Chapter 17
Measurement and Evaluation

Under the guidance of the sampling theory, correct sampling procedures are taken, after which measurement can be performed with a variety of methods to determine the particle size, number, and distribution. After scientific evaluation is made on the measurement results, the correct conclusion can be finalized. This chapter will focus on the introduction of the principle of measurement and evaluation for particle concentration, filter, and cleanroom.

17.1 Particle Concentration Measurement

17.1.1 Particle Mass Concentration Method

Particle mass concentration method is the most basic method for determination of particle concentration. There are many kinds, and one of the precise methods is the filter paper weight concentration method, which will be mainly introduced here.

The basic principle of the filter paper weight concentration method is that airborne particles will be effectively captured on the filter media when the air with known volume passes through the filter media, and then the increase of weight on the filter media is weighted with the balance. The particle mass concentration in the sampled air is

\[ C = 1,000 \times \frac{\Delta G}{q t} \]  (17.1)

where

- \( C \) is the weight concentration (mg/m\(^3\));
- \( \Delta G \) is increase of filter media weight, namely, the difference of filter media weight before and after the balance weighting process (mg);
The sampling rate \( q \) (L/min); the sampling time \( t \) (min).

The most frequently used material of the measurement is the glass fibrous paper, because of its high efficiency.

When the glass fibrous paper is used as the filter media, there is a problem that humidity affects the weight of the filter. There are two aspects if the influence is considered:

1. The relative humidity is different between weighing location and measurement location.

   Experiment performed at Institute of HVAC of China Academy of Building Research shows that in the actual operation, it takes more than 1–2 min for the adjustment of the balance for weighting the filter paper. During the period, equilibrium is reached quickly between the filter paper and the air within the balance chamber through direct contact and humidity exchange. In the weighting place, the influence of the moisture absorption and release remained is extremely small, which is within the fluctuation range of the balance. As long as enough time is provided for the equilibrium of the moisture, the influence of humidity can be ignored.

2. The change of relative humidity in weighing location.

   Sometimes due to various reasons, the filter paper cannot immediately be weighed after sampling. During this period, the relative humidity within the balance chamber may change significantly, and the papers will absorb or release moisture, so the final weight measured does not reflect its true value. Experiment performed at Institute of HVAC of China Academy of Building Research showed that when the air relative humidity within the balance chamber changes from 65 to 70 %, the weight changes caused by moisture absorption were 0.074 and 0.02 mg for glass fiber filter paper and synthetic fiber filter paper with diameter of 60 mm and average weight of 180 mg, respectively. If the increase of the filter paper weight in the general environment is 0.25 mg, the error caused by absorption of moisture will be 30 % and 80 %, respectively. The experimental result curve is shown in Fig. 17.1. When the relative humidity within the balance chamber changes, it is necessary to make correction for the moisture absorption quantity on filter media. According to Fig. 17.1, the moisture absorption quantity on filter paper can be calculated as follows:

\[
G_p = G_1 (\varepsilon_2 - \varepsilon_1) \tag{17.2}
\]

where

\( G_p \) is the moisture absorption quantity on filter paper (mg); \( G_1 \) is initial weight of filter paper (mg); \( \varepsilon_1 \) and \( \varepsilon_2 \) are the moisture absorption quantity on filter paper per unit weight before and after and before weighting (mg/mg).
During the application of Eq. (17.2) to calculate the mass concentration, the moisture adsorption quantity $G_p$ should be subtracted from the weight gain of the filter paper.

If the weighing process cannot be carried out in one place before and after particles are captured on the filter paper or if the relative humidity is not easy to determine, double sampling filter media method can be used in order to eliminate the influence of humidity. Because the weight efficiency of the first filter paper (top one) is 100%, the increase of the weight on the second filter paper because of the dust collection should be zero in fact. If there is the moisture absorbing effect, the weight of the second filter paper should be varied before and after sampling. So the real weight gain of the filter media $\Delta G$ in Eq. (17.1) can be calculated with the following formula:

$$\Delta G = \frac{G_1}{C_0} G_01 - \frac{G_2}{C_0} G_02$$

where

$G_1$ is the weight of the top filter media after sampling;
$G_{01}$ is the weight of the top filter media before sampling;
$G_2$ is the weight of the bottom filter media before sampling;
$G_{02}$ is the weight of the bottom filter media before sampling.

Calculation can be made according to Eq. (17.1) without correction of the relative humidity.

As for the detachment of fibers on the filter media under high sampling air velocity, it can be completely ignored according to experiment.
17.1.2 Particle Counting Method with Membrane Microscope

17.1.2.1 Principle

With the development of air cleaning engineering, it cannot meet the requirement with the weight concentration to describe the particle concentration. So the particle counting methods with both the chemical membrane microscope and the light scattering particle counter are widely used in the determination of particle concentration in clean environment. In the standards about cleanroom in some foreign countries, the particle counting method with membrane microscope was used as standard method for the determination of 5 μm particles. Before the development of photoelectric technique to measure particles, membrane counting method was once even used for measurement of particles with diameter ≥ 0.6 μm. Even today, it is still an available method for measurement under certain condition, because particles can be directly observed (size, shape, and color) with the membrane counting method, so in the certain condition.

