Chapter 14
Local Clean Area

It is called the comprehensive cleaning method when the environment in whole working area indoors is clean by the air cleaning and other comprehensive treatment measures. It is called the local cleaning method when the environment in local working area indoors or the particular local space is clean only by the local air cleaning measures. For the application where local cleaning method can be used, the comprehensive cleaning method should be avoided as much as possible.

14.1 Application of Mainstream Area Concept

There are three main development circumstances for the air cleaning methods: application in cleanroom alone, application as the local air cleaning device (such as the cleaning bench) alone, and application both in cleanroom and as the local cleaning device, namely, both the overall and the local cleaning methods are used.

But since a long term, because the understanding of the pollution control technology is not enough, the so-called pigeon cage type construction is usually adopted in the cleanroom, where the environment with the requirement of air cleaning is divided into smaller spaces. Although it is helpful to control the pollution, the disadvantage is also increasingly apparent:

1. The building plane is complex, and the cost increases with an excessive use of enclosure structure.
2. With the development of new process and new technology, the working procedures are often changed to form the new production line, which needs different air cleanliness level or methods. But it cannot be adapt to the requirement of this change.
3. For the production line where partition and obstruction are not allowed, and the application where people will enter in or out frequently, it is not easy for use.
4. When the core zone with small area but high air cleanliness requirement is needed, and the surrounding area with low air cleanliness requirement is also essential, it is not feasible to enclose the core zone. It is clear that the above disadvantage can be avoided with the comprehensive cleaning method for large area space, but it is economically unreasonable. If the comprehensive cleaning method for large area space with low air cleanliness requirement is used (e.g., the air cleanliness level is Class 100000 for the whole workshop), and local cleaning device is used to achieve the air cleanliness level Class 100, this is economically better than the comprehensive cleaning method with higher air cleanliness level, but the above shortcomings are still not completely avoided. For example, sometimes the rotation magnitude of the component in the process equipment is so large that it cannot be covered inside the workbench (such as the lifting and displacement of the bell jar for vacuum coating machine).

With the above situation, the concept of “mainstream area” was proposed in theory in 1978, which was introduced in Chaps. 11, and 12. When the process is placed in the mainstream area, the particle concentration can be smaller than the room average concentration by 30 % or a half, which is shown in Table 14.1. This means when the particle concentration in the mainstream area is designed with the room average concentration, the air change rate will be reduced by 30–50 %. It has been improved with practice that the effect of these schemes was quite good. Figure 14.1 shows the layout of the cleanroom by a foreign company, where HEPA filters were placed fully on two sides of the ceiling so that mainstream area with air cleanliness level Class 100 was achieved below. The clean air concentrated towards the room center. With the further effect of air supply outlet with a few HEPA filters placed in the center of the ceiling, the air cleanliness level in the middle space can reach Class 1000. For the application where the processes are mainly placed at two sides, this method is much economical compared with the method to achieve the air cleanliness level Class 100 by placing air filters fully on the ceiling.

Table 14.1 Values of \( \frac{N_v}{N} \) and \( \frac{N_a}{N} \)

|                      | Turbulent flow cleanroom with small air change rate | Turbulent flow cleanroom with large air change rate \((120 \text{ h}^{-1} \text{ or above})\) | HEPA filters installed on the ceiling (or wall) with 40 % area | Filters installed fully |
|----------------------|----------------------------------------------------|-------------------------------------------------|-------------------------------------------------|------------------------|
| Calculation with room average concentration \( \frac{N_v}{N} \) | 1–1.2                                              | 0.64–0.86                                       | 0.4                                             | –                      |
| Calculation with concentration in mainstream area \( \frac{N_a}{N} \) | 0.75–0.84                                         | 0.43–0.65                                       | 0.2                                             | 0.1                    |

Note: \( N \) and \( N_v \) are the room average particle concentrations calculated with the uniform and the nonuniform distribution theories, respectively. \( N_a \) is the particle concentration in the mainstream area calculated with the nonuniform distribution theory.
As for the air supply mode when the mainstream area concept is used, the concentrated air supply can be replaced by an independent unit. For vertical air supply mode, the ceiling unit can be used; while for horizontal air supply mode, the horizontal unit can be used. The same unit can be hung on the ceiling or placed on the ground so that horizontal airflow can be supplied. It is used according to the specific need, which is shown in Fig. 14.2.

By the application of the above mainstream area concept for local clean area, ideal effect was obtained in the operating room of the hospital [1]. Figure 14.3 is an example. The right part of this figure shows that the mainstream areas are 20 cm inside both sides of the edges. The tested particle concentrations are shown in Table 14.2.

From the table, the air cleanliness in the mainstream area can reach up to Class 100 in 5 min, and it only takes 7 min for the air cleanliness in the vortex area to reach Class 100. The effect is quite good. From Fig. 14.3, it is related to the ratio which reached 45 % between the air filter area and the ceiling area.

It should be emphasized that it is not reasonable to think that unidirectional flow with air cleanliness Class 100 can be reached with the ratio of blowing area 45 %.

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It should be emphasized that it is not reasonable to think that unidirectional flow with air cleanliness Class 100 can be reached with the ratio of blowing area 45 %.
Although the air cleanliness level in the vortex area can also reach Class 100, the self-cleaning time after 7 min is much larger than that of the unidirectional flow cleanroom. In terms of anti-disturbance ability and other properties, this kind of

![Diagram](image)

**Fig. 14.3** Local clean area with Class 100 in operating room of the hospital. (a) Plan and profile (b) Schematic of streamline

**Table 14.2** Particle concentration in local clean area of the operating room (0.4 m above the floor)

|                         | Particle concentration with diameter ≥0.5 μm (pc/L) |
|-------------------------|-----------------------------------------------------|
|                         | Mainstream area | Vortex region |
| Before starting up      | 4,350           | 4,200         |
| After starting up/min   |                 |               |
| 1                       | 2,750           | 4,260         |
| 2                       | 225             | 4,060         |
| 3                       | 76              | 1,840         |
| 4                       | 20              | 480           |
| 5                       | 0.4             | 98            |
| 6                       | 0.035           | 6.2           |
| 7                       | 0               | 1.7           |
| 8                       | 0               | 0.25          |
| 9                       | 0               | 0.12          |
| 10                      | 0               | 0.035         |
| 11                      | 0               | 0.07          |
| 12                      | 0               | 0             |
cleanroom is comparable with the room with filters placed fully on the ceiling. There is local Class 100 for this kind of cleanroom.

Figure 14.4 shows one form of a local clean area which is much smaller. Table 14.3 shows the measured particle concentrations. Although the effect is poorer than the above local clean area which is much larger, the air cleanliness level in the working area is close to Class 100. Since the complete aseptic operation

| Sampling position | 0.9 m above the floor |
|-------------------|-----------------------|
|                   | On the ceiling         |                   |
|                   |                       |                   |
|                   | Particle concentration with diameter ≥0.5 μm (pc/L) | Particle concentration with diameter ≥5 μm (pc/L) |
|                   | 31,500 | 60 | 31,500 | 60 |
| Before starting up| 20 min after starting up (without surgery operation) |
| 1                 | 0 | 0 | 3.5 | 0 |
| 3                 | 0 | 0 | 3.2 | 0 |
| 5                 | 0 | 0 | 5 | 0.6 |
| 7                 | 16 | 2.5 | 7 | 0.6 |
| 8                 | 16 | 1.4 | 5.3 | 0 |
| At the return air grille | 10 | 9.5 | 0.6 |
| 12                | 11 | 0.9 |  |  |

Fig. 14.4  Local clean area in the operating room. (a) Profile, 1 Prefilter, 2 HEPA filter, 3 return air opening. (b) Schematic of streamline. (c) Layout of the sampling points

Table 14.3  Particle concentration in local clean area of the operating room

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is performed, the average particle concentration during the operating process is about 1,000 #/L, and the average bacterial concentration is only 0.0016#/L, which is within the range of Class 100 [1].

There are three points which should attract attention for cleanroom with local air cleanliness level Class 100:

1. The area of local clean area with Class 100 should be larger than that of the working area. At least it should be bigger by 15–20 cm for each side.
2. The ratio of blowing area is also a problem. When the air supply area for local Class 100 is used as the total area, its relationship with the air filter area should meet the definition of the ratio of blowing area introduced in Chap. 8.
3. In order to guarantee the Class 100 effect in the working area and the certain cross-sectional air velocity (such as the lower limit of air velocity), especially when the area of the local Class 100 area is relatively small, there should be enough air supply velocity and the partition wall with curtain should be added. The detailed information will be given in the next section.

14.2 Characteristics of Mainstream Area

14.2.1 Air Distribution Characteristic

In order to make full use of the mainstream area and the expanded mainstream area, the characteristics of the air distribution should be understood.

