             |
| 6   | 0.398                  | 81, 52, 67                             | 0.34                 | 90                            | 18                                                     |             |
| 7   | 0.37                   | 62, 67, 65                             | 0.356                | 50                            | 9                                                      |             |
| 8   | 0.313                  | 92, 68, 80                             | 0.36                 | 180                           | 22.5                                                   |             |
| 9   | 0.274                  | 57, 64, 60                             | 0.374                | 160                           | 17.4                                                   |             |
| 10  | 0.1                    | 90, 83, 87                             | 0.412                | 300                           | 49                                                     |             |
| 11  | 0.274                  | 177, 64, 120                           | 0.449                | 160                           | 17.4                                                   |             |

(These are measurement data in China. The largest value 0.76 m/s in Case No. 11 was omitted)

References

1. Xu ZL (1994) Design of cleanroom. Seismological Press, Beijing (In Chinese)
2. Xu ZL (1996) Essential measures to insure cleanliness in computer rooms. J HVAC 26(6):65–69 (In Chinese)
3. Xu ZL, Zhang YZ (1997) Three stage filtration in fresh air handling for better IAQ. J HVAC 1:5–9 (In Chinese)
4. Wada E (1991) Anti-bacterial fan coil unit. Mag Build Equip 42(5):41–44 (In Japanese)
5. Practical handbook of air conditioning technology, 1974 (In Japanese)
6. Austin PA, Timmerman SW (1965) Design and operation of clean rooms. Business News Publishing Co, Detroit, USA
7. Kazuya H et al (1972) Study of cleanroom (1). J SHASE Jpn 46(9):1–12 (In Japanese)
8. Fukuda M et al (1978) Design method of biological cleanroom. Jpn Air Cond Heat Refrig News 18(2):44–48 (In Japanese)
9. Oshitari Laboratories, Inc. (1974) Test report of cleanroom for experiment (In Japanese)
10. Bringold W (1972) Reine Räume und Reine Werklänke. Schweiz Bläther Heiz Lüft 39:3 (In German)
11. Kamishima K (1981) Air cleanliness level in cleanroom with 0.1 μm particles as the study object. Jpn Air Cond Heat Refrig News 21(5):91–99 (In Japanese)
12. Morrison PW (1973) Environmental control in electronic manufacturing. Van Nostrand Reinhold Company, New York, USA, pp 278–292
13. Schichr HH (1973) Clean room technology-principles and applications. Sulzer Techn Rev 1:3–15
14. Нонезов РТ, Знаменский РЕ (1973) Обеспыливание воздушной среды в"Чесмых комнатах". Водоснабжение и Санитарная Техника 3:29–32 (In Russian)