To capture common aerosol particles, membrane with diameter 0.3–0.8 μm should be chosen, whose collecting efficiency is very high. Its efficiency is higher than the single-layer glass fiber paper by 2–3 orders of magnitude, but the resistance of membrane is also higher than that of the ordinary glass fiber filter paper by dozens of times.

In China, it was Research Institute of Mining and Metallurgy at China Academy of Science that firstly used the membrane technology in sampling of mine dust. Later Institute of HVAC of China Academy of Building Research studied the application of the membrane technology on the particle counting method of dust in air cleaning technology and developed the corresponding membrane. This particle counting method will be outlined as follows.

The principle to measure the particle counting concentration with membrane is that after the particles are trapped on the membrane surface, since membrane can be treated to be transparent under a microscope, particles are then observed and counted. Since membrane pores are filled with air, a number of optical boundaries are formed, which destroy the forward direction of light; membrane becomes opaque. In order to make the membrane transparent, the optical interface must be wiped out, which can be processed with the oil dripping method and the acetone steam fumigation method.

Oil Dripping Method

Oil with the same refraction rate as the membrane itself is dipped onto the membrane. Then oil will penetrate into the membrane, driving away the air in the micropore, so that the membrane becomes an optically homogeneous whole body and transparent. This method is suitable for observing particles with diameter more than 5 μm.
Acetone Steam Fumigation Method

After acetone vapor immerses the membrane, the membrane becomes slightly soluble to expand and then contract, eliminating the air in the micropores, which makes the membrane transparent. This method makes the transparent performance of membrane good. But when the temperature and the volume of acetone vapor are not enough, the membrane edge is prone to curl. When the temperature and the volume are too much, the membrane will be dissolved too much, which affects the measured particle distribution on it. The method is also suitable for detecting small particles.

Specific fumigation device is shown in Fig. 17.2. The membrane is placed on a clean glass cover slip with the sampling face upward. It is fumigated in the beaker filled with 50 °C acetone vapor. (For the beaker with volume 600 mL, about 15 mL acetone is added. After operated with three samples, 5 mL acetone is added again.) Take the membrane out when it is transparent. Then fasten the cover slip onto the object slide in reverse (aluminum foil ring or a paper ring is used to separate the cover slip from the slide). Then, the cover slip is sealed around with glue or wax.

17.1.2.2 Particle Counting Method

Fix the prepared specimen slice on the proper position of the worktable of microscope. If particles with diameter above 5 μm are counted, the microscope with 100 times magnification ratio is used. If particles with diameter above 0.5 μm are counted, the microscope with high magnification ratio must be used, which is generally 1,500 times (100 times of immersion objective lens and 15 times for the eyepiece).
During the counting process, the micrometer is adjusted vertical to the moving direction on the worktable of the microscope. When the worktable is moving slowly, specimens on the table will also move accordingly. In the microscopic field, we can see that particles continuously go through the micrometer. Particle sizes can be readout from the micrometer (see Fig. 1.2 in Chap. 1). Manual counter is used, and counting is performed according to the channel range.

Particle counting size can generally be classified as $<0.5 \ \mu m$, $0.5$ to $<1.0 \ \mu m$, $1.0$ to $<2.0 \ \mu m$, $2.0$ to $5.0 \ \mu m$, and $\geq 5.0 \ \mu m$.

The total counting area is about $0.02 \times (2–4) \ mm^2$ on one specimen. Larger value is used when counting big particles, and smaller value is adopted when counting small particles.

In order to avoid too much focus of the counting areas, it should randomly measure with several segments that are not on the same straight line in a specimen. Edges of each segment should not stay too close to the edge of the specimen (Fig. 17.3). The readings on the micrometer on the worktable should be recorded when counting, which prevents the generation of error.

When immersion objective lens with 100 times of magnification ratio is used, big and small particles cannot be seen on the membrane simultaneously because of the small focus depth. So the focal distance needs to be continuously adjusted within a certain range. When the membrane sampling method is used and the sampling flow rate, the sampling time, and the membrane filtration area are known, the particle density on the membrane surface can be calculated, which can be used to obtain the particle concentration. But there is a problem which needs to be noticed; the effects of the background value should be considered. Because particles exist in the solution which is used for the manufacturing of the membrane, the prepared membranes also contain dust. This is called “the background density of membrane.” Before measurement, we must determine the background density for the same group of produced membrane. In this way, the true sampling density can be obtained.