The supplied air in the mainstream area can be considered as a weak jet flow from the overall filter. Compared with normal jet, it is vulnerable to be affected by factors such as the type, shape, and location of air supply outlet, the ratio between the air supply outlet area and the effective area of the whole room, the air supply velocity, the location of return air opening, and the envelope structure of the room.

The boundary of this weak jet flow also expands outwardly, as shown with the outer dotted lines in Fig. 14.5. The triangular region surrounded by two dotted lines is equivalent to the boundary layer. Because the external airflow is induced, the particle concentration will be higher than that of the supplied air in the mainstream area. The isoconcentration line with the concentration ratio between outside and inside \( N/N_0 = 1 \% \) can be calculated, which starts from two ends of the air supply outlet and has an inclination angle 10.7° from the plumb line [2, 3]. The observed expansion angle by domestic study showed it is smaller than 10° [4]. The concentration variation in the mainstream area from place B to A can be expressed with the curve in the figure. This conclusion is valid in the region which is about four times of the air supply outlet size below the air supply outlet (except the region near the floor). Obviously, the clean area formed with this kind of air supply mode is relative narrow. When the air supply diffuser plate is 2.4 m above the floor, at the height of 0.8 m above the floor, each side of the airstream boundary border in the mainstream
area will contract $(2.4 - 0.8) \times \tan 10.7^\circ \approx 0.3$ m. So the working area is vulnerable to the external interference, as shown in Fig. 14.6.

According to streamline displayed with the bubbles [5], when the air supply velocity is not less than 0.31 m/s for this kind of air supply mode, the bubbles are suppressed at the air supply outlet once they are generated, until to the region near the floor. But the cross-sectional air velocity in the working area is much less than 0.25 m/s.

The characteristic of air distribution in the mainstream is also influenced by the induction coefficient $\phi$ by different types of air supply outlets, which thus influences the turbidity of the airflow below. From Chap. 13, the values of $\phi$ for diffuser air supply outlet and the ceiling air supply outlet with perforated diffuser plate are larger than that of the air supply outlet with filter by 1.3–1.4 times. Curves can be plotted with the calculated values in Table 13.12, which is shown in Fig. 14.7 [4].

With the increase of $\phi$, more airflow outside of the mainstream area will be induced into the mainstream area, which will inevitably increase the concentration in the mainstream area. Therefore, perforated plate should not be used as the air supply surface in the mainstream area. The performance of mesh damping layer is better than the perforated plate. The leakage prevention layer introduced later with larger resistance and better filtration effect is most suitable for the air supply in the mainstream area.
14.2.2 Velocity Decay Characteristic

With the influence of a weak jet and the surrounding induced airflow, the air velocity below the air supply surface decays, but it is much smaller than the decay speed for the jet flow.

Liu Hua obtained the relationship between the number of air supply outlets, i.e., the air supply area of the mainstream area, and the relative decay rate of velocity $v/v_0$ by experiment, which is shown in Fig. 14.8 [4]. In the figure, $v$ is the average velocity at the cross section of the working area, $v_0$ is the average velocity at the air supply outlet, $x/r$ is the dimensionless distance from the edge of the air supply outlet, $r$ is the equivalent radius of the air supply surface $[r = (\text{length} \times \text{width})/(L + W)]$, and $x$ is the vertical distance from the air supply surface. In the figure, the solid line is the regression result on the experimental data. The expression for the maximum decay rate $\lambda$ is:

$$\lambda = 1 - \frac{v}{v_0} = 0.093 \frac{x}{r}$$  \hspace{1cm} (14.1)

The above fitted result is compared with the 16 cases of engineering measurement data which contain the parameter about the size of air supply surface [4]. There are no differences.

$$1 - v/v_0 \text{(experimental average value)} = 81\%$$

$$1 - v/v_0 \text{(fitted average value)} = 81.4\%$$
With another group of experimental data [6], the calculated results by Eq. (14.1) can be obtained, which are shown in Table 14.4. It is clear that the calculated results are very close to the experimental data and simulated velocity field. However, the relationship between the air supply velocity and the velocity decay rate is not obviously seen from the experiments and measured results. The simulated velocity field showed that with the increase of the air change rate, which corresponds with the increase of the air supply velocity or the reduction of the number of air supply outlet under the same air change rate, the velocity decay rate reduces accordingly, which is shown in Fig. 14.9 [7].

There are a lot of factors that affect the velocity decay rate, and the effect is very complex. The applicable range of $x/r$ is 1–4, and for safety reason, it should be considered with 3–4. So the resultant velocity decay rate is in the range 0.28–0.37. According to the experimental results by Niu Weile [8], the maximum velocity decay rate reached 0.35. It is recommended that this range can be used as the basis.

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**Table 14.4** Comparison between the experimental and the calculated velocity decay rates

| Number of air suppliers $(0.5 \text{ m} \times 0.5 \text{ m})$ | Air velocity on the outlet surface $(2.46 \text{ m})$ (m/s) | Air velocity on the working surface $(0.8 \text{ m})$ (m/s) | Measured decay rate of velocity | Calculated decay rate with Eq. (14.1) | Average decay rate |
|--------------------------------------------------------|---------------------------------------------------------|---------------------------------------------------------|---------------------------------|--------------------------------------|------------------|
| 15                                                     | 0.54                                                    | 0.32                                                    | 0.41                            | 0.61                                 | 0.43             |
| 2                                                      | 0.27                                                    | 0.15                                                    | 0.44                            | 0.46                                 | 0.46             |
| 25                                                     | 1.02                                                    | 0.55                                                    | 0.46                            | 0.61                                 | 0.45             |
| 2                                                      | 0.50                                                    | 0.28                                                    | 0.44                            | 0.46                                 | 0.44             |
| 3                                                      | 0.34                                                    | 0.20                                                    | 0.41                            | 0.41                                 | 0.41             |
| 4                                                      | 0.25                                                    | 0.13                                                    | 0.48                            | 0.38                                 | 0.38             |
for the design air supply velocity in the local clean area (mainstream area). It can also be expressed in another way. Let $\lambda_0$ be the amplification magnitude between the air velocity at the working area and the air supply velocity. When $\lambda = 0.36$, $\lambda_0 = \frac{1}{C_0} (1 - 0.36) = 1.56$.

### 14.2.3 Particle Concentration Characteristic

When the air supply mode to form the mainstream area with concentrated placed air supply outlets is used in the finite space which is not very large, the average particle concentrations in both this space and the mainstream area can be calculated with the method introduced in Chap. 13. Moreover, this kind of air supply mode can be approximated as the air supply outlets in Fig. 14.5. Its specific concentration field can be expressed with the analytical expression, which has already been verified by experiment [2, 3].

When the number of centralized placed air supply outlets increases, the area of the mainstream area also increases, whenever the air supply volume increases or not. The particle concentration in the mainstream area at this time does not rise but appears a declining trend, which is the expect result of engineering applications. Simulation results show that the particle concentration in the mainstream area with two air supply outlets is the lowest when the air supply volume is less than 15 h$^{-1}$, which has the best effect, while the particle concentration in the mainstream area with three or four air supply outlets is the lowest when the air supply volume is larger than 25 h$^{-1}$. When the number of air supply outlets increases, the particle concentration in both cases increases. The data with the air change rates 15 and 25 h$^{-1}$ are shown in Table 14.5.
Figures 14.10, 14.11, 14.12, 14.13, 14.14, 14.15, 14.16, and 14.17 are the calculated particle concentration by Zhang Yanguo [7]. There are 1–4 air supply outlets in the mainstream area. The air change rates are 15 and 25 h\(^{-1}\), respectively.

The analysis of related experimental data will be performed in the next section.
**Fig. 14.11** Planar concentration field in the mainstream area formed by two air supply outlets and the air change rate 15 h⁻¹

**Fig. 14.12** Planar concentration field in the mainstream area formed by three air supply outlets and the air change rate 15 h⁻¹

**Fig. 14.13** Planar concentration field in the mainstream area formed by four air supply outlets and the air change rate 15 h⁻¹
**Fig. 14.14** Planar concentration field in the mainstream area formed by one air supply outlet and the air change rate $25\text{ h}^{-1}$

**Fig. 14.15** Planar concentration field in the mainstream area formed by two air supply outlets and the air change rate $25\text{ h}^{-1}$

**Fig. 14.16** Planar concentration field in the mainstream area formed by three air supply outlets and the air change rate $25\text{ h}^{-1}$
As for the optimal number of air supply outlets which are centralized placed in the mainstream area (namely, the size of the mainstream area), when the area of air supply outlets increases to a certain extent that the velocity reduces by a half, and the air supply velocity reduces to 0.13 m/s which is the lower limit, the effect will be lower if the air supply velocity decreases further [6].

