Chapter 15
Theory of Leakage Preventing Layer

It is a brand new concept for leakage prevention layer. The practice to place HEPA filter at the terminal is improved when the theory of leakage prevention layer applies, which becomes the core of novel air distribution method in cleanroom.

15.1 Overview

Air pollution control mechanism in clean space is realized by the supply of clean air through HEPA filter placed at the air supply terminal, which is the largest difference for the concept between the cleaning air conditioner and the general air conditioner. However, it is inevitable that minor apertures and cracks invisible to the naked eyes may be generated during manufacturing, delivering, and installation processes. Therefore, the problem of leakage cannot be effectively solved only with sealing and leakage stoppage. In practice, the incidence of the abrupt increase of particle concentration or bacteria concentration in some region occurs more than one time. After careful and repeat check, the leakage pore is found on the air supply surface of HEPA filter. But it is still unknown whether the leakage pore is produced by filter media with poor quality, formed by scrape during installation, or generated gradually with the supplied air with the former two reasons. The leakage phenomena are much more along the frame. It will not attract people’s attention when the air cleanliness level of turbulent flow cleanroom is not affected by these leakages. But whenever leakage occurs at the terminal, the safeguard system is not guaranteed. Severe or un-retrieved consequences may be generated, especially for unidirectional flow cleanroom with high level of air cleanliness.

As for the leakage problem on air filter, there are various methods to seal. But it cannot seal all the leakage passages through ceiling frame, air filter frame, head glue, and filter paper. Therefore, the concept of leakage prevention layer is proposed [1].

The purpose of leakage prevention layer is to decouple three functions including leakage stoppage, filtration, and flow equalization [2]. Leakage stoppage is realized
with HEPA filter at the terminal. Filtration should have certain efficiency. Flow equalization is equivalent with high value for the ratio of air distribution area. Leakage prevention layer can disperse, dilute and filter the penetrated air flow. The possible local leakage is converted into the complete integral un-leakage. The closed property of the system upstream of the air supplier is not modified.

The concept of leakage prevention layer is completely different from that of sealing the frame of air filter. The latter only aims to remove the leakage near the frame. The former aims to convert the problem of possible leakage at the last defense line or along other leakage passages into the integral un-leakage, which is equivalent with stopping the leakage.

The concept of leakage prevention layer is also completely different from that of the damping layer. The latter only plays the role of limited flow equalization and has certain decoration effect (when perforated plate is used, particles will be deposited instead). The former can have substantial effect to improve the cleaning performance with several mechanisms (introduced later).

When the concept of leakage prevention layer is combined with that of expanding mainstream area, new air distribution type will be formed, namely, the terminal air distribution with leakage prevention layer. The traditional model that HEPA filters must be placed at terminal is changed from both theoretical and practical point of view. The quality of air distribution and the ability of leakage stoppage are further improved.

### 15.2 Leakage Equation

Leakage equation is used to estimate the quantity of leakage.

Leakage is a kind of jet flow, since it is the phenomenon of high speed outflow through the hole. Because the cross-sectional area of leakage hole is much smaller than that of air filter, it can be omitted, so the related principle of free jet flow is valid to describe the leakage jet flow.

The influence of polluted flow through the leakage jet flow is the maximum for unidirectional flow. The local particle concentration near the working area will be elevated, which will bring particles to the object directly. If there are too many leakage positions, the polluted flow will overlap, which will increase the particle concentration on certain surface of the working area. The resultant average concentration in the whole room will be influenced, which is shown in Fig. 15.1.

For the common HEPA filter air supply inlet with diffusion plate with partial leakage as shown in Fig. 15.2, the concentration of air supply should be:

\[ N_1 = K_1 N_0 \]  \hspace{1cm} (15.1)

where

\( N_0 \) is the upstream concentration of air filter;
**Fig. 15.1** Influence of leakage flow on the working area

**Fig. 15.2** HEPA filter air supply inlet with diffusion plate

\( N_1 \) is the downstream concentration of air filter, which is the concentration of air supply mentioned here; 
\( K_1 \) is the penetration of air filter.

For the air supply inlet with leakage hole as shown in Fig. 15.3, the particle concentration of polluted flow constitutes of the following two parts, when \( Q_{m1} \) is the flow rate of leakage through the hole, \( Q_M \) is the total flow rate through air filter, \( Q_{s1} \) is the flow rate of polluted flow when the leakage jet flow is mixed, \( \alpha_1 \) is the leakage coefficient with \( \alpha_1 = \frac{Q_{m1}}{Q_M} \), and \( a_1 \) is the mixture coefficient with \( a_1 = \frac{Q_{s1}}{Q_M} \).

1. In the unit volume of polluted flow, the particles brought in by leakage jet flow are \( \frac{N_0 \alpha_1}{a_1} \).
2. In the unit volume of polluted flow, the particles brought in by the proportion of original flow before mixture are \( \frac{N_0K_1(a_1 - a_1)}{a_1} \).

So the particle concentration in the unit volume of polluted flow, i.e., the average concentration \( N'_1 \), is made of the summation of above two items, namely,

\[
N'_1 = \frac{N_0\alpha_1 + N_0K_1(a_1 - a_1)}{a_1} = N_0 \left[ K_1 + \frac{\alpha_1}{a_1} (1 - K_1) \right] = N_0(K_1 + \Delta K_1) = N_0K'_1
\]  

(15.2)

With the comparison between Eqs. (15.1) and (15.2), the penetration of air filter with leakage for polluted flow increases from \( K_1 \) to \( (K_1 + \Delta K_1) \). \( K_1 + \Delta K_1 = K'_1 \) is called the penetration with leakage.

There are two kinds of mixture of leakage jet flow with supplied air. One is the mixture during the process of jet flow. The other is the mixture with ambient flow, namely, mixed with the turbulent flow near the air supply inlet. When unidirectional flow, which is greatly affected by the leakage, is taken into account, the second kind of mixture is not considered here.