So, the particle counting concentration can be calculated by the following equation:

$$N = \left( \frac{c_1}{f_1} - c_0 \right) \frac{f_0}{q t} \left( \# / L \right)$$

(17.4)

where

- $c_0$ is the background density of membrane ($\#/mm^2$);
- $c_1$ is the total number after sampling ($\#/mm^2$);
\[ f_0 \] is the effective filter area (mm\(^2\));
\[ f_1 \] is the total area for counting after sampling (mm\(^2\));
\[ q \] is the sampling rate (L/min);
\[ t \] is the sampling time (min).

### 17.1.2.3 Applicable Condition

If the background density of the membrane is very big, in addition to the collected particles when counting after sampling, it also has the possibility to measure the intrinsic particles. The possibility is big if the background number is big. According to the result at Institute of HVAC of China Academy of Building Research, when the ratio between the counting density and the background density reaches above 4 times, the influence of the background density on the counting results is stabilized. In other words, the counting result is no longer different too much with different values of background densities.

For membranes manufactured in the general environment, the background density is often greater than 1,000#/mm\(^2\). They can only be used in the environment where the airborne concentrations are greater than 1,000#/L. If the sampling rate is 15 L/min, the sampling time needed is generally only 2 h (suppose the filter sampling area is 490 mm\(^2\)). For membranes manufactured in the clean environment, the background density is still greater than 10#/mm\(^2\). It should not be used in the environment where the airborne particle concentration is less than 10#/L. Otherwise the sampling time needed is more than 2 h. When it is used for the measurement of cleanroom with air cleanliness Class 100, half a day or even a day is needed, which is inconvenient.

By the counting method with membrane microscope, direct counting can be performed, and the properties of color, luster, and shape can be observed under the microscope, which can be used to identify if it contains metal fragments, fibers, or other impurities. When the airborne particle concentration is detected to be high suddenly with other fast dust detector, the microscopic counting method can also be used to observe the property of particles. It helps to determine whether the increase of dust particle is normal or abnormal, which can be used for further location of new dust source.

### 17.1.3 Particle Counting Method with Light Scattering Particle Counter

#### 17.1.3.1 Principle

Both the filter paper weight method and the microscopic counting method are the method with particle capture, namely, airborne particles are captured with other measures, then the concentration is determined later. The instantaneous distribution
(or in a very short interval) of airborne particles cannot be understood. The method to measure the particle concentration when particles are still kept airborne is called the airborne measurement method. Light scattering particle counter is used for counting with this method.

The light scattering phenomenon appears when airborne particles are exposed in the light irradiation. It is related to the particle size, wavelength, particle refractive index, light absorption characteristics, and so on. But a basic law exists between the scattering light intensity and the particle size. The intensity of particle scattering light is proportional to the surface area of particles. Especially for 0.3–1.0 μm particles, this relationship is more obvious. Although this relationship to describe particles with diameter larger than 1 μm is relative poor, the difference between the nominal size measured with the above proportional relationship and the actual size is acceptable in practice, when the size of the instrument channel between 1.0 and 10 μm is relative coarse so that the deviation between the nominal size in the channel and the actual size in the channel is not small. By measuring the intensity of scattering light, the particle size can be obtained, which is the principle of light scattering particle counter. With the photoelectricity multiplier, the pulse by light scattering of particles is linearly transformed to the pulse signal with corresponding amplitude. Some electronic circuits are used to complete the counting of the electric pulse. Since a certain relationship exists between the scattering intensity and the particle size, photoelectricity multiplier has a linear relationship of conversion, the amplitude of various electrical pulses corresponds to different particle size, and the number of pulses corresponds to the particle number.

The relationship between the particle size and the output signal is [1]

\[ d_p^n = ku \]  
(17.5)

where

d_p is the particle diameter;
k is the conversion coefficient;
u is the signal level (mV);
n is the coefficient dependent on the instrument structure, which is between 1.8 and 2 (the experimental value in Ref. [1] was 1.8).

The above formula can be converted to be:

\[ n \lg d_p = \lg u + \lg k \]  
(17.6)

It is apparent that a linear relationship exists between \( d_p \) and \( u \) in log-log paper. With the influence of the sensitivity performance of instrument, the calibration curve and the theoretical curve will be crossed, as shown in Fig. 17.4 [2].

This figure shows that if 0.60–0.69 μm standard particles are chosen to inspect the instrument sensitivity (the stipple line in the figure), 0.5 μm particles may be mistaken as 0.4 μm particles without recording by particle counter, so the output
signal amplitude < 60 mV. On the contrary, if 0.40–0.49 μm standard particles are chosen for instrument calibration, 0.4 μm particles may be mistaken as 0.5 μm particles with recording by particle counter, which will cause error.

The specific working principle of the instrument is that the light from a light source is focused on measuring region by a group of lens; when every particle in the sampled airflow quickly passes through the region, the incident light scatters for once time, which forms a light pulse signal. This signal is sent to the negative pole of the photoelectricity multiplier by a group of lens (Fig. 17.5), where it is converted into electric pulse signal proportionally. After amplification and screening, signals required are sorted and then displayed by the counting system. The amplitude of electric pulse signal reflects the particle size, and the number of signals reflects the particle number, as shown in Fig. 17.6.