In German standard DIN4799, the minimum air flow rate in the operating room is specified to be $417 \text{ m}^3/(\text{h} \cdot \text{m}^2)$, i.e., 0.12 m/s, which seems that it is not coincident.

It is of course good to improve the air supply velocity for the mainstream area. Figure 14.18 shows the particle concentration field for air supply mode when the air supply velocity is 0.5 m/s and air curtain with velocity 0.5 m/s is also placed at two sides [9]. The size of the clean area below is much larger.

Fig. 14.17 Planar concentration field in the mainstream area formed by four air supply outlets and the air change rate 25 h\(^{-1}\).

Fig. 14.18 Particle concentration field when the air supply velocity is 0.5 m/s ($X$ represents the measuring height (1 m). The concentration ratios of the three regions from the mainstream area towards outside are below 1 %, 1–10 %, and above 10 %.)
14.2.4 Contamination Degree in Mainstream Area

With the concept and characteristic of the mainstream area introduced before, the air cleanliness level in the mainstream area is higher than other area. The evaluation method of this characteristic will be discussed below.

It is known from Eq. (11.16) that

\[ N_v \approx \psi N \]

It is also known from Eq. (12.4) that the concentration at the return air opening is the room average concentration. So we can get:

The concentration in the mainstream area

\[ N_a = \psi_a N \] (14.2)

The concentration in the vortex area

\[ N_b = \psi_b N \] (14.3)

The concentration at the return air opening

\[ N_c = \psi_c N = N \] (14.4)

where \( N_v \) is the room average concentration with nonuniform distribution. \( N \) is the room average concentration with uniform distribution. \( \psi_a, \psi_b, \) and \( \psi_c \) are nonuniform distribution coefficients in various areas. We know that:

\[ \psi_a = 1 - \frac{\beta}{1 + \varphi} \] (14.5)

\[ \psi_b = \frac{1 + \varphi - \beta}{\varphi} \] (14.6)

\[ \psi_c = 1 \] (14.7)

The advantage of the air supply mode with the mainstream area formed by centralized placed air supply outlets compared with the conventional scattered placed air supply outlets can be expressed with the following methods:

1. Expressed with \( \psi_a/\psi \). This expression has some inadequacy, because the average concentration of the mainstream area is included in the room average concentration. So the lower the concentration of the mainstream area is, the less the room average concentration will be. The value of this ratio will not reduce too much, so the superiority of the mainstream area is not shown. At the same time, when the mainstream area is formed by centralized placed air supply outlets, the opinions of the room average concentration will be different. Because it is quite difficult to determine the number of the measuring points in the mainstream area, as well as their respective weighting coefficients, it is not easily applicable.
2. Expressed with $\psi_a/\psi_c$. This is also expressed with $\psi_a$. This expression way has certain of operability, since the concentration at the return air opening can be measured. But it also has some shortcomings. The working position cannot be arranged in the return air area, because they are not the most concerned area. The contamination degree in the aforementioned German concept is such a ratio. It cannot answer the question that when air supply outlets area centralized arranged, how about the situation in the surrounding area without air supply outlets? How much difference exists in these two areas? Therefore, the practical implication is quite poor. In addition, although the concentration in the return air area can be measured, concentrations are obviously different with the return air opening at different positions. All of the concentrations at the return air opening should be measured so that the error caused is not too big.

3. Expressed with $\psi_a/\psi_b$. This can be used for clear description of the phenomena. As stated earlier, the vortex area means the turbulent flow area containing vortex at both sides of the mainstream area. Its concentration represents the concentration in other main regions outside of the mainstream area and the return air area, which is also the concentration in the surrounding areas of the mainstream area. So $\psi_a/\psi_b$ can be used to reflect the concentration difference between the working area and the nonworking areas. At the same time, the concentrations of these two areas can be measured with the setting of samplers in different areas. The size of the mainstream area at the height of the working area can be considered slightly larger than the projected area of the air supply outlet, according to the experiment and numerical simulations (detailed information will be given below). During the actual test in the cleanroom, measurement is performed with the classification of areas, and the projected area is used.

So the contamination degree in the mainstream area is the relative particle concentrations between the mainstream area and the surrounding area, which is also the nonuniform distribution coefficients between two areas. If the contamination degree in the mainstream area is defined as $B$, we can get:

$$ B = \frac{\psi_a}{\psi_b} $$

(14.8)

Generally speaking, the bacteria concentration is proportional to the particle concentration, so the value of $B$ is also suitable for the evaluation of the bacteria concentration in the mainstream area.

In 1977, Prof. Esdorn from Berlin University of Technology in Germany proposed the contamination degree for the bacteria concentration in the operating room [10], which was

$$ u_s = \frac{K_s}{K_r} $$

(14.9)

where $u_s$ is the contamination degree, $K_s$ is the bacteria concentration in the working area, and $K_r$ is the room average bacteria concentration (equivalent to that of return air opening). When the air change rate was 20 h$^{-1}$ and the mainstream
area was formed by centralized placed air supply outlets above the operating table, the bacteria concentration in the mainstream area is only a half of the room average bacteria concentration, which means $u_s = 0.5$. This is the difference of the performance with the mainstream area formed by centralized placed filters and the conventionally placed filters.

From the above introduction, the contamination degree in Germany is only limited to the bacteria concentration. If the nonuniform distribution coefficient is used, it can be expressed as:

$$u_s = \frac{\psi_a}{\psi_c}$$

It is obvious that $u_s$ is different from $B$. In the original literature, $u_s$ was only obtained through experiment. Here both $u_s$ and $B$ can be obtained through calculation. For example, the calculated parameters in the mainstream area with different number of centralized placed air supply outlets are shown in Table 14.6 [6, 7]. The above method was also used for the classification of the clean operating rooms in China, which is shown in Table 14.7 [6].

The air change rates are different for the same air cleanliness level, which is much prominent in engineering projects. When the air supply area is larger, the value of $\beta$ is larger, so the calculated nonuniform distribution coefficient is not large. Therefore, for the same air cleanliness level, $\psi_d/\psi_b$ will be apparently different by experiment, calculation and field test. When these results are used for plot as shown in Fig. 14.19, the variation characteristics of the contamination degree in mainstream area are consistent. The range between two lines corresponds with the most frequently appeared contamination degree in the mainstream area.

If the value of $B$ which is used to describe the particle concentration is more than 1, the possibility of leakage on air filter should be checked. If the value of $B$ which is used to describe the bacteria concentration is more than 1, there will be leakage on air filter. For example, there is one measurement in engineering project where $B = 2.92$ for description of particle concentration and $B = 2.1$ for description of bacteria concentration, which belongs to this kind of situation. This is not included in the statistical investigation as shown in Fig. 14.19.

| Particle generation type | Number of air supply outlets | Ratio of area between air supply outlet and the ceiling | $\psi_a/\psi_c$ | $\psi_d/\psi_b$ |
|--------------------------|-----------------------------|------------------------------------------------------|----------------|----------------|
| No artificial particle generation | 1                           | 0.03                                                 | 1.16           | 0.80           |
|                           | 2                           | 0.06                                                 | 1.05           | 0.65           |
|                           | 3                           | 0.09                                                 | 0.98           | 0.55           |
|                           | 4                           | 0.12                                                 | 1.00           | 0.41           |
| Average                  |                             |                                                      | 0.60           | 0.57           | 0.48           |
| Type                        | Design condition | Centralized air supply area | Ratio of air supply area | Surgery area (as-built) | Surrounding area (as-built) |
|-----------------------------|------------------|-----------------------------|--------------------------|-------------------------|-----------------------------|
| Ordinary clean operating room | 15 h⁻¹, Class 100000 | 1 m² | 0.05 | 0.76 | 0.69 | 0.57 | Class 100000 |
| Ordinary clean operating room | 20 h⁻¹, Class 100000 | 2.8 m² | 0.09 | 0.48 | 0.44 | 0.29 | Class 1000 | Close to Class 1000 |
| Clean operating room       | 30 h⁻¹, Class 100000 | 5.4 m² | 0.18 | 0.37 | 0.44 | 0.21 | Class 1000 | Class 1000 |
| Special clean operating room | Local Class 100 | 7.2 m² | 0.19 | 0.27 | 0.44 | 0.17 | Class 100 | Close to Class 100 |

**Fig. 14.19** Comprehensive comparison of the contamination degree in the mainstream area. ▲ Measured average value in engineering project (There are 14 cleanrooms with air cleanliness Class 100 in 8 hospital, 37 cleanrooms with air cleanliness Class 1000 in 9 hospital, 38 cleanrooms with air cleanliness Class 10000 in 11 hospital), Δ Theoretical calculated average value, ● Simulated average value (the ratio of particle generation among ceiling, wall and floor is 1:5:100), — Calculation, --- Measurement, ○ Measured average value in lab (22 h⁻¹, no particle generation)
Figure 14.20 shows the measured value of $u_s$ from Germany [11], which was between 0.08 and 1.3. When the ratio of blowing area of the air supply surface is very large in the cleanroom with return air grilles fully placed at both sides, which reached 0.95, we obtain $\psi_a = 0.095$ and $u_s = 0.095$. It is close to the measured value 0.08. So the measured data from Germany are in the theoretical calculation range. It can be seen from Fig. 14.19.