For the mixture during the process of jet flow, we obtain:

\[
\frac{\alpha_1}{a_1} = \frac{Q_{m1}/Q_M}{Q_{s1}/Q_M} = \frac{Q_{m1}}{Q_{s1}}
\]  

(15.3)

When Eq. (15.2) is expanded, it is converted into:

\[
N'_1 = N_0K_1 + N_0 \frac{\alpha_1}{a_1} - N_0K_1 \frac{\alpha_1}{a_1}
\]  

(15.4)
where \( N_0 K_1 \) is the outlet concentration of filter, which is also the ambient concentration near the exit of the leakage jet. Let it be \( N_e \), i.e.,

\[
N'_1 - N_e = (N_0 - N_e) \frac{a_1}{a_1} \quad (15.5)
\]

Substituting it into the Eq. (15.3) gives:

\[
\frac{N'_1 - N_e}{N_0 - N_e} = \frac{Q_{m1}}{Q_{s1}} \quad (15.6)
\]

According to Г.Н. Абрамович (referred to as the A’s), the law of concentration difference in jet flow derived before the 1960s is the following equation[3], where the concentration is inversely proportional to the flow rate and is proportional to the change of the speed:

\[
\frac{\Delta N_1}{\Delta N_0} = \frac{Q_0}{Q} \quad (15.7)
\]

where

\( \Delta N_1 \) is the difference of mass average concentrations between the cross section of jet flow and the environment, i.e., \( N'_1 - N_e \) in Eq. (15.5) (in order to keep the symbols in the book consistent, we change the subscript in A’s formula from 2 to 1);
\( \Delta N_0 \) is the difference of mass average concentrations between the jet flow outlet and the environment, i.e., \( N_0 - N_e \) in Eq. (15.5);
\( Q \) is the flow rate at the cross section after mixture, i.e., \( Q_{s1} \);
\( Q_0 \) is the leakage flow rate, i.e., \( Q_{m1} \).

Therefore,

\[
\frac{Q_0}{Q} = \frac{Q_{m1}}{Q_{s1}} \quad (15.8)
\]

Equation (15.7) also becomes:

\[
\frac{\Delta N_1}{\Delta N_0} = \frac{N'_1 - N_e}{N_0 - N_e} = \frac{Q_{m1}}{Q_{s1}} \quad (15.9)
\]

From Eqs. (15.5) and (15.9), we can see that the leakage equation is derived from the principle of cleanroom, which is exactly the same as the concentration difference formula of jet flow derived with the principle of jet flow structure by A’s. This means the jet flow theory is valid to describe the pinhole leakage phenomenon.

But since 1960s, A’s amended his formula and then obtained

\[
\frac{\Delta N_1}{\Delta N_0} = \frac{Q_{m1}}{Q_{s1}} \sqrt{\frac{N_e}{N_0}} \quad (15.10)
\]
Compared with Eq. (15.9), a factor is multiplied in Eq. (15.10), that is, \( \sqrt{\frac{N_c}{N_0}} \). If this formula is applied for the leakage jet flow, the value of \( \Delta N_1/\Delta N_0 \) will be smaller than that with the original formula by several hundreds, because \( N_0 \) is larger than \( N_c \) by about 10 thousands of times. In other words, the jet flow diffuses faster, which is correct to describe the temperature change. In A’s opinion, the heat diffusion is faster than the momentum diffusion, so the development of temperature boundary layer is faster, which is thicker, than the velocity boundary layer. It is shown in Fig. 15.4 [4]. From the foregoing derivation process about leakage equation, Eq. (15.9) is correct. It is inappropriate to use Eq. (15.10) for describing the concentration difference of jet flow or leakage jet flow, because it does not fully comply with the fact. It should be considered that the concentration diffusion cannot fully apply the law of temperature diffusion, especially for the diffusion with low concentration in the air cleaning technology.

As pointed out in the derivation process of Eq. (15.2), there are two parts of particles brought in by the polluted flow. But in theory the amount of particles by diffusion should be considered. Since the concentration of leakage jet flow is greater than the ambient concentration, particles are mainly taken outside. Given to the fact that diffusional movement of particles is mainly influenced by the Brownian motion of the gas, the diffusion coefficient of the particles is much smaller than the diffusion coefficient of the gas molecules, which is about 100,000 of the latter value. Result will never reduce by hundreds times even if it is taken into consideration. This has been proved by both experience and experiment.

According to the principle of pinhole leakage and round hole jet flow, the relationship between the axial velocity of round hole leakage jet flow and the exit velocity is

\[
\frac{v_1}{v_0} = \frac{0.48}{\frac{aS_1}{d_0} + 0.147}
\]  

(15.11)

where

- \( v_1 \) is the axial velocity of leakage jet flow, and it is 0.3 m/s;
- \( v_0 \) is the exit velocity of round hole;
- \( S_1 \) is the distance from the mouth of the round hole when the velocity is \( v_1 \) (m or mm);
\(d_0\) is the diameter of the leakage aperture (m or mm); 
\(\alpha\) is the turbulence coefficient, and it is 0.08 for round hole.

The relationship between the flow rates is:

\[
\frac{Q_{m1}}{Q_{s1}} = \frac{1}{4.4\left(\frac{\alpha v_1}{d_0} + 0.147\right)} \quad (15.12)
\]

So

\[
\frac{S_1}{d_0} = \frac{0.48v_0 - 0.147v_1}{\alpha v_1} \quad (15.13)
\]

The relationship between the exit velocity \(v_0\) of the leakage aperture and the differential pressure \(\Delta P\) (Pa) across two sides is

\[
v_0 = \varphi \sqrt{\frac{2\Delta P}{\rho}} \quad (15.14)
\]

where

\(\varphi\) is the flow velocity coefficient, and it is defined as the ratio of actual flow velocity to the ideal value. Given the resistance of the leakage aperture, it is obtained that \(\varphi = 0.82\);

\(\rho\) is the gas density 1.2 kg/m\(^3\). The value is shown in Table 15.1.

The initial operating condition during leakage detection and the vertical leakage aperture are used as the basis. The differential pressure \(\Delta P\) is set 200 Pa. Then the following expression is obtained:

\[
\frac{S_1}{d_0} = 297.4
\]

It is shown that when the differential pressure \(\Delta P\) and the axial velocity \(v_1\) are fixed, and \(S_1/d_0\) is constant since \(\frac{a_1}{a_{l1}} = \frac{Q_{m1}}{Q_{s1}}\), we obtain the following expression:

\[
\frac{a_1}{a_{l1}} = \frac{1}{4.4(0.08 \times 297.4 + 0.147)} = 0.0095
\]

If \(d_0 = 1\) mm, \(S_1 \approx 300\) mm. When this distance is reachable, namely, \(a_1/a_{l1}\) is not more than 0.0095, \(d_0\) must be larger. So for the predetermined distance 300 mm,
\( \alpha_1/a_1 \) will be greater than 0.0095, which means the leakage extent is more serious. Otherwise, structure should be improved to increase \( S_1 \).