Various disturbance signals (the so-called noise signal) are generated with the common light source as the incident light of the particle counter itself, which affects the sensitivity of the instrument. The amplitude of signals generated by this kind of instrument with 0.3 μm particles is not much different from that of noise. It is hard to detect it from the noise. For example, the noise level is generally 20 mV, and the output signal under the sensitivity state for 0.5 μm particles is 0 mV, and that for 0.3 μm particles is 23 mV, which is very close to the noise level. So for the particle
counter with common light source as incident light (that is the so-called incandescent lamp light source particle counter), the sensitivity for particles with diameter less than 0.3 μm is very low, or the sampling efficiency is very low, which is from 10 % to 40–50 %. So although the channel with 0.3 μm is labeled, it is only suitable for detection of particles with diameter above 0.3 μm especially above 0.5 μm. In some product instructions manual, this is not mentioned, and sometimes it is noted that it is able to measure 0.3 μm particles, which is not appropriate.

17.1.3.2 Nominal Diameter and Diameter Channel

The particle size shown in the particle counter during the counting process is called the nominal size. This is just a representative of a certain particle size range. As for the actual particle size it represents, it is relevant with the standard particle size used during calibration. Table 17.1 is the first particle counter J-73 type developed by Institute of HVAC of China Academy of Building Research China. Taking the particle size range with 0.5 μm particles as the standard particles for calibration as an example [1], generally speaking, there are less particle size channels for simple instrument, which are often 5 channels, namely, 0.3, 0.5, 1, 2, and 5 (μm).
size channels are more for some precision instrument, which are often for 15 channels, namely, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0, 1.2, 1.5, 2, 3, 4, 5, 6, 8, and 10 (μm).

After the appearance of laser particle counter, smaller particle size can be measured, thus the particle size channels are finer and more. Table 17.2 is the particle size channels for Royco LAS-226 laser particle counter; there are 16 channels for particle size 0.1–6.1 μm. Later, there are also 16 channels for 236 type.

There are two specifications for another PMS LAS-x laser particle counter. One has 16 channels, and the other one has more and finer channels. There are 4 grades with 15 channels, which are equally divided into 60 channels. It is shown in Table 17.3.

### 17.1.3.3 Errors of Measurement

**Overlapping Error**

For the particle counter with the application of photoelectricity theory, the main error is the overlapping error caused by application of this theory. That means when there are 2 or more than 2 particles entering into the measuring space simultaneously (Fig. 17.5) – scattering cavity – only one enlarged signal is output from the instrument. This is the result of particles overlapping. At this time, the particle concentration indicated by the particle counter is less than the actual value.

According to Chap. 1, the density function of the situations when 1, 2, ..., \( n \) particles appear in the detection space (i.e., the air column irradiated by the light beam) of the instrument follows the Poisson distribution in general. When particles

### Table 17.1 Particle size range of J-73 type particle counter (μm)

| Channel | 0.3 | 0.4 | 0.5 | 0.6 | 0.8 | 1.0 | 1.2 |
|---------|-----|-----|-----|-----|-----|-----|-----|
| Particle size range | 0.3526–0.4261 | 0.4261–0.5000 | 0.5000–0.6067 | 0.6067–0.7349 | 0.7349–0.8918 | 0.8918–1.067 | 1.067 |

### Table 17.2 Particle size channels of LAS-226 type particle counter

| Channel | 1 | 2 | 3 | 4 | 5 | 6 |
|---------|---|---|---|---|---|---|
| Particle size (μm) | 0.12 | 0.17 | 0.27 | 0.42 | 0.62 | 0.87 |
| Range (μm) | 0.12–0.17 | 0.17–0.27 | 0.27–0.42 | 0.42–0.62 | 0.62–0.87 | 0.87–1.17 |

| Channel | 7 | 8 | 9 | 10 | 11 | 12 |
|---------|---|---|---|----|----|----|
| Particle size (μm) | 1.17 | 1.52 | 1.92 | 2.37 | 2.87 | 3.42 |
| Range (μm) | 1.17–1.52 | 1.52–1.92 | 1.92–2.37 | 2.37–2.87 | 2.87–3.42 | 3.42–4.02 |

| Channel | 13 | 14 | 15 | 16 |
|---------|----|----|----|----|
| Particle size (μm) | 4.02 | 4.67 | 5.37 | 6.12 |
| Range (μm) | 4.02–4.67 | 4.67–5.37 | 5.37–6.12 | Above 6.12 |
overlap, no matter how many they are, they are only counted as 1 particle. So the total number in the detection space with overlapping, i.e., the counting concentration in the detection space, can be calculated with Eq. (1.16), so it should be

\[
C = 1 \times P(1) + 1 \times P(2) + \cdots = 1 \times P(\zeta \geq 1) = 1 \times \{1 - P(\zeta = 0)\}
\]

\[
= 1 - e^{-\lambda} = 1 - e^{-\lambda V N}
\]

\[
\lambda = VN
\]

where

\(P(1)\) is the probability of the occurrence of 1 particle, and it is analogous for others; 
\(\lambda\) is the average particle number in the detection space of the instrument for a long term, i.e., the mathematical expectation value; 
\(N\) is the particle concentration of the airflow through the detection chamber (#/cm\(^3\)); 
\(V\) is the volume of the detection chamber.