14.2.5 Concept of Expanded Mainstream Area

In 2000, author proposed the concept of expanded mainstream area (refer to Sect. 14.2.3) [6]. In the clean operating room in China, air supply outlets were placed centralized above the operating table. The air cleanliness level in this area is higher than that of the surrounding area by one magnitude. This is the concept of the mainstream area, especially the expanded mainstream area, because the area of air filter is less than the centralized air supply area.

It has been proved with the calculation theory of uniform distribution that the air cleanliness level Class 5 cannot be realized in turbulent flow cleanroom with scattered placed air supply outlets (the flow rate through each air filter in the air
supply outlet is close to the rated flow volume), or when the air change rate is above 200 h$^{-1}$, the particle concentration can reach 3#/L (see Fig. 13.5 where the ratio of fresh air is 0.3 and $N_s = 1.5$ #/L), while according to traditional knowledge, the air cleanliness level Class 5 and higher is realized in unidirectional flow cleanroom.

However, when the calculation theory of nonuniform distribution and the expanded mainstream area are combined, the air cleanliness level Class 5 can be realized in turbulent flow cleanroom when the air change rate is not very large. Of course, the requirements of several conditions in unidirectional flow cleanroom are not satisfied in this kind of air cleanliness level Class 5, and only the value is reached. In the monograph “Design, Operation and GMP Certification of Cleanroom in Pharmaceutical Factory” (the second version) [12], this research finding was introduced. From the theoretical point of view, it is possible to create the at-rest air cleanliness level Class 5 for the background environment B zone (non-unidirectional flow) of the aseptic core zone A zone (unidirectional flow), which has already been verified by practice.

For the concept of expanded mainstream area, the flow rate of each air supply outlet is much less than the rated flow volume. So for the given design flow rate, the number of the air supply outlets will increase. According to Table 13.16, when the nominal rated flow volume with the increased number of air supply outlets is used to calculate the air change rate, which can be further used to find the value of $\psi$, we can find that the value of $\psi$ reduces accordingly.

This can be proved from the parameters in Tables 13.11, 13.12, and 13.14. For example, when the number of the air supply outlets increases, which equivalent to the situation that 0.3 m$^2$ of the air filter (the perforated plated area of air filter with dimension 484 mm × 484 mm and rated flow volume 1,000 m$^3$/h) is responsible for the room area <2.5 m$^2$, $\phi < 0.3$–0.65. For the operational status, $\beta \approx 0.8$. When the nominal rated flow volume of air filter is equivalent with the air change rate 120 h$^{-1}$ or larger, it can be calculated with the mainstream area as mentioned before, so $\psi = 1 - \frac{\beta}{1 + \phi}$. When $\phi$ is set 0.6 since we know $\phi < 0.65$, for the condition of so many air supply outlets and the condition of at-rest status without any particle generation from occupant and equipment, it is equivalent with the condition that particles generated will be removed by the streamline in the mainstream area, so $\beta \approx 1$ and $\psi = 0.375$.

For the special case of the non-production B zone under the at-rest status and without occupant, it is specified in GMP that, when the self-purification time from Class 7 to Class 5 should be less than 20 min, the air change rate is less than 46 h$^{-1}$ when the air cleanliness level reached Class 5 in turbulent flow cleanroom (the detailed calculation can be seen in the monograph “Design, Operation and GMP Certification of Cleanroom in Pharmaceutical Factory” (the second version), Tongji University Press, 2010).

The above results are based on the assumption that each air filter with dimension 484 mm × 484 mm is responsible for the room area <2.5 m$^2$ (In the room with area 30 m$^2$, there should be 12 air filters of this dimension). The actual flow rate through the air filter is obtained through the air change rate above (46 h$^{-1}$). The actual flow rate is only about 1/3 of the rated flow volume.

This theoretical finding has already been validated by several practical projects (papers will be published soon).
14.3 Clean Area with Partial Wall

In order to make full use of the clean air below the HEPA filter, the USA had proposed the air supply device with curtain in the 1960s [13], which is shown in Fig. 14.21. This device is slightly different from the cleanroom with curtain later. It is just a local device, and the curtain is not the substitute of wall. It just reached above the workspace. The aim is to guarantee that the unidirectional parallel airflow can reach the working table. It is apparent that it is not convenient to use the nonstationary curtain. Therefore, later someone tested the situation when the partial wall was placed along the flow direction (it can be rigid board or soft curtain) [3, 14]. This device can be called the clean area with partial partition wall. This is equivalent with the increase of the air supply outlet size or the decrease of the distance between the air supply outlets to the working area. This kind of partial wall can be perpendicular to the air supply surface. It can also be inclined with the air supply surface by an angle, or even an orifice plated can be added below, which are shown in Figs. 14.22, and 14.23.

In the former Federal Germany, vertical unidirectional flow cleanroom with partial wall was designed, which was used for the filling and packaging processes of the medicine in pharmaceutical industry with requirements of high air cleanliness level, as shown in Figs. 14.24 and 14.25 [15]. They were also applied in the continuous production line, as shown in Fig. 14.26 [16]. They were application examples which attracted attention.

It is especially suitable to design the horizontal air supply mode for the clean area with partial wall. The cleanrooms in Heilongjiang People’s Hospital introduced in Chap. 9 adopted this kind of design, which is shown in Fig. 14.27. The partial wall can be bilateral or unilateral. It can be fixed or mobile. Figure 14.28 shows several types of cleanrooms in hospital [17]. Practical operation shows that the airborne bacterial concentration is only 1/40 of the normal operating room, and the depth infection rate is only 1/5.

![Fig. 14.21 Air supply device with curtain in the USA (For medical applications)](image-url)
Fig. 14.22 Air supply outlet with partial vertical wall

Fig. 14.23 Air supply outlet with inclined partial wall

Fig. 14.24 Local clean area with curtain (HEPA means high-efficiency particulate filter)
14.4 Air Curtain Cleaning Booth

14.4.1 Application

Although the performance of the clean area with partial wall is improved compared with that without partial wall, there is limit because this kind of partial wall cannot be too long. Although the anti-disturbance ability improves with the increase of the
air supply velocity on the whole cross section, it is not economic. In this case, people began to think the scheme with elevated surrounding air velocity to protect the central mainstream area, which is the combination of surrounding air curtain and the vertical unidirectional flow. It can be called the air curtain cleaning booth.

In the early 1960s, the USA first made improvement on the air supply device with curtain, and the air curtain cleaning booth was manufactured, which was applied to the inspection and assembly of huge rocket components [13]. In order to protect the

Fig. 14.27 Schematic diagram of the clean area with partial wall for the horizontal air supply mode in operating room

Fig. 14.28 Several types of partial walls. (a) Horizontal unidirectional flow, partial wall placed at both sides. (b) Horizontal unidirectional flow, partial wall placed at one side. (c) Horizontal unidirectional flow, partial wall placed with inclination. 1 Prefilter, 2 HEPA filter, 3 Fan, 4 partial wall, 5 partial wall with sliding glass, 6 operating table. (d) Application of partial wall in opening room
component from the influence of external flow during the stop of the air supply, the curtains around are pulled to the ground. Later, this device was also been applied successfully in the 150 m long automatic production line of color TV set.

The UK established the experiment device for air curtain cleaning booth [9]. The device was hung on the ceiling, with the distance 2.15 m above the floor and the size of the mainstream area $1.26 \times 2.34$ m, which is shown in Fig. 14.29.

In a hospital in Switzerland, the combination of the surrounding air curtain and the central rectangular air supply perforated plate was used with success. The area of perforated plate is $2.4 \times 3.3$ m. When the air change rate in the mainstream area is $130$ h$^{-1}$, the size of the clean area available can be $3.6 \times 4.5$ m, which is shown in Fig. 14.30 [18]. It is worthy noticed that the air velocities in both the air curtain and the center of the device are not large, and the decay of velocity field is also not fast. But particles are easily deposited on the perforated plate, which is difficult to clean, so the appearance is rather poor.
These devices with air curtain belong to the centralized placed air supply mode, and they are not local purification equipments. Neither the design data nor the theoretical analysis is provided. Shen Jinming developed this combination form into local purification equipment, and theoretical study was performed [19]. The quantitative indicators for the isolation performance of air curtain were obtained. The idea for application in large space was proposed, which was shown in Fig. 14.31. This can be used to overcome the shortcomings that cleanroom was divided into small rooms as mentioned in Section one of this chapter. Figure 14.32 is one form of the device (for vacuum coating machine).