In Eq. (15.2), the larger the value of \( \alpha_1/a_1 \) is, the larger the concentration by leakage pollution is. It is also shown from Eq. (15.12) that the farther it is from the leakage aperture (i.e., the larger \( S_1 \)) and the less the pinhole is (i.e., the smaller \( d_0 \)), the smaller the value of \( \alpha_1/a_1 \) is, which means the polluted concentration is reduced. However, the value of \( S_1 \) cannot be infinite, namely, the jet cannot diffuse and dilute unlimitedly. The leakage jet flow mentioned here is not in the stationary space but in the surrounding flow along the same direction with the same velocity (or velocity component). According to the jet flow theory, jet flow will not disperse when the axial velocity of the leakage jet flow is equivalent with that of the surrounding flow. It will move forward with the surrounding flow and become part of the surrounding flow.

For full placed HEPA filter air suppliers, the surrounding flow velocity is essentially the same, so the velocity of unidirectional flow can be considered 0.3 m/s. Since the velocity below the air supply inlet in the turbulent flow cleanroom is relative large, the velocity in the mainstream just below the air supply inlet can also decay to 0.3 m/s. When it is smaller, the turbidity will be large. Moreover, when the velocity decay to 0.25 m/s, the pollution concentration obtained finally will be slightly less than the case with 0.3 m/s. From the safety aspect, it is only extended to 0.3 m/s.

In Eq. (15.2), \( (1 - K_1) \approx 1 \). From Chap. 4, it is known the penetration \( K_1 \) of HEPA filter should reach 0.00002 (for particles with diameter \( \geq 0.5 \) \( \mu \)m)

\[
N'_1 \approx N_0(K_1 + 475K_1) = K_1N_0 + 475K_1N_0
\]  

(15.15)

This means when leakage occurs without installation of leakage prevention layer, the concentration \( N'_1 \) of polluted air flow by leakage will be larger than the normal concentration \( K_1N_0 \) in the supplied air by 475 times, when the above velocity decays to the proximity of supplied velocity. So leakage is the most important factor affecting the air cleanliness with HEPA filter. Leakage prevention layer is the most important measures to improve the cleanliness.

Therefore, Eq. (15.2) can reflect the extent of leakage, which is termed as leakage equation.

### 15.3 Equation for Leakage Prevention

In this chapter, leakage prevention layer is proposed, where the air distributor with a certain value of penetration and resistance is placed below the HEPA filter. It is shown in Fig. 15.5.

When the penetration of leakage prevention layer is also the same value, i.e., \( K_2 = K_1 \), it is equivalent with the condition when two HEPA filters are installed.
If the method to seal the frame of HEPA filter is adopted to threat the frame of the leakage prevention layer, it is impractical since this is not within the scope of leakage prevention. For the leakage prevention layer mentioned here, special sealing is basically not considered for the connection between it and the frame. There may be three situations when polluted flow, caused by the leakage through the frame of air filter, passes through this kind of leakage prevention layer. It is shown in Fig. 15.6.

1. Polluted airflow directly reach and cover the entire aperture and the surface of the leakage prevention layer, which makes the concentration of this flow through the leakage prevention layer $N_0 K_1$. The polluted flow through the aperture of leakage prevention layer will not be mixed with the clean air whose concentration is $N_0K_1$. This is the worst situation. But it is impossible to happen, because part of the clean air not through the leakage may pass through the leakage prevention layer.
The derivation process of the polluted flow after the leakage prevention layer is similar as that of $N'_{01}$. It is also composed of two parts, i.e.,

$$
N'_{2} = \frac{N'_{01}a_2 + N'_{1}K_2(a_2 - a_2)}{a_2} = N'_{01} \left[ K_2 + \frac{a_2}{a_2} (1 - K_2) \right]
$$

$$
= N_0 \left[ K_1 + \frac{a_1}{a_1} (1 - K_1) \right] \left[ K_2 + \frac{a_2}{a_2} (1 - K_2) \right] \tag{15.16}
$$

or

$$
N'_{2} = K'_1K'_2N_0
$$

where the meanings of $a_2$, $a_2$, $K_2$ and $N'_{2}$ are the same as that of $a_1$, $a_1$, $K_1$, and $N'_{01}$, respectively. They are parameters for the second layer, i.e., the leakage prevention layer.

2. All the polluted airflow goes through the aperture of the frame on the leakage prevention layer. The leakage concentration $N'_{01}$ after passing the leakage prevention layer becomes $N_0K_1K_2$. In this case, the polluted air through leakage will be mixed with the most clean air through the leakage prevention layer. This is the best situation, but it is also impossible to happen. At this time, it is

$$
N'_{2} = \frac{N_0K_1K_2(a_2 - a_2)}{a_2}
$$

Inserting the expression of $N_0K_1$ in Eq. (15.2) into (15.17) gives

$$
N'_{2} = N_0 \left[ K_1 + \frac{a_1}{a_1} (1 - K_1) \right] \left[ K_2 + \frac{a_2}{a_2} (1 - K_2) \right]
$$

$$
- N_0 \frac{a_1}{a_1} \left( 1 - \frac{a_2}{a_2} \right) K_2 (1 - K_1) \tag{15.18}
$$

It is known from the later calculation that both $\frac{a_2}{a_2}$ and $K_1$ are $<< 0.1$. So both $\left( 1 - \frac{a_2}{a_2} \right)$ and $(1 - K_1)$ can be considered approximately 1. Equation (15.18) can be simplified as:

$$
N'_{2} = N_0 \left[ K_1 + \frac{a_1}{a_1} (1 - K_1) \right] \left[ K_2 + \frac{a_2}{a_2} (1 - K_2) \right] - N_0 \frac{a_1}{a_1} K_2 \tag{15.19}
$$

or

$$
N'_{2} = K'_1K'_2 - K_2 \frac{a_1}{a_1} N_0 \tag{15.20}
$$
3. One part of the polluted airflow goes through the frame aperture of the leakage prevention layer, which has the concentration of \( N'_{1} \). The other part of the polluted airflow goes through the leakage prevention layer. So the leakage airflow through the aperture of the leakage prevention layer will be mixed with the air which is neither clean nor dirty (the mixed flow by the combination of \( N_{0}K_{1}K_{2} \) and \( N'_{1}K'_{2} \)). It is the condition between the above two situations. In this case, the proportion of the polluted air flows through the aperture of the leakage prevention layer and its surface is unknown, so it is difficult to determine the value of \( N'_{2} \). When the averaged value of the first and second situations is used, the value of \( N'_{2} \) can be obtained:

\[
N'_{2} = N_{0} \left[ K_{1} + \frac{a_{1}}{a_{1}} (1 - K_{1}) \right] \left[ K_{2} + \frac{a_{2}}{a_{2}} (1 - K_{2}) \right] - N_{0} \frac{K_{2}a_{1}}{2a_{1}}
\]  

or

\[
N'_{2} = \left( K'_{1}K'_{2} - \frac{K_{2}a_{1}}{2a_{1}} \right) N_{0}
\]  