For incandescent light particle counter such as Royco 202, we can obtain:

\[
V = \frac{\pi(0.1585)^2}{4} \times 0.1 = 0.00197 \text{ cm}^3
\]

For laser particle counter such as LAS-x, we can obtain:

\[
V = \frac{\pi(0.025)^2}{4} \times 0.02 = 0.00000982 \text{ cm}^3
\]

| Table 17.3 | Particle size channels of LAS-x type particle counter |
|-------------|------------------------------------------------------|
| The first type | Channel | 1 | 2 | 3 | 4 | 5 | 6 |
| Particle size (\(\mu m\)) | 0.09 | 0.11 | 0.15 | 0.20 | 0.25 | 0.30 |
| Range (\(\mu m\)) | 0.09–0.11 | 0.11–0.15 | 0.15–0.20 | 0.20–0.25 | 0.25–0.30 | 0.30–0.40 |
| Channel | 7 | 8 | 9 | 10 | 11 | 12 |
| Particle size (\(\mu m\)) | 0.40 | 0.50 | 0.65 | 0.80 | 1.00 | 1.25 |
| Range (\(\mu m\)) | 0.40–0.50 | 0.50–0.65 | 0.65–0.80 | 0.80–1.00 | 1.00–1.25 | 1.25–1.50 |
| Channel | 13 | 14 | 15 | 16 |
| Particle size (\(\mu m\)) | 1.50 | 2.00 | 2.50 | 3.00 |
| Range (\(\mu m\)) | 1.50–2.00 | 2.00–2.50 | 2.50–3.00 | Above 3.00 |

The second type

| Channel | 1 | 2 | 3 | 4 |
| Range (\(\mu m\)) | 0.09–0.195 | 0.15–0.30 | 0.24–0.84 | 0.60–3.00 |
| Interval (\(\mu m\)) | 0.007 | 0.01 | 0.04 | 0.16 |
| Channel No. | 15 | 15 | 15 | 15 |
The proportion of the particle number after and before overlapping is:

\[
\frac{1 - e^{-VN}}{VN}
\]  

(17.9)

Since non-overlapping particles are already contained in \(1 - e^{-VN}\) and \(1 - e^{-VN}\) is always less than \(VN\), the ratio cannot be considered as the overlapping rate. Overlap rate can be 1, i.e., 100 %, which means all each measured particle is from the overlapping particles. For example, if each two particles overlap among the original 100 particles, the total number becomes 50, which can be thought that the overlapping rate for this group of particles reaches 100 % instead of 50 % (namely, half overlap).

If the particle loss rate after overlapping is \(\beta\), we can obtain:

\[
\beta = 1 - \frac{1 - e^{-VN}}{VN}
\]  

(17.10)

When the specific values of \(V\) are inserted into the above formula and set \(N = 100,000#/L\), the overlapping loss rate of particles for Royco 202 is 0.092, and that of LAS-x is 0.0005. The difference between them is large. The reason is that the incandescent light particle counter is suitable for testing low concentration because of its large test chamber, while laser particle counter is aimed to measure high concentration because of the small test chamber in order to make the laser beam finer. Therefore, the incandescent light particle counter manufacturers claim that in order to reduce the overlapping error, the maximum allowable detection concentration is 100,000#/L or 35,000#/L (the error \(\beta\) will be under 3.5 %). For laser particle counter, the maximum allowable concentration is 17,000#/cm³ (such as the error for LAS-x is \(\beta = 8 \%\); it is indicated in product manuals from PMS company that in this condition, the overlapping error is under 10 %) or 5,000#/cm³ (now \(\beta < 2.5 \%\)).

Space-Time Error

Besides the overlapping error, there is a space-time error. For a particle counter, its response time from the output of electric pulse signal is certain. So the particle counter can only record these particles which pass through the scattering cavity with the time interval greater than the response time. But those particles with time interval less than the response time will not be recorded, which produces the error (set it \(\delta\)).

Space-time error is derived as follows [3]:

\[
\delta = 1 - e^{\frac{-e^{-VN}}{q}}Nq\sigma_r
\]  

(17.11)

where \(q\) is the sampling flow rate. For Royco 202 it is 5 cm³/s. For LAS-x it is 1 cm³/s;
$\Delta t$ is the response time of the instrument(s). Reference [3] gave a complicated calculation method, but in general, it is in the range of 0.00001–0.000015.

Then, we can get:

\[
\begin{align*}
\text{Royco 202} & \quad \delta = 0.0005 \\
\text{LAS-x} & \quad \delta = 0.005
\end{align*}
\]

Since the space-time error is very small, which can be ignored, the detailed derivation process will not be introduced here.