14.4.2 Isolation Effect of Air Curtain

Only when the air curtain reaches the floor, its isolation function can be realized which is shown in Fig. 14.33 [20]. In this case, air curtain is used to completely separate the pollution area from the clean area (or the dust-free area). When the air velocity from the air curtain increases above a certain value but the isolation effect is not improved, the air supply velocity of the air curtain is called the shield velocity under this condition. From the performance of linear air curtain shown in Fig. 14.34 [20], the corresponding shield velocity can be obtained.

The above study shows that for the surrounding air curtains with fixed nozzle width and air velocity, the isolation effect under steady state is the same, no matter
whether clean air is supplied beforehand in the central area. Therefore, the isolation effect of air curtain is realized with the continuous induction of air at both sides, which is unlike the prevention of particle penetration by solid wall. Dirty air is continuously diluted and removed (because clean air is supplied from the nozzle of the air curtain), so that particles cannot penetrate the air curtain. Only a few particles may enter the central area because of the lateral fluctuation of airflow. Therefore, with the same amount of flow rate, the larger the nozzle width is, the less the induction flow rate is, and the less the penetrated particles are. It is more difficult for particles to penetrate when the lateral distance is larger. At this time, the isolation effect is much better (Fig. 14.34).

Fig. 14.32 One form of air curtain cleaning booth for the application of vacuum coating machine

Fig. 14.33 Theoretical cross section of linear air curtain
14.4.3 Theoretical Analysis of the Isolation Effect by Air Curtain Cleaning Booth

Under the steady state situation, three-zone mathematical models can also be proposed for the air curtain cleaning booth, which is shown in Fig. 14.35 [19].

In the finite space, we know

\[
\frac{dN_a}{dt} = \frac{(Q_a - Q')N_a + Q'N_d - (Q_a + Q' - Q')N_a}{V_a}
\]

\[
\frac{dN_d}{dt} = \frac{Q_dN_d + Q'N_a + Q''N_b - (Q' + Q'' + Q_d)N_d}{V_d}
\]

\[
\frac{dN_b}{dt} = \frac{G_b + Q_aQ_d/Q_a - Q + (Q' + Q_d)N_d + Q_aN_a - (Q'' + Q_a + Q_d)N_b}{V_b}
\]

where

- \(N_a\) is the particle concentration in the mainstream area, #/L;
- \(N_d\) is the particle concentration in the air curtain area, #/L;
- \(N_b\) is the particle concentration in the vortex area, #/L;
- \(N_s\) is the average particle concentration in the mainstream area and the air curtain area, #/L;
- \(G_a\) is the particle generation rate in the mainstream area, #/L;
- \(G_b\) is the particle generation rate in the vortex area, #/L;
- \(Q_a\) is the air supply volume in the mainstream area, L/min;
- \(Q_d\) is the air supply volume in the air curtain area, L/min;
- \(Q'\) is the induced air volume between the air curtain area and the mainstream area, L/min;

*Fig. 14.34 Shield effect of air curtains with different nozzle widths (outlet width of air curtains, Δ means 0.085 m, × means 0.15 m, ○ means 0.23 m)*
$Q''$ is the induced air volume between the air curtain area and the vortex area, L/min;
$V_a$ is the volume of the mainstream area, L;
$V_d$ is the volume of the air curtain area, L;
$V_b$ is the volume of the vortex area, L.

Let $\varphi_1$ be the induction coefficient of the air curtain for the mainstream area, so $\varphi_1 = \frac{Q}{Q_d}$. Let $\varphi_2$ be the induction coefficient of the air curtain for the vortex area, so $\varphi_2 = \frac{Q''}{Q_d}$. Let $\alpha$ be the ratio of the air supply volume between the air curtain area and the mainstream area, so $\alpha = \frac{Q}{Q_s}$. Let $V$ be the total volume of the finite space (L). Let $G$ be the particle generation rate per unit volume [#//(m$^3$ · min)].

So we obtain:

$$Q_a + Q_d = \frac{nV}{60}$$

$$\frac{G_a + G_b}{V} = G \times 10^{-3}$$

When $t \to \infty$, the particle concentrations in three zones can be expressed as:

$$N_b = N_s + 0.06 \frac{G}{n}$$  \hspace{1cm} (14.11)

$$N_d = \frac{(1 + \varphi_1)N_s + \varphi_2 N_b}{1 + \varphi_1 + \varphi_2}$$  \hspace{1cm} (14.12)

$$N_a = (1 - \alpha \varphi_1)N_s + \alpha \varphi_1 N_d$$  \hspace{1cm} (14.13)
Then we obtain:

\[
\frac{N_a}{N_b} = \left(1 - \frac{\alpha \varphi_1 \varphi_2}{1 + \varphi_1 + \varphi_2}\right) \frac{N_s}{N_b} + \frac{\alpha \varphi_1 \varphi_2}{1 + \varphi_1 + \varphi_2} = (1 - f) \frac{N_s}{N_b} + f
\]  

(14.14)

\[
f = \frac{\alpha \varphi_1 \varphi_2}{1 + \varphi_1 + \varphi_2} = \text{const.}
\]  

(14.15)

The less the value of \(\frac{N_a}{N_b}\) is, the better the isolation effect of the air curtain is. It is obvious that the actual isolation effect of the air curtain cleaning booth is different under different environment. When \(N_b\) is very large, such as \(N_b > 2,000\#/L\), the particle concentration \(N_s\) at the air supply outlet through HEPA filter is usually \(0.1 \sim 0.2\#/L\). So \(\frac{N_s}{N_b} \approx 10^{-4}\), and

\[(1 - f) \frac{N_s}{N_b} \ll f\]

So we obtain:

\[
\frac{N_a}{N_b} \approx f
\]  

(14.16)

Therefore, \(f\) is considered as the intrinsic property of the isolation effect by the air curtain cleaning booth. This means, when the environmental particle concentration is very large, the measured value of \(\frac{N_a}{N_b}\) can reflect the isolation effect, which is the value of \(f\). It is the best isolation effect with this kind of device. It should be noted that when the isolation effect reaches the maximum, the particle concentration in the mainstream area is not the minimum. When the environmental particle concentration is large, the particle concentration in the mainstream area will be correspondingly large, but the isolation effect is large.

The item \((1 - f) \frac{N_s}{N_b}\) in Eq. (14.14) shows the influence of the environmental concentration \(N_b\). It is called the environmental additional item of the isolation effect.

Since it is quite difficult to determine the coefficients of \(\varphi_1\) and \(\varphi_2\), it is not easy to calculate the value of \(f\). In Eq. (14.15), both \(\varphi_1\) and \(\varphi_2\) will not be less than \(10^{-1}\), and \(\alpha\) will also be larger than \(10^{-1}\) for this device, so \(f\) is usually not less than \(10^{-2}\). This means the isolation ratio of the air curtain cleaning booth will not be lower than 0.01. This is the reason why the measured value of the isolation ratio (corresponding to the clean area with practical implication), namely, the particle concentration ratio between the inside and the outside of this device, is not less than 0.01 so far from literatures at home and abroad.

It is shown from Eq. (14.15) that the induction ratio of the flow rate can be reduced by the air curtain with low velocity and large width, which can decrease the value of \(f\). So the better isolation effect can be obtained, which is also the case for the application where the space is large and the particle generation rate is large.
In the application where space is small and the particle generation rate is small, the advantage of the air curtain with large width is not realized, but better effect may be achieved by the air curtain with narrow width. In the past, it was thought that the isolation effect of the air curtain with large velocity was better, but this is not true according to the above analysis.

### 14.4.4 Performance of Air Curtain Cleaning Booth

The experimental study of the air curtain cleaning booth above was carried out in an equipment with two air supply systems provided for the central area and the air curtain area (for the convenience of adjustment during test). Indoor air enters the plenum chamber of the central area and the air curtain, respectively. Air is supplied into the room after passing through fine air filter and HEPA filter.

#### 14.4.4.1 Proper Air Velocity at the Outlet of the Air Curtain

In the central area surrounded by the air curtain, vertical unidirectional flow was supplied, which increased the interior pressure. It will inevitably expand outwards. A lateral force will be exerted on the air curtain, which makes the air curtain flow outwards and enlarges the size of the central mainstream area. Moreover, flow is induced by the air curtain. The resultant velocity field in the central mainstream area will decay quickly, which is very detrimental for the steady of the large clean area. It is shown that this situation can be ameliorated by application of suitable nozzles and air supply velocity at the outlet of air curtain (i.e., the partition velocity). For this kind of nozzle, vertical partition plates were used (which is equivalent with the case that one nozzle is separated into many small nozzles) and the outer plate was not used. Airflow is supplied when it is attached to the inner surface of steel plate. The suitable air velocity of the air curtain was obtained through experiment, which is shown in Table 14.8.