Under the common situation, the concentration of polluted air formed by the leakage jet flow after passing through the leakage prevention layer is less than that of the worst situation by \( N_{0} \frac{K_{2}a_{1}}{2a_{1}} \). The multiplication of the first and second items in Eq. (15.21) is \( N'_{1} \).

Both Eqs. (15.21) and (15.22) can reflect the effect of leakage prevention, which are the leakage prevention equations.

### 15.4 Leakage Prevention Effect

If there is no special seal between the leakage prevention layer and the frame, and it is not tightly pressed, apertures through the longitudinal sealing pad will exist. From the side view, they look like the holes, so it should still be applicable to describe it with the round hole jet flow.

Assuming that the differential pressure across the leakage prevention layer is \( \Delta P = 120 \) Pa, and the exit velocity of the leakage jet flow through the leakage prevention layer is \( v_0 = 9.5 \) m/s, and the axial velocity of the leakage jet flow decays to 0.3 m/s, it is then obtained \( S_2/d_0 = 230 \). So we get \( \alpha_2/a_2 = 0.0122 \).

Now a simple analysis will be presented to show what range of \( K_2 \) should be selected. From Eq. (15.16) which corresponds to the most unfavorable situation with the minimal effect of the leakage prevention, it is known that the less the value of \( K_2 + \alpha_2/a_2(1 - K_2) \) is, the better it is. And it seems it is better if \( K_2 \) is as small as possible. But if \( K_2 \) is so small that it is near the value of filter media with high efficiency, which is only below one tenths of \( \alpha_2/a_2 \), the contribution appears trivial.
on the leakage prevention effect. At this time, the leakage prevention effect mainly depends on $\alpha_2/a_2$, so only the resistance and the cost will increase when $K_2$ is reduced.

From Eq. (15.16), it is better $K_2$ and $\alpha_2/a_2$ are comparable, namely, it is most appropriate that $K_2$ corresponds to the efficiency 95–99% for sub-HEPA filter media. In this case, it not only has good performance of both leakage prevention effect and prevention of the air pollution by backflow but also simplifies the requirement on the filtration and sealing performance of the leakage prevention layer, which has practical meaning.

The influence of $K_2$ on the leakage prevention effect can be calculated with the following steps.

It is known

$$\frac{\alpha_2}{a_2} = 0.0095$$

$$\frac{\alpha_2}{a_2} = 0.0122$$

For particles with diameter $\geq 0.5$ μm, we have

$$K_1 = 0.00002$$

$$K'_1 = K_1 + \frac{\alpha_1}{a_1} (1 - K_1) = 0.00952$$

The concentration $N'_2$ of leakage polluted air through the leakage prevention layer is shown in Table 15.2. It is shown when $K_2$ decreases from 0.01 to 0.001, $N'_2$ does not change very much. So corresponding to the sealing condition with $\alpha_2/a_2 = 0.0122$, the effect of reducing the polluted concentration is little with high-efficiency leakage prevention layer $K_2 = 0.001$, which means it is unnecessary to chose high performance materials as the leakage prevention layer. When sub-HEPA leakage prevention layer is chosen and the most unfavorable condition without the mixture of turbulent flow is taken into consideration, the polluted air concentration at the downstream of the leakage prevention layer which has leakage aperture can be reduced to below 0.04 of that without the leakage prevention layer. Because there is mixture of turbulent flow in actual applications, it would be much less than this value.

Table 15.3 shows the test results before and after the leakage prevention layer is installed, where the size of test chamber is 3.4 m × 2.4 m [4, 5].

1. With the leakage prevention layer, the indoor particle concentration is much lower than that without the leakage prevention layer.

| $K_2$   | 0.05 | 0.01 | 0.001 |
|---------|------|------|-------|
| $K'_2$  | 0.0616 | 0.022 | 0.0132 |
| $K_2\alpha_1$ | 0.0002375 | 0.0000475 | 0.0000475 |
| $\frac{\alpha_1}{a_1}$ | 0.0366 | 0.017N'1 | 0.0127N'1 |
| $N'_2$ Eq. (15.21) | 0.000349 $N_0$ | 0.000162 $N_0$ | 0.000121 $N_0$ |
| $N'_2$ Eq. (15.22) | 0.000349 | 0.000162 | 0.000121 |

Table 15.2 Calculated value of $N'_2$
2. With the leakage prevention layer, the influence of the existence of both leakage and fresh air is not obvious on the indoor particle concentration, which means the leakage prevention layer has played its role properly.

3. When the artificial leakage source is added, where the leakage flow rate of 12 pipes is 0.74 m$^3$/h, the total amount of particles injected into the upstream of HEPA filter is $1.57 \times 10^6$ pc/h, and the indoor concentration can be increased by 0.17 pc/L. But due to the leakage prevention layer, this effect is not prominent.