Comprehensive Error [4]

If the error caused by the variation of the air change rate and the particle concentration is not considered, and the error caused by the particle counter’s photoelectricity parameters is neither taken into consideration, while only the sampling error is considered, according to the error theory, this comprehensive error $\sigma$ can be expressed as

\[
\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2 + \sigma_5^2 + \sigma_6^2}
\]

(17.12)

where

- $\sigma_1$ is the error caused by the sampling flow rate of the particle counter, which is about $\pm 3\%$;
- $\sigma_2$ is the error caused by the non-isokinematic sampling, which is about $-5\%$ (the maximum allowable value);
- $\sigma_3$ is the error caused by settlement in the sampling tube, which is about $-2\%$ (the maximum probable value);
- $\sigma_4$ is the error caused by collision and coagulation in the sampling tube, which is about $-1\%$ (the maximum probable value);
- $\sigma_5$ is the error caused by the overlapping in the particle counter (for incandescence particle counter, it is $-3.5\%$ when the concentration $\geq 35,000#$/#/L, and it is $-9.2\%$ when the concentration $\geq 100,000#$/#/L; for laser particle counter, it is $-0.05\%$ when the concentration $\geq 100#$/#/cm$^3$, it is $-2.5\%$ when the concentration $\geq 5,000#$/#/cm$^3$, and it is $-8\%$ when the concentration $\geq 17,000#$/#/cm$^3$);
- $\sigma_6$ is the error caused by the space-time interval in the particle counter (for incandescence particle counter, it is $-0.05\%$; for laser particle counter, it is $-0.5\%$).

Then, we can get the possible errors of the particle counter during every sampling process, which is listed in Table 17.4. From the table, when this maximum detection concentration 35,000#/L is taken as the basis, the maximum sampling error of the incandescence particle counter is 7.2%, while that of the laser particle counter is 10.2%.
The above result is consistent with the conclusion in the national standard draft explanation of *Inspection Method of Particle Concentration Measurement Performance of Particle Counter*. In the conclusion, the error of the particle counter is between 7 and 10% when both the sampling efficiency and the leakage flow rate of the instrument itself are considered.

It should be pointed out for the measurement error between two instruments. In some current research reports where results were obtained with two particle counters (the flow rate may be different), the calibration results of concentration between them is not given, and maybe the calibration process was not carried out. It seems to ignore the difference of the results between two instruments, which is unfair.

One example is the measurement of the cleanroom with 0.5 μm particles published by foreign countries [5]. With the first instrument, all the particle numbers among 15 sampling positions for particles larger than 0.5 μm are 0, through which the air cleanliness level reached Class 1 for 0.5 μm particles, but with the second instrument, the data among 15 sampling positions are between 0.1 and 2.6#/ft³, through which the air cleanliness level belonged to Class 10. So the minimum difference is above 300%. So the president of IES-RP-50, who was responsible for the revision committee of 209B in the USA, pointed out that “... the accuracy of the test method is very low. For the particle counters produced by different manufacturers, or even different particle counters produced by the same manufacture, the allowable error is 10–20%.” Author’s test experience also shows that it is not rare that the difference between measurement results is more than one time when particle counters produced by different manufactures are used. So when the measurement data are treated, the error of this aspect must be considered.

### 17.1.3.4 Measurement Methods

The measurement methods of the particle counter can be divided into single recording and total recording. The former only measures the number of particles in one particle size channel. The latter can determine the total number of the particles that is above one particle size channel.
The shifting ways can be divided into manual and automatic. For the automatic way, the sampling time is recorded automatically every time, which is specified alone for each instrument. For example, there are 20, 60, 120, 180, and 300 s. For the manual way, the sampling time is decided by the operator.

The sampling flow rate of particle counter first produced at home and abroad is usually 0.3 L/min, which is called small flow particle counter. Because of the small sampling flow rate, relative large effort will be caused during the measurement of the environment with very low particle concentration. And later the large flow particle counter came to the market in the USA (such as Royco 245 type). The sampling flow rate can reach 28.3 L/min (1 ft³/L) and even bigger. This provides the convenience to measure the environment with low particle concentration. The relationship between the air cleanliness of the environment and the sampling flow rate will be discussed in detail later.

**17.1.3.5 Dilution**

When the overlapping error is required to less than 5 %, the dilution system is needed for the sampled air when the concentration for the incandescent light particle counter is more than 50,000#/L and when the sample concentration for laser particle counter is more than 10,000#/cm³.