#### 14.4.4.2 Concentration Field

Various curves can be plotted as shown in Fig. 14.36 for the particle concentration generated by the air curtain cleaning booth with different widths, when the particle concentration ratio between the central area and the environment (non-clean area)
The operational conditions of each curve in the figure are

| No. | Air curtain width (mm) | Air supply velocity (m/s) | Exit velocity at the air curtain outlet (m/s) | Total flow rate (m³/h) | $\frac{N}{N_0} < 1\%$ | $1\% < \frac{N_a}{N_b} < 10\%$ |
|-----|------------------------|---------------------------|-----------------------------------------------|------------------------|------------------------|--------------------------|
| 1   | 200                    | 0.31                      | 0.69                                          | 8,743                  | -1-                    | -1'                      |
| 2   | 150                    | 0.31                      | 0.92                                          | 8,743                  | -2-                    | -2'                      |
| 3   | 100                    | 0.31                      | 1.37                                          | 8,743                  | -3-                    | -3'                      |
| 4   | 75                     | 0.31                      | 1.94                                          | 8,743                  | -4-                    | -4'                      |
| 5   | Without air curtain    | 0.31                      | 0                                             | 4,397                  | -5-                    | -5'                      |

Fig. 14.36  Concentration field of the air curtain cleaning booth with different widths (profile)
It is shown that the performance of the air curtain with low velocity and large width is better than that of the air curtain with high velocity and narrow width. The concentration field of the air curtain with width 150 mm is better than other kinds of air curtain in terms of the width and the extent to approach the floor (the air velocity of air curtain with width 150 mm is slightly less).

### 14.4.4.3 Size of Clean Area

The sizes of clean area formed by the air curtain cleaning booth with different widths of air curtains are different. Table 14.9 presents the comparison between the measured data and foreign data.

It is shown from Table 14.9 that when the total flow rate is not too large, the performance of air curtain cleaning booth with the width 150 mm of the air curtain is the best.

**Table 14.9** Comparison of the size of clean area when \( \frac{N_a}{N_b} < 1 \% \)

| No. | Condition             | Air supply velocity in clean area (m/s) | Total flow rate/(m³/h) | Ratio of the minimum side length of the cross section in clean area at the working height to the side length of the air supply cross section (%) | The minimum cross-sectional area in the clean area at the working height (m²) | Ref.     |
|-----|-----------------------|----------------------------------------|------------------------|--------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|---------|
| 1   | 150 mm air curtain    | 0.31                                   | 8,743                  | 105                                                                                                                                 | 2.1 × 2.1                                                                         | [19]    |
| 2   | 100 mm air curtain    | 0.31                                   | 8,743                  | 85                                                                                                                                 | 1.7 × 1.7                                                                         |         |
| 3   | 75 mm air curtain     | 0.31                                   | 8,743                  | 85                                                                                                                                 | 1.7 × 1.7                                                                         |         |
| 4   | 225 mm air curtain    | 0.3                                    | 11,529                 | 131                                                                                                                                 | Convert with square: 2.4 × 2.4                                                   | [19]    |
| 5   | 75 mm air curtain     | 0.3                                    | 6,561                  | 60                                                                                                                                 | Convert with square: 1.51 × 1.51                                                 | [9]     |
| 6   | Vertical uni-directional flow without air curtain | 0.31                                    | 4,397                  | 64                                                                                                                                 | 1.28 × 1.28                                                                         | [19]    |
| 7   | Vertical uni-directional flow without air curtain | 0.5                                    | 7,200                  | 78.7                                                                                                                                | Convert with square: 1.64 × 1.64                                                 | [9]     |
According to Table 14.9, the sizes of clean area for the unidirectional flow supply mode before and after the air curtain is used were compared by author, which is shown in Fig. 14.37. For the former case, energy consumption is not wasted because of air curtain. With the same total flow rate (the flow rate through the air curtain is included when the air curtain is used) and the same air supply area (i.e., the area of air filter), the size of clean area is the smallest at the working height where is 0.8–1.5 m above the floor, which is the largest when air curtain cleaning booth is used. Although the narrowest size of clean area with unidirectional flow supply equipment when air curtain is not used, which means the air supply areas are combined, is almost the same as that with air curtain cleaning booth, it is too large to be installed with convenience, so it is not suitable to be used as mobile equipment. It has the disadvantage of no protection from air curtain and being likely to be disturbed for the central mainstream area, so the air curtain cleaning booth is still superior, which can be energy saving.

It is shown from Table 14.9 that, although the size of clean working area provided by air curtain cleaning booth with width 225 mm was larger than that with width 150 mm based on the foreign experiment, the superiority of technical and economical indexes cannot be reflected since this was performed under the condition of artificial high concentration. For the former case, the total flow rate is much larger when the width of the air curtain is larger, so the energy consumption becomes larger and both the structure and the weight are correspondingly enlarged, which is not practical. Therefore, from the practical point of view, the air curtain with width 150 mm under usual particle concentration is relative appropriate.

It should be emphasized that from the development of the technology, semi-centralized air cleaning system is the trend proposed both at home and abroad. Only
fresh air with certain parameters is supplied through central air supply system, and local clean area with high air cleanliness is generated with “terminal device” such as the air curtain cleaning booth. The self-circulation ability of this device is extreme strong, which can reduce the particle concentration greatly. In this way, the system is simplified and the cross-sectional area of air pipeline is reduced, but the resultant noise may be larger.

This kind of air curtain cleaning booth has the above features. It is suitable to be suspended and mobile because of the simple structure, the small volume and the light weight. So it provides the possibility for the application in large area workshop where the production process is variable.

### 14.5 Partition Curtain Cleaning Booth

#### 14.5.1 Application

Partition curtain cleaning booth is popular, since it is a kind of local cleaning equipment with less investment, fast implementation, high performance, and low energy consumption.

This kind of transversely placed tubular filter dates back to the former Soviet Union in 1950s [21]. At that time, the folded HEPA filter made of glass fibrous filter paper was not available. The main filter medium was vinylidene chloride, namely, $\Phi \Pi$ filter cloth. When the filtration velocity was 0.01 m/s, the penetration was 3.2 %. It was equivalent with the performance of sub-HEPA filter in China. Since this kind of filter medium was thick, it was not easily folded but could be pasted. So flexible pipe with diameter 400 mm was made with $\Phi \Pi$-15-17 filter cloth. It was applied in the cleanroom in the late of 1960s. They were uniformly placed on the ceiling to form the transversely placed air supply surface. Air was supplied into the cleanroom through the flexible pipe and the perforated ceiling below made of organic glass (it was not cleaning booth, but in essence it was the same). Air was returned through both bottom sides. Return air was delivered to the air conditioner placed outside of the cleanroom.

The above air filter and cleanroom are shown in Fig. 14.38.

The similar cleaning booth appeared in 1990s in China. Filter tubes made of polypropylene fibrous filter paper were transversely placed to form the air supply surface. The difference is that the plastic curtains were placed around in the common room. Filter tubes were transversely placed sub-HEPA filters. When complete self-circulation was used, the air cleanliness in the booth could only reach Class 100 [22]. Similar as Fig. 14.38, air was supplied from one side.

As for the double filter tubes and one side air supply mode, theoretical analysis was performed for a new type of cleaning booth with air curtain. The following innovation items were adopted in the structure [23].
1. Multiple filtrations were simplified into one filtration. The important design principle for this new type of cleaning booth was that when circulation mode was used, only sub-HEPA tubular filter was needed according to theoretical analysis, while the previous prefilter can be omitted.

2. One side air supply mode is changed into bilateral air supply mode. Since the diameter of filter tube cannot be very large, the static pressure inside the tube cannot be stable and the filtration velocity along the whole filter tube cannot be very uniform. It also means that it is impossible to improve the uniformity of the air velocity inside the filter tube. Another way is that although there is nonuniformity in the tube, the whole flow field becomes uniform with the overlap of the uniform flow from single filter tube, when half of the filter tube supply air from one side and the other half of the filter tube supply air from the other side.

3. The circular filter tube becomes the wedge filter tube. It is known that for a certain area, the edge length of circle is the minimum, and the effective filtration area is only the low half of the circumference. For the given cross-sectional area, when the filtration area should be increased, and both the internal space of filter tube and the resistance of the airflow after filtration are required to be reduced, the best way is to change the circular filter tube into wedge filter tube, which is
The key factors are how to determine appropriate height and bottom side length.

4. Partition support is used to fix the filter tube. In order to avoid the collision between filter tubes, the partition supports are used to separate and fix each filter tube. They can be placed one by one, which increases the filtration area and avoids the high air velocity between tubes. The other important purpose is to change circular tubes into wedge tubes.