### Table 15.3 Comparison of the situations with full leakage prevention layer and without leakage prevention layer

| Leakage prevention layer | Total flow rate (m$^3$/h) | Fresh air volume (m$^3$/h) | Upstream concentration of HEPA filter ($\geq 0.5$ μm) (pc/L) | Additional leakage position | Indoor concentration ($\geq 0.5$ μm) (pc/L) | Remark |
|--------------------------|---------------------------|-----------------------------|----------------------------------------------------------|------------------------------|--------------------------------|--------|
| With                     | 9,500                     | 201                         | 2,119                                                   | Without                      | 1.98 3.30                   | Leakage exists on filter frame, which has been stopped by measures |
| Without                  | 9,500                     | 201                         | 2,119                                                   | Without                      | 0.36 0.80                   |        |
| Closed                   | 457                       | 2,119                       | Without                                                 | 0.46 0.60                    | Ave. 0.07                   |        |
| Closed                   | 457                       | 2,119                       | With                                                    | 0.33 0.70                    | Ave. 0.68                   |        |
| Closed                   | 457                       | 2,119                       | With                                                    | 0.36 0.70                    | Ave. 0.68                   |        |

15.5 Mechanism of Leakage Prevention Layer

#### 15.5.1 Leakage Prevention with Dilution Effect

1. Mixed dilution with jet flow. From the above calculations, we can know that due to the mixture of jet flow, the concentration of leakage polluted jet flow can be diluted to 1/100 of the original level, when the conditions are that there must be long enough for the expansion of jet flow from the leakage position to the leakage prevention layer. With the previous calculation for $S_1/d_0 = 297.4$, when the leakage aperture diameter is $d_0 = 1$ mm, the length needed will be 300 mm. When the leakage prevention layer is separately placed from the filter, the air filter is used for filtration only and the leakage prevention layer is used to distribute airflow only, which is shown in Fig. 15.7. The terminal HEPA filter is designed in the filter box placed in the technical interlayer, which is connected to the leakage prevention layer for air distribution through a short pipe. Since the
distance between the leakage position and the leakage prevention layer is much larger than the above value $S_1$, it is beneficial for the complete dilution of polluted jet flow, which will reduce both $\alpha_1/a_1$ and $K'_{1}$. 

2. The dilution with turbulent flow. If the polluted concentration should be further reduced, the turbulent mixture of airflow must be used for dilution. With the definition of $\alpha_1$, the value of $\alpha_1/a_1$ will be the smallest if the polluted air is full of the whole supplied air, i.e., $Q_1/Q = Q_M$ and $a_1 = 1$. As shown in Fig. 15.7, the mixture dilution is intensified because the unidirectional flow streamlines are destroyed and the velocity increases after air passes through the contracting part and the elbow. Moreover, the baffle board is placed at the entrance of the plenum chamber, which further increases the mixing effect, the value of $a_1$ in this situation is much larger than the situation when these measures are not taken. The filtration area of HEPA filter in the filter box is much smaller than that of the leakage prevention layer, which not only saves the material for air filter, but also makes the sealing convenient. During the sealing process, the area for sealing is much smaller, and it is operated outside of the plenum chamber.

Experiment and calculation have proved that it is quite difficult to increase the value of $a_1$. Usually it is already very good when $a_1$ becomes 0.1–0.3. In this case, the penetration only increases by about 3 times on average.

The influence of $a_1$ on the mixing effect of airflow is shown in Table 15.4.

### 15.5.2 Leakage Prevention with Filter

It is shown from Eq. (15.2) that the leakage prevention effect of the leakage prevention layer is related to the filtration effect of this layer. When there is no leakage prevention layer, the concentration of supplied air is:

$$N'_1 = N_0K_2$$
When the leakage prevention layer is installed, the concentration of supplied air is

\[ N'_2 = N'_1 K'_2 = N_0 K'_1 K'_2 \]

where \( K'_2 \) contains the information reflecting the filtration effect \( K_2 \) of the leakage prevention layer. \( K'_2 \) will be smaller if \( K_2 \) is smaller. As explained earlier, \( K_2 \) does not need to be too small, because too small value of \( K_2 \) will increase the resistance, where the meaning of the leakage prevention layer is lost. Even if it is only one tenth or two tenths of the value \( a_2/a_2 \), namely, the filtration efficiency is equivalent to more than 99.5 %, its effect is almost offset by \( a_2/a_2 \).

But the appropriate value of \( K_2 \) for the leakage prevention layer will further play its role in reducing the concentration \( N'_2 \) of supplied air. As analyzed before, when there is no obvious requirement for the sealing measures taken for the leakage prevention layer, it’s better to have the filtration effect of sub-HEPA filter.

### 15.5.3 Leakage Prevention with Reduced Differential Pressure

The leakage flow rate through the aperture depends on the differential pressure, which is clearly shown in Table 15.5 about the leakage formula. The final resistance
of HEPA filter under the (0.5–1) times of the rated air flow can reach up to 200–400 Pa. When the leakage prevention layer is placed and the low resistance and sub-high-efficiency material is used as the leakage prevention layer, the differential pressure across the planar leakage prevention layer can be reduced to 100–120 Pa. The smaller the differential pressure is, the less the leakage flow rate is. In this case, more airflow will pass through the leakage prevention layer, so more air will be subjected to the second filtration process. With the reduced differential pressure, the condition for the sealing of the frame can be simplified, which has practical implication. When the differential pressure reduces, \( v_0 \) decreased, and thus \( v_2 \) will reduce. But it will reflect the change of the particle concentration in unit volume of air, so there is no direct reflection in both the leakage equation and the leakage prevention equation.

From Table 15.5, it is shown that when the differential pressure is reduced by one half, the leakage flow rate will be reduced by 30 %.

### 15.5.4 Barrier Leakage Prevention

Even though only hard contact exists between the frame of the leakage prevention layer and the frame, there is still resistance for the leakage airflow, namely, there is still the
barrier effect. In this case, there is still a certain sealing effect, which plays the role of reducing \( a_2 \). When there is still considerable sealing effect if no obvious measure of sealing was adopted for the leakage prevention layer, the value of \( a_2 \) for the leakage prevention layer will be further reduced, so as the value of \( \alpha_2/a_2 \). For example, the soft material is attached on the frame, which can avoid the hard contact. When appropriate value of \( K_2 \) is adopted, the value of \( K' \) will be reduced further, which will improve the leakage prevention effect. But as mentioned before, if the leakage prevention layer with sub-high-efficiency is used, the value of \( \alpha_2/a_2 \) should not be much smaller than \( K_2 \).

### 15.6 Air Supply Terminal with Leakage Prevention Layer

#### 15.6.1 Overview

In Sect. 15.1 of this chapter, it has pointed out that the mechanism of air pollution control in cleanroom is that HEPA filter placed at the end of air supply terminal supply the clean air into the cleanroom. But different air cleanliness levels will appear with different air distributions, including the dilution distribution of turbulent flow, the piston-type extrusion distribution with unidirectional flow, and with different forms with leakage in the terminals. The change of conventional air distribution modes in the quantity and quality is accompanied by the number of HEPA filters proportionally, namely, the number of HEPA air supply inlets will increase with the increase of the expanded supply area. So it is of little practical significance, and the influence of occasional leakage of the air terminal on the property of clean space cannot be ruled out.