Dilution system has two kinds of forms:

1. Only with the flow mixer where the clean air and the sampled air are mixed, which is shown in Fig. 17.7 [6]. High-concentration DOP aerosol is sampled directly from the pipeline, which is powered by the positive pressure in the pipeline. When the pressure is insufficient, specialized exhaust fan should be supplemented so that the sampled air will not enter the mixer.
2. With the mixer and a buffer bottle, which is shown in Fig. 17.8 [7]. For example, this kind of system is used when the particle counter is calibrated with the standard particles. Positive pressure exists in both the standard particle flow and the clean airflow. They enter the mixer and then the buffer bottle so that the total flow rate is bigger than the sampling flow rate of the particle counter. A part of the excessive mixed airflow will spill over from the buffer bottle. The mixture performance of this system is better.

In addition to the dilution system, the dilution device of the particle counter itself can also be used, which is also produced in China. With the dilution system, the measured concentration should be multiplied with the dilution ratio. When the error of the dilution system is also considered, the actual concentration can be obtained. The dilution ratio for common instrument is 10 times, and some also has 100 times. But the small dilution ratio should be used.

17.1.3.6 Modulation of Light Source [2]

The main light sources of particle counter include the incandescent light bulb, the halogen lamp, and the laser source. After the light is emitted from the light source, it should focus as much as possible in the detection chamber of the scattering cavity through the optics system. But because of the error of the installation location for the light source and because the filament in some incandescent bulb are not winded homogeneously and concentrated consistently, the sensitivity of the instrument will be affected, which represents the measured aerosol concentration and the particle size distribution.
The method to judge whether the light source has been well adjusted is as follows:

1. After the light passes through the lens of the optical system, it will focus on the slit. The smaller the focus area is, the more concentrated the light is.
2. The light focusing area should face directly against the slit and cover it evenly.

A method to adjust is as follows:

1. Loose-related screws connected with the lamp bulb. Move the bulb forward and backwards. The optimal state is obtained when the light focus on the slit.
2. Then adjust the lamp position up and down. Observe the change of the counting by particle counter with standard aerosol. This is used to determine whether adjustment is fine.

17.1.3.7 Calibration

Particle counter can directly determine the particle size and number, but the values of both the size and the number are also converted from other signal, which is still not an absolute value. If the instrument sensitivity was not set properly, it will directly affect the true extent of measurement results. Therefore, the sensitivity of instrument needs correction, which is called calibration. Particle counter calibration should include two aspects: one is the calibration of particle size, and the other is the calibration of particle number or concentration.

Calibration of Particle Size

During the calibration process of particle size for particle counter, the “equivalent diameter” mentioned in Chap. 1 is used for comparison. Namely, when the scattering light intensity of the measured particles is the same as that of the standard particles, the size of the standard particles is treated as that of the measured particles. The closer the properties between the selected standard particles and the measured particles are, the larger the reliability of this “equivalent” is. At present polystyrene sphere latex (PSL) particles are chosen as the standard particles at home and abroad, whose physical properties are close to the atmospheric dust. The density of PSL is 1.059 g/cm³, and the refractive index is 1.595 (at 20 °C). PSL particles are generated by polymerization of emulsion with polyethylene monomer. After dilution, spray and dry, monodisperse aerosol is generated, which is called PSL. Figure 17.9 is an electron microscopic photo of PSL standard particles developed by Wu Zhiyu et al. in China. Figure 17.10 shows the particle size distribution. It is clear that 70–95 % of particles focus on a certain size range, which means the monodispersivity performance is very good [8].

Usually PSL particles are stored in a cool place, which takes more than one year. During calibration operation, polystyrene latex is diluted with the secondary distilled
water or the further filtered water with 0.3 μm microporous membrane. The concentration of dilution liquid is shown in Table 17.5 [9]. The diluted solution is sprayed and then introduced to the instrument. The spray process is shown in Fig. 17.11.

During the calibration of particle size for particle counter, when standard particles with known size are introduced into the particle counter, it will test
whether all the records of the instrument are in the known particle size range. For example, when the average particle size of standard particles is 0.555 μm and the standard deviation of size distribution is 0.0186, more than 95% of particles are within the diameter range of 0.52–0.59 μm, which means the concentration degree is very high. Therefore, when these standard particles are used for instrument calibration, most of the measurement results data shall be recorded in the range 0.5–0.6 μm, which should have a prominent peak as shown in Fig. 17.12. But with the influence of factors such as the instrument and the aerosol generation condition, in some test results, there may be the particle size distribution with larger standard deviation than that of the standard particles themselves, and the peak value is much lower [2]. How big the peak value of the particle number frequency should be at least? According to the calibration work experience, it is equivalent with the conclusion by analysis of concentration. For a particle counter with 15 size channels, it should not be lower than 60% during single recording process, namely, that the number of measured particles in the certain calibrated size channel range shall be not less than 60% of the total number. If the calibrated peak value is lower than this standard value, or even abnormal distribution appears, the following reasons should be considered and then eliminated.

| Diameter of PSL particles (μm) | Mass concentration (%) |
|--------------------------------|------------------------|
| 0.5                            | 0.001                  |
| 1                              | 0.005                  |
| 2                              | 0.1                    |

Fig. 17.11 Schematic diagram of particle generation process.  
1 sprayer, 2 rotary drier, 3 flowmeter, 4 pressure gauge, 5 adjustment valve, 6 inlet of pressurized air, 7 outlet of aerosol.
The pressure in the photoelectricity multiplier tube is high, which is not normal. This should be checked at first. If it is sure that the high pressure is not normal, the adjusting knob can be used to raise or lower the conversion sensitivity of the instrument. When the conversion sensitivity is adjusted appropriately, a prominent peak will appear in a predetermined size channel.

As for the light source problem, if the filament fails to align with the slit of the optics system when the lamp bulb is replaced, it should correct after discovery.

As for the problem of standard particle generation, we should consider whether the concentration of dilution liquid with PSL particles is appropriate, whether the flow rate of mixed air and its dry condition are enough, whether the spray pressure is appropriate, and whether the dilution solution needs to be cleaned. For this last point, pure distilled water can be used for check.

As for the problem of the counting component, when the above problems do not exist, the counting parts should be checked to find out if there are errors.

If all the problems above are not present, it is likely that the instrument itself has problem.

Calibration work of particle size should be carried out regularly. When particle counter is used to measure the concentration of some particles forever and when the refractive index between the measured particle and the standard particle is different a lot, correction with electron microscopy should be performed in advance. Figure 17.13 shows one corrected case [10].

Concentration Calibration

In order to know whether the measured particle counting concentration of particle counter is correct, it needs to calibrate the concentration of the instrument. Although there is standard about this aspect in China, this job has not been carried out yet.
Among the calibration methods of concentration in foreign reports, vibration aperture method is one matured method [8]. In Fig. 17.14, aerosol jet flow is released from the orifice of the generator. Synchronous vibration occurs on the generator with the vibration effect of piezoelectric ceramic. The jet column is then fractured into small droplets, which mix with the air from the perforated plate after air passes through HEPA filter. The volume of each fractured droplet is:

$$V = \frac{Q}{f} = \frac{1}{6} \pi D_d^3 \quad (17.13)$$

So the particle size is

$$D_d = \left(\frac{6Q}{\pi f}\right)^{1/3} \quad (17.14)$$

where

$Q$ is the liquid flow rate through the aperture (mL/s);  
$f$ is the perturbation frequency (s$^{-1}$).

The calculated droplet radius is slightly larger than the jet diameter. If it is a nonvolatile solute (such as sodium chloride) in the volatile solvent (such as ethanol), the solvent in the liquid drop becomes volatile after passing through the vibration aperture, then aerosol are generated with the nonvolatile solute. The particle size is determined by the following formula:

$$D_d = \left(\frac{6QC}{\pi f}\right)^{1/3} \quad (17.15)$$

where $C$ is the volumetric concentration of solute in the solution.
It is clear that $D_p$ is only $\sqrt[3]{C}$ times of $D_d$. This means $D_p$ can reduce to one of scores of $D_d$.

Due to the synchronization of the jet fracture and the vibration of piezoelectric ceramic, the number of particles from aerosol generator is determined by the vibration frequency, and it is monodisperse. Because the vibration frequency can be accurately measured, the particle counting concentration can be known.

### 17.1.4 Other Particle Counting Method

Except for the above He-Ne laser particle counter, there are other counting methods that can be used to determine the concentration of $\leq 0.1 \mu m$ particles. Their principles are summarized later.
17.1.4.1 Electron Microscope Method

Particles with diameter above 0.01 μm are captured by the thermal or electrostatic type samplers. Then, the particle size and number can be measured through electron microscopy or automatically scanning electron microscope.

17.1.4.2 Condensation Nucleus Counters Method (CNC for Short)

Particles with different sizes are classified by other methods at first. Then, they pass through the saturated vapor (35 °C) of the medium liquid (such as n-butanol), where the saturated vapor encloses the particles. Then, they get into the condensation tube with the temperature maintained at 10 °C, where n-butanol vapor is condensed on the particles surface and particles become droplets with diameter 12 μm. But now only counting process can be performed. Other classification methods must be used together to measure the size of particles with diameter above 0.001 μm.

(a) Electrostatic Classifier (DMA). The distribution of migration can be measured when particles are charged so that the number of particles can be counted, which can be used to measure particles with diameter 0.003–1 μm. When the condensation nuclei counter is used, the method is expressed as DMA + CNC.

(b) Diffusion Classifier (DB). The smaller the particle is, the larger the diffusion distance by Brown motion is. When the condensation nuclei counter is used, the method is expressed as DB + CNC.

The detailed parameters about the two kinds of classification methods can be referred to Ref. [10].

17.1.5 Relative Concentration Method

The relative concentration method, the weight concentration method, and the particle counting concentration method are three kinds of basic methods. For the relative concentration method, there are the photoelectric colorimetry method, the photoelectric turbidity method, and so on. However, due to the development of light scattering particle counter, the two methods have been rarely used in air cleaning technology. But the latter method has transient characteristic as a leak detection method; it is more suitable than the particle counter at this