5. When multiple rows of filter tubes are combined to one row, the partition support can provide a good solution to this problem.

6. The ceiling height where air filters are installed can be further reduced. When two rows are combined to one row, the height only reduces to 250 mm, which is only half of the height of the device abroad.

### 14.5.2 Theoretical Analysis of Cleaning Effect

Whether the air cleanliness level Class 100 can be achieved with the cleaning booth when sub-HEPA filters are used as the final filters? What kind of conditions should it be so that the air cleanliness level can reach Class 100? What kind of conditions should it be so that the air cleanliness level cannot reach Class 100? The conclusion cannot be made with measurement by only one or two devices. The relationship between indoor air cleanliness, the air change rate, the filter efficiency, the indoor particle generation rate, and the fresh air flow rate should be considered through theoretical analysis. The regular conclusion should be found out [24, 25]. The typical example can be simplified as the mathematical model shown in Fig. 14.40.
1. Particles entering the cleaning booth of unit volume per unit time at equilibrium state

(a) Due to the leakage of doors and windows, and because of entering in and out, particles enter into the buffer, then supplied into the cleaning booth through the air cleaning system of the cleaning booth.

\[
\frac{Mn_3}{60} \varepsilon \left(1 - \eta_n\right) = \frac{Man_1 \varepsilon}{60} \left(1 - \eta_n\right)
\]

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

\[
a = \frac{n_2}{n_1}
\]

\[
\varepsilon = \frac{n_3}{n_2}
\]

where

- \(M\) is atmospheric particle dust concentration (#/L);
- \(n_1\) is the air change rate of self-circulation through the cleaning booth;
- \(n_2\) is the equivalent air change rate of the buffer chamber from the self-circulation flow rate through the cleaning booth;
- \(n_3\) is the equivalent air change rate of the buffer chamber from the total leakage flow rate;
- \(\eta_n\) is the total efficiency of the cleaning system for the cleaning booth.

(b) Particles generated in the buffer chamber and then enter the cleaning booth can be expressed as

\[
G_2 \times 10^{-3} \left(1 - \eta_n\right) = bG_1 \times 10^{-3} \left(1 - \eta_n\right)
\]

\[
b = \frac{G_2}{G_1}
\]

where

- \(G_1\) is the particle generation rate in unit volume of the cleaning booth [#//(min \cdot m^3)];
- \(G_2\) is the particle generation rate in unit volume of the buffer chamber [#//(min \cdot m^3)].

(c) Particles enter the cleaning booth by the return air can be expressed as

\[
\frac{s_1 n_1 N_1}{60} \left(1 - \eta_n\right)
\]

where

- \(N_1\) is the average particle concentration in the cleaning booth, which can be considered as the concentration of the return air (#/L);
- \(s_1\) is the ratio of return air. It is one for complete circulation.

(d) The particle generation rate inside the cleaning booth is \(G_1 \times 10^{-3}\).
2. At equilibrium state, particles exhausted from the unit volume of the cleaning booth per unit time can be expressed as \( n_1 N_1 / 60 \).

3. The balance of particles in and out can be expressed as:

\[
\left( \frac{Man_1 \varepsilon}{60} + bG_1 \times 10^{-3} \right) (1 - \eta_n) + G_1 \times 10^{-3} = \frac{n_1 N_1}{60} - \frac{s_1 n_1 N_1 (1 - \eta_n)}{60}
\]

When \( s = 1 \), we can obtain:

\[
N_1 = \frac{60G_1 \times 10^{-3} [1 + b(1 - \eta_n)] + Man_1 \varepsilon(1 - \eta_n)}{n_1 \eta_n}
\]  

(14.17)

If nonuniform distribution theory is used for calculation, when the nonuniform distribution coefficient is \( \psi \) and the average particle concentration inside the cleaning booth is \( N_{v,booth} \), we obtain:

\[
N_{v} = \psi N_1
\]

In order to calculate \( N_1 \), the following parameters need to be determined.

(a) At the as-built state, \( G_1 = 0.5 \times 10^4 \). When there is one person at rest, the dynamic-to-static ratio can be assumed 3. The occupants’ density can be the average value between 1/2 and 1/4, namely, 0.375. At this time, \( G_1 = 5 \times 10^4 \). When the dynamic-to-static ratio is 7, \( G_1 = 11 \times 10^4 \).

(b) \( a \) – when areas between inside and outside are equivalent, \( a = 1 \); when the outside room is large, \( n_2 \) is small and \( a < 1 \); when the outside room is small, \( n_2 \) is big and \( a > 1 \).

(c) \( b \) – according to Eq. (14.17), the effect of \( b \) is not large due to the influence of \( 1 - \eta_n \). Because the outside room is the buffer chamber, the occupant’s activity is very large, it is assumed \( b = 10 \) for safety consideration.

(d) \( \varepsilon \) – in the buffer chamber, there are usually one non-closed door and a single layer stationary airtight window. Since the pressure inside the buffer chamber is “0,” the influence of wind pressure from outside ambient can be taken into account, which is the intermittent pressure 5–10 Pa. When the slot length is assume 11 m, according to the data about the leakage flow rate for this kind of door and windows [26], the total leakage flow rate is:

\[
L = 11 \times \left[ \frac{(17 + 24) + (1 + 0.7)}{2} \right] = 234.9 \text{ m}^3/\text{h}
\]

Since the wind pressure is intermittent, the leakage flow rate can be assumed half, i.e., 118 m³/h.
According to the area of the cleaning booth, the air velocity on the cross section is usually 2,000–2,500 m$^3$/h. Although $n_2$ varies with the size of the buffer chamber, the air leakage flow rate is fixed, namely,

$$\frac{118}{2,000 - 2,500} = 0.059 - 0.047$$

In the table, $\varepsilon = 0.02$, 0.04, and 0.06, respectively.

(e) $n$ is usually about 500 h$^{-1}$.

(f) $\psi$ – from Table 13.16, it is 0.05 for return air at both bottom sides. In the cleaning booth, air is returned at four bottom sides, so the flow uniformity is poorer than the situation when air is returned on both bottom sides. But because the chamber width is small, it can be still calculated with the situation when air is returned on both bottom sides.

Figure 14.41 shows the calculation results.
4. Particle concentration in the buffer chamber

Let $N_2$ be the particle concentration in the buffer chamber. According to the balance of particle concentration, the equilibrium expression can be made:

$$\frac{n_2 N_2}{60} = G_2 \times 10^{-3} + \frac{S n_1 N_v}{60} + \frac{M n_2 \epsilon}{60}$$  \hspace{1cm} (14.18)

Because $n_2 = a n_1$, $S = 1$, and $G_2 = b G_1$, we can obtain

$$a n_1 N_2 = 60 b G_1 \times 10^{-3} + n_1 N_v + M a n_1 \epsilon$$

$$N_2 = \frac{60 b G_1 \times 10^{-3} + n_1 N_v + M a n_1 \epsilon}{a n_1}$$  \hspace{1cm} (14.19)

where the implications of each symbol are the same as before. Under the most unfavorable situation, the calculated results are shown in Table 14.10.

Through the above analysis and calculation, the cleaning booth with transversely placed filter tubes has the following features in performance:

1. When $M$ is not more than $10^5$ and the filter efficiency $\eta_n$ is only 0.99 (the penetration $K$ is less than 1 %), the air cleanliness level can reach Class 100 under the condition of self-circulation (except several individual cases). When $\eta_n$ is close to 0.999, the air cleanliness level can reach Class 100 as long as $M$ is less than $2 \times 10^5$.

The filtration velocity inside the filter tube is generally 3–5 cm/s, which is 3–5 times larger than the standard specific velocity 1 cm/s of the filter media. When the specific velocity is assumed to increase by four times, according to Chap. 4 the penetration will increase about 20–40 times, which can be considered 30 times.

According to the above requirements, for particles with diameter $\geq 0.5 \mu m$ we know:

$$K \times 30 = 1 \%$$

$$K = \frac{1}{100 \times 30} = 0.00033 = 0.033 \%$$

$$\eta_n = 1 - K = 1 - 0.033 \% = 99.96 \%$$

It shows that the filtration velocity should be less than 5 cm/s for the air supply surface with transversely placed filter tubes made of polypropylene fibrous filter material whose efficiency is 99.99 %, so that the cleaning booth with air cleanliness level Class 100 can be manufactured, where coarse and medium

| Table 14.10  | Particle concentration in the buffer chamber (#/L) |
|--------------|---------------------------------------------------|
| $M$          | $a$      | $G_1$ | $\epsilon$ | $b$ | $n_1$ | $N_v$ | $N_2$ |
| $2 \times 10^5$ | 1.0     | $11 \times 10^4$ | 0.04 | 10  | 500  | 3.5   | 5,344 |
| $1 \times 10^5$ | 0.5     | $11 \times 10^4$ | 0.02 | 10  | 500  | 3.5   | 2,016 |
efficiency air filters are not used. With self-circulation, the particle concentration in the buffer chamber is lower than the required value for Class 200000, where the gravimetric concentration is much less than 0.1 mg/m$^3$.