The meaning of mainstream area has been clarified in Chap. 14. So the new air distribution mode by air supply terminal with the leakage prevention layer is put forward, when the leakage prevention layer is combined with the expanded mainstream area.

#### 15.6.2 Structure of Air Supply Terminal with Leakage Prevention Layer

The air supply terminal with the leakage prevention layer has been patented, which is also called the leakage prevention type clean air supply ceiling. There are two forms:

##### 15.6.2.1 Made of Single Leakage Prevention Layer

The equipment made of single leakage prevention layer shown in Fig. 15.8 can also be termed as the air supply inlet with the leakage prevention layer. Filters can be placed inside the air supply inlet (Fig. 15.8a) and can also be outside the air supply inlet (Fig. 15.8b). For the latter case, it is installed in the filter box.
The equipment of this form can be directly connected with the large system. Since the area of the leakage prevention layer can be larger than the cross-sectional area of the filter, the mainstream area will be expanded, which is suitable for turbulent flow cleanroom. With the same number of filters, the area of air supply outlet can be enlarged by one time, which increases the clean area and strengthen the unidirectional flow property in the mainstream area.

15.6.2.2 Made of Multiple Leakage Prevention Layers

With multiple leakage prevention layers, Class 100 locally or in the whole room can be achieved when the room area is relative large.

The above two forms include the following parts:

(a) Filter Box
(b) Thin Plenum Chamber

The thickness of each plenum chamber is only 250–350 mm.

There is device for promotion of mixing inside the plenum chamber. According to the principle of leakage prevention layer, the mixing coefficient can be improved to more than 0.3.

The inlet velocity of plenum chamber should not be too big, and baffle should be placed [8]. Otherwise, negative pressure will be formed at the inlet, and the exit velocity at the remote end will increase, which is shown in Fig. 15.9 [9].

(c) Terminal of Leakage Prevention Layer

![Diagram](image-url)
It is very convenient for installation because the special sealing means is not needed. Especially when the ratio of blowing area with clean air is about 95 %, its considerable resistance makes the airflow in the plenum chamber stable and uniform easily.

(d) Short Jointed Plumbing

The air supply terminal of leakage prevention layer has four main features including: preventing leakage, expanding the mainstream area, reducing the story height, and easy replacement and maintenance of air filter and decoration layer outside of room. So it is widely used in engineering projects.

15.6.3 Property of Air Supply Terminal of Leakage Prevention Layer

15.6.3.1 Decay of Air Supply Velocity

Experimental study has been performed by Niu Weile for the property of air supply terminal of leakage prevention layer. The study of anti-disturbance property of mainstream area with concentrated air supply mode has valuable for practical work. Data cited here are all from the result of this study [9]. Table 15.6 shows the experimental results.

The conclusions can be reached from the above table:

1. As mentioned before, the relationship between decay rate of supply velocity and the magnitude of supply velocity is not very obvious. But it is shown that the larger the supply velocity is, the smaller the decay rate is.
2. When the velocity \( v \) on the working surface is between 0.2 and 0.25 m/s (which is required in clean operating room at home and abroad), the air supply velocity \( v_0 \) may be between 0.35 and 0.40 m/s, which has the significance of energy saving (for status 1).
3. When the temperature difference is only 1.4 °C, the decay rate increases, which means larger air supply velocity \( v_0 \) is needed for the same velocity required on the working surface. When the temperature of hot air supply is reached, air may...
Table 15.6  Property of air velocity, decay rate, and frequency

| Frequency (Hz) | 44 | 45 | 46 | 47 | 48 | 49 | 50 |
|---------------|----|----|----|----|----|----|----|
| Temperature difference of supplied air, 0 °C | $v_0$ | 0.396 | 0.414 | 0.424 | 0.431 | 0.443 | 0.452 | 0.462 |
| | $v$ | 0.250 | 0.264 | 0.270 | 0.272 | 0.281 | 0.300 | 0.322 |
| | $\lambda$ | 0.369 | 0.362 | 0.363 | 0.369 | 0.366 | 0.336 | 0.303 |
| Temperature difference of supplied air, +1.4 °C | $v_0$ | 0.394 | 0.407 | 0.424 | 0.431 | 0.444 | 0.464 | 0.497 |
| | $v$ | 0.212 | 0.226 | 0.229 | 0.241 | 0.251 | 0.268 | 0.280 |
| | $\lambda$ | 0.462 | 0.445 | 0.441 | 0.444 | 0.445 | 0.422 | 0.437 |

Table 15.7  Property of turbidity and frequency

| Frequency (Hz) | 44 | 45 | 46 | 47 | 48 | 49 | 50 |
|---------------|----|----|----|----|----|----|----|
| Status 1 | Face turbidity of supplied air | 0.096 | 0.093 | 0.093 | 0.089 | 0.089 | 0.084 | 0.080 |
| | Face turbidity of working area | 0.266 | 0.245 | 0.232 | 0.227 | 0.208 | 0.199 | 0.202 |
| Status 2 | Face turbidity of supplied air | 0.099 | 0.104 | 0.092 | 0.094 | 0.094 | 0.087 | 0.081 |
| | Face turbidity of working area | 0.361 | 0.342 | 0.346 | 0.354 | 0.344 | 0.301 | 0.296 |

not come down. This is why in both German and Chinese standards the required air supply temperature in the cleanroom should be smaller than room temperature. When cold air is supplied, the precool effect becomes better.

15.6.3.2  Turbidity

Table 15.7 shows the experimental results.

The conclusions can be reached from the above table:

1. The difference of turbidity under two statuses is very small, because the face velocity of supplied air was measured at 5 cm below the air supply outlet and the difference of statuses is not obviously shown.
2. The turbidity at the working area (0.8 m above the floor) reduces when the temperature difference of supplied air changes from “+” to “0.” It can be expected that it will reduce further when the temperature difference changes from “0” to “−.”
3. The larger the supplied air velocity is, the less the turbidity is. With the elevated working height, the turbidity may reduce, but the influence of return air grille should be considered.

15.6.3.3  Anti-disturbance

1. Anti-disturbance of the Activity from people in the Surrounding Area around Mainstream Area

Sampling positions are shown in Fig. 15.10. Three minutes after particle concentrations are stable, one person without wearing clean cloth began to walk with velocity 1 m/s in the surround area of mainstream area. After the
walk for three minutes, concentration variation was monitored since the fourth
minute. When the person stops, the concentration variation was continuously
recorded for 3 min. Table 15.8 shows the experimental result.

The conclusions can be reached from the above table:

(a) The influence of walk in the surround area is small for the particle concen-
tration in mainstream area. There are only three positions in eight positions,
where small particle concentration slightly exceed the value suggested in
standard. Particle concentrations in other positions are within the range
suggested in standard.
(b) The influence vanishes immediately when the person stops walking.

2. Anti-disturbance of the Activity from people in Mainstream Area

As shown in Fig. 15.11, the person stands in the center and waves the front arms continuously from the first and fifth minutes. Table 15.9 shows the experimental result.

The conclusions can be reached from the above table:

(a) With the increase of the distance between the sampling positions and mainstream area, the particle concentration first increases and then decreases. The maximum arrives at 550 mm from the center, where it is the boundary of occupant activity.

(b) The increased concentration is less than three times of upper limit concentration (for Class 5), which meets the required ratio between dynamic and static statuses for unidirectional flow cleanroom (refer to Chap. 17).

3. Anti-disturbance of Door Opening

The distance between the door and the center of mainstream area is only 2.3 m, and it is only 1.1 m between the door and the boundary of mainstream
area. There are seven sampling positions in total, which is shown in Fig. 15.12. The period of opening door is more than 2 h.

Experimental results are plotted on Fig. 15.13. The conclusions can be reached from the above figures:

(a) The air cleanliness level outside of the door can be considered as Class 8.
(b) Particle concentration decreases from the outside of the door to the mainstream. The larger the air supplied velocity is, the faster the decline of velocity is.
(c) Particle concentration at the fourth sampling position, i.e., 800 mm from the door, reaches the level of Class 6. It is between 1.83 pc/L (with minimum air supplied velocity) and 0.35 pc/L (with maximum air supplied velocity) at the fifth sampling position, i.e., the boundary of the mainstream area. This means the ability to anti-disturbance of the mainstream area for the incoming flow from the door with concentrated air supply mode is extreme strong. In reality, door is open for temporary period, so the influence is much less.
15.6.4 Application of Air Supply Terminal of Leakage Prevention Layer

15.6.4.1 Application in Cleanroom with Local Unidirectional Flow Cleanroom

It is No.301 Hospital built in 1994 where air supply terminal of leakage prevention layer was first applied in cleanroom with local unidirectional flow. The difficulty of low story height was overcome. It provided the guarantee that the terminal is without a leak. During 8 years of operation, the effect is very good.

The official application of patented product starts in the cleanroom with Class 1 in Longyan No.1 Hospital in Fujian Province, which was built in 2002. It is shown in Fig. 15.14.

In “Building standard of hospital clean operating department” and “Building technical specification of hospital clean operating department,” it specified for the concentrated air supply area above the operating table in clean operating room with Class 1, where the local air supply area with Class 100 should be $2.6 \times 2.4 = 6.24 \text{ m}^2$. The area of room served should be no more than 1.2 times of that of large-scale cleanroom (45 $\text{m}^2$), which is 54 $\text{m}^2$.

According to the usually practical method, dozens blocks of perforated plates or decoration layers should be placed at the bottom of the plenum chamber. But when the air supply terminal of the leakage prevention layer, i.e., clean air supply ceiling with leakage prevention type, is used, only four blocks are needed, where a small square in the middle is prepared to be empty in advance which is equivalent with the size of the square externally connected with the rod of shadowless lamp. The bottom view of the air supply ceiling is shown in Fig. 15.15, where two tracks are used for guiding the transfusion.
According to standard, the projected area of the concentrated air supply ceiling is the area of operating table, and other area is the surrounding area. The air cleanliness levels which is specified in standard, measured in the field test in laboratory, measured in two clean operating rooms with Class 1 by the State Inspection Center of Construction Engineering are shown in Table 15.10, as well as the measured air cleanliness range with most common air supply methods.

**Fig. 15.15** Bottom view of clean air supply ceiling with leakage prevention type in cleanroom with Class 1 (with guide rail)

**Table 15.10** Basic performance of Class 1 type air supply ceiling with leakage prevention type

| Class I operating room | Air supply ceiling | Clean air supply ceiling with leakage prevention layer | In-field test with common air supply modes |
|------------------------|--------------------|-----------------------------------------------------|------------------------------------------|
| Basic property         | Air supply velocity (m/s) | Standard | Measured by experiment | In-field test | 1 | 2 | 35–0.4/0.5 |
|                        | Air velocity at the working area (m/s) | 0.25–0.3 | 0.30 | 0.30 | 0.32 | 0.25–0.3 |
|                        | Particle concentration in operating area (μm) | Max. | ≤3.5 | 0.06 | 0.05 | 0.05 | 0.35–2 |
|                        |                     | Min. | ≤3.5 | 0.07 | 0.05 | 0.05 | 0.35–2 |
|                        | ≥5 μm               | Max. | 0 | 0 | 0 | 0 |
|                        |                     | Min. | 0 | 0 | 0 | 0 |
|                        | ≥0.5 μm             | Max. | ≤35 | 0.59 | 0.8 | 0.2 | 3.5–35 |
|                        |                     | Min. | ≤35 | 0.27 | 0.5 | 0.2 | 3.5–35 |
|                        | ≥5 μm               | Max. | ≤0.3 | 0 | 0 | 0 | 0–1 |
|                        |                     | Min. | ≤0.3 | 0 | 0 | 0 | 0–1 |
| Self-cleaning time/min | <15 | 2 |
Fig. 15.16  Clean air supply ceiling with leakage prevention mode installed in blood ward with area 7 m². (a) Interior scene. (b) Ceiling consisting of four leakage prevention clean air supply models

15.6.4.2  Applied to the Whole Room Unidirectional Flow Cleanroom

When the area especially the width of cleanroom is not large, ceiling supply surface constituting of the plenum chamber with two leakage prevention layers can be used, where air is supplied into the plenum chamber from the side. At present, the maximum size of the plenum chamber with single leakage prevention chamber is 1.2 m × 1.3 m. It is not convenient to use larger product.

Figure 15.16 shows the photo of clean air supply ceiling with leakage prevention mode which was installed in three blood wards, each of which is 7 m², at Shenzhen Hospital of Peking University.

When the area of the cleanroom is large, two or more clean air supply ceilings with leakage prevention mode should be installed. And air should be supplied into the plenum chamber from the top. Since there is no ceiling frame, hoisting method can be adopted. The installation process of cleanroom with Class 100 for larger area can be simplified, so that good quality can be ensured.
15.6.4.3 Applied to Turbulent Flow Cleanroom

Dispersed Air Inlets

As shown in Fig. 15.8a, the leakage prevention layer is used to replace the dispersion plate on the common air inlet, or the area of the leakage prevention layer increases to two times of the original area of air inlet. For the latter situation, the effect of increasing the mainstream area is realized (refer to Chap. 14). Since the air supplied velocity is reduced and air filters can be uninstalled exterior of cleanroom (such as the technical layer), it is especially suitable for the application where low and uniform velocity is needed and cross infection is not allowed, such as sterile animal raising room. According to the operational result in animal raising room, the performance is very good. This method is also applicable for the clean operating room where indoor pollution should not be increased, as well as the blood ward.

Concentrated Air Inlets

Air inlets can also be allocated concentratedly in turbulent flow cleanroom, where the flow rate and number of air filter area unchanged. A larger mainstream area is thus formed. Since the air supply velocity is smaller than that of unidirectional flow, the property of quasi-unidirectional flow appears below the air inlet. Patented products were developed for clean operating room with Class II and III, including clean air supply ceiling with leakage prevention mode, which is shown in Figs. 15.17 and 15.18. For the former case, air is supplied with concentrated air inlets with air change rate corresponding to Class 10000 so that the air cleanliness level in operating area is Class 1000 while it is Class 10000 in surrounding area. For the latter case, air is supplied with concentrated air inlets with air change rate corresponding to Class 100000, so that the air cleanliness level in operating area is Class 10000, while it is Class 100000 in surrounding area. The actual performance is far better than these values, which is shown in Table 15.11.

15.6.5 Comparison of Several Air Supply Terminals

Comparisons of the air supply terminal with leakage prevention layer and common air supply terminals are shown in Table 15.12.

Appearance comparisons between the common air supply ceiling with perforated plate and without guide rail and the clean air supply ceiling with leakage prevention mode are shown in Figs. 15.19 and 15.20 shows the foreign air supply ceiling consisting of many blocks of screen or perforated plates[10].
Fig. 15.17  Upward view of clean air supply ceiling with leakage prevention mode used in clean operating room with Class II

Fig. 15.18  Upward view of clean air supply ceiling with leakage prevention mode used in clean operating room with Class III

Table 15.11  Basic performance of clean air supply ceiling with leakage prevention mode for Classes II and III

| Operating room | Air supply ceiling (3 rooms) | Clean air supply ceiling with leakage prevention mode |
|----------------|-----------------------------|-------------------------------------------------------|
| Basic          | Standard                    | Class II (3 rooms) Measured | Class III |
|                | ≥30                         | ≤36 | ≥20 | 25.7–26.6 |
|                | ≤43                         | ≤29 |
| Turbidity      |                             |     |
| Particle       | ≥0.5 µm                     | Max. | 0.1–0.5 | ≤350 | 2.5–4.9 |
| concentration  | Statistical                 | ≤35 | 0.2–0.6 | ≤350 | 2.9–5.5 |
| in operating   | ≥5 µm                       | Max. | 0 | ≤3 | 0 |
| area (pc/L)    | Statistical                 | ≤0.3 | 0 | ≤3 | 0 |
| Particle       | ≥0.5 µm                     | Max. | 0.9–1.6 | ≤3,500 | 4.9–7.9 |
| concentration  | Statistical                 | ≤350 | 0.6–1.3 | ≤3,500 | 4.8–7.8 |
| in surrounding | ≥5 µm                       | Max. | 0 | ≤30 | 0–0.5 |
| area (pc/L)    | Statistical                 | ≤3 | 0 | ≤30 | 0–1.2 |
Table 15.12  Comparison of several air supply terminals

| Item                        | Leaks prevention mode | Common nylon net | Common perforated plate |
|-----------------------------|-----------------------|------------------|-------------------------|
| Principle                   | The concept of leakage prevention layer is used | The traditional concept of air supplier with air filter is used |
| Property                    | Decoupling of three functions including filtration, flow equalization, and leakage stoppage | Integration of three functions including filtration, flow equalization, and leakage stoppage |
| Flow                        | Unidirectional flow with good uniformity of air velocities at the cross section. The streamlines are intensive and parallel. The anti-disturbance ability is good | The uniformity of streamlines is relative poor. Air is likely to disperse. The anti-disturbance ability is poor |
| Possibility of leakage      | No                    | Yes              | Yes                     |
| Air distribution ratio      | Extreme large         | Maybe large      | Small                   |
| Number of HEPA filters      | A few and the condition that the flow rate should be less than 80% of the nominal value is satisfied | Many for planar layout; a few for installation at two sides, but the condition that the flow rate should be less than 80% of the nominal value is not easily satisfied | Many for planar layout; a few for installation at two sides, but the condition that the flow rate should be less than 80% of the nominal value is not easily satisfied |
| Turbidity                   | Relative small        | Higher           | The highest             |
| Reverse ash blowing         | Yes                   | It is possible when air filter is placed with planar allocation; it is impossible when air filter is placed with side allocation | It is possible when air filter is placed with planar allocation; it is impossible when air filter is placed with side allocation |
| Installation                | Easy and can be installed in site | Difficult and part is manufactured in site, which causes large error | Difficult and part is manufactured in site, which causes large error |
| Appearance                  | Consistence in module and specification | The randomness degree is large, which depends on the workers’ skill | The randomness degree is large, which depends on the workers’ skill |
| Leakage detection and stoppage | No                    | Yes              | Yes                     |
| Maintenance indoors         | No                    | Needed           | Needed                  |
| Life time                   | Semi-eternal          | Relative long    | Frequent cleaning is needed, and corrosion may occur |
Fig. 15.19 Comparison of appearance for air supply ceiling. (a) Leakage prevention mode (consisting of four blocks). (b) Common perforated plates (consisting of 15 blocks).

Fig. 15.20 Common air supply ceiling in clean operating room in Japan
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