When the gravimetric concentration is assumed 0.05 mg/m$^3$, the dust holding capacity of filter media 40 g/m$^2$, the total filtration area of cleaning booth 20 m$^2$, and the filtration efficiency 0.99, the service life can be obtained when it operates continuously everyday under the flow rate 2,000 m$^3$/h:

$$T = \frac{20 \times 40 \times 10^3}{2,000 \times 24 \times 0.05 \times 0.999} = 334$$

It is shown that when only a sub-HEPA filter is used, the service life can also maintain nearly one year or longer. Not only the application requirements are met but also the device structure is simplified and the cost is reduced.

2. Because self-circulation is very important for the device, the leakage rate should be reduced as much as possible. The leakage rate is almost proportional to the particle concentration $N_v$. This also applies for the situation when $\eta_n = 0.99$.

So if fresh air is supplied into this device, sub-HEPA filter must be placed along the passage of fresh air. If fresh air is supplied into the buffer chamber to maintain the positive pressure, $\varepsilon = 0$, and the air cleanliness level in the cleaning booth will be greatly improved. It is better to use this device together with the fresh air handling unit containing sub-HEPA filter.

3. The larger the buffer chamber is, the smaller the particle generation rate $G_2$ per unit volume is. When equilibrium state is reached, it will contribute to the air cleanliness. From Fig. 14.30, when $a = 0.5$, namely, the area of the buffer chamber is larger than that of the cleaning booth by one time, the particle concentration inside the cleaning booth reduces by half, and the volume of the buffer chamber is inversely proportional to the particle concentration in the cleaning booth. When more outdoor fresh air infiltrates into the buffer room, $G_2$ becomes larger and the particle concentration inside the cleaning booth increases faster.

4. If the airflow in the cleaning booth can be approximated as unidirectional flow, when the particle generation rate $G$ per unit volume of air increases by 22 times, the increase of particle concentration is still less. In the condition $\eta_n = 0.999$, it increases only by 1/10 to 1/3. When $\eta_n = 0.99$, it increases by 1–3 times. When the airflow is much closer to the unidirectional flow, the performance is much better.

### 14.5.3 Experimental Effect

Table 14.11 shows the experimental data after the system operated for half an hour in the cleaning booth where are two testing people inside. The cleaning booth was placed inside the ordinary room.

From the measurement result, when sub-HEPA filter tube was used, the particle concentration was sensitive to the inlet particle concentration. Even so, when the cleaning booth operates with self-circulation mode in the buffer chamber
with concentration 50,000 #/L, the air cleanliness level inside the buffer chamber can reach Class 10000 and that inside the cleaning booth can reach Class 1000000. If the initial concentration corresponds with Class 100000, the air cleanliness inside the buffer chamber can also reach Class several thousands.

### Table 14.11 Summary of particle concentration measurement in cleaning booth (≥0.5 μm, #/2.83L)

| Condition | Item | Initial concentration in buffer chamber before measurement | During operation of cleaning booth | Concentration in buffer chamber after operation | Concentration in cleaning booth |
|-----------|------|----------------------------------------------------------|----------------------------------|-----------------------------------------------|-------------------------------|
| Air supply system in buffer chamber operates | 5 × 10³(Class 100000) | 0.5 h | ~130 | 1.8 |
| Air supply system in buffer chamber is stopped | ~5 × 10⁴ | 0.5 h | ~1,000 | 5.4 |
| Both inner and outer doors are open in buffer chamber | ~5 × 10⁴ | 0.5 h | ~5 × 10⁴ | 317 |

**Fig. 14.42** Laminar hood in the cleaning tunnel (no auxiliary air supply at the operating surface and only partition board is placed (mm))

with concentration 50,000 #/L, the air cleanliness level inside the buffer chamber can reach Class 10000 and that inside the cleaning booth can reach Class 1000000. If the initial concentration corresponds with Class 100000, the air cleanliness inside the buffer chamber can also reach Class several thousands.

### 14.6 Laminar Flow Hood for Cleaning Tunnel

#### 14.6.1 Requirement of Anti-disturbance

Basically the conventional cleaning tunnel can be divided into two sections, namely, the process area assembled with the laminar flow hood and the operation channel area for transportation and passage. In the process area, comprehensive unidirectional flow is supplied from laminar flow hood. In the operation channel area, turbulent air is supplied. Partition board is usually used to separate the process area from the operation channel area (Fig. 14.42). Since the production line with air
cleanliness level Class 100, especially Class 10 or higher, is extremely sensitive to
the disturbance of pollution. The clean area in the process area with this kind
of conventional cleaning tunnel reduces, so it is difficult to reach the prescribed
air cleanliness level. This is because when turbulent flow is supplied in the
operation channel, vortex circulation is easily formed by the airflow between the
ceiling and the partition board in front of the hood. Pollution, especially the
pollutants generated at the head of the operational personnel, will retain for a
long term. Airflow will be easily induced below the partition board and vortex
will be produced, which increases the risk of the pollutant invasion from the
operation channel into the cleaning area. During operation, hands will be swing
back and forth, which will cause disturbance and reduce the air cleanliness
inside the hood.

Therefore, the following three requirements are proposed for the anti-
disturbance ability of the laminar flow hood applied in the cleaning tunnel.

1. Remove the vortex area at the above corner of the laminar flow hood in the
process area. Get rid of the possibility of the pollution induction into the laminar
flow hood from the bottom of the partition board.
2. If particle generation source exists near the laminar flow hood, it should be
removed as soon as possible, so that it will not cause risk for the clean area inside
the laminar flow hood.
3. Improve the anti-disturbance ability by the activity in front of the hood (namely,
the disturbance with a certain lateral velocity).

14.6.2 Effect of Auxiliary Air Supply at the Working Surface

In order to realize the above three purposes, Wang Jie [27] proposed the measures
of auxiliary air supply hood placed at the working surface of the laminar flow
hood. Through experiment and theoretical study, the effect obtained was
quite good.

In Figs. 14.43 and 14.44, hood with inclination angle $30^\circ$ or $60^\circ$ was placed at
the working surface, or the hood with inclination angle $45^\circ$ and regulating board
was added.

14.6.2.1 Effect of the Hood Shape

1. In terms of the total effect, the performance of the hood with inclination angle
$30^\circ$ is better than that with partition board only and without hood. The hood
with inclination angle $60^\circ$ is better than that with inclination angle $30^\circ$. The hood
with inclination angle $45^\circ$ and regulating board is better than that with inclina-
tion angle $60^\circ$.

Curves $a$, $b$, and $c$ in Fig. 14.45 show the theoretical boundaries under the
above three situations with air cleanliness Class 100. It is shown that the range of
Fig. 14.43 Auxiliary air supply hood placed at the working surface (with inclination angle 60° (mm))

Fig. 14.44 Auxiliary air supply hood placed at the working surface (with inclination angle 45° and regulating board (mm))

Fig. 14.45 Theoretical boundary of region with air cleanliness Class 100 for three kinds of laminar flow hoods
Curve $c$ is the largest. Fig. 14.46 shows the boundary of clean area (better than air cleanliness level Class 100000) obtained by experiment with the same total flow rate.

2. In terms of anti-disturbance from the lateral (horizontal) velocity, when lateral air pollution (simulated with hair dryer) exists at the working height where is 730 mm from the operation surface, the hood with inclination angle $30^\circ$ and $60^\circ$ can completely resistant the intrusion of disturbance, and their performances are not different from each other. When no hood is placed, the polluted air will invade to a certain range.

3. From the pollution near the front partition board, particles can be removed quickly when the hood is placed in front. When there is no hood, vortex area will be formed near the partition board and induction could be found inside the hood.

14.6.2.2 Effect of the Air Velocity Ratio

The air velocity ratio means the ratio between the exit velocity $v_1$ of the auxiliary air supply and the exit velocity $v_2$ of the laminar flow hood. Experiment has shown that it is better not to increase the value of this ratio only. For example, when $v_1/v_2$ increases from 0.57 to 0.86, although the flow rate only increases by 4 %, the range of the region with air cleanliness level Class 100 is obviously enlarged. If it increases from 0.86 to 1.43, although the flow rate only increases by 8 %, the range of the region with air cleanliness level Class 100 is almost unchanged. Experiment shows that the suitable air velocity ratio should be 0.77, when the cross-sectional area of the clean area is slightly larger than that with 0.86 and the invasion range by lateral velocity disturbance is also the minimum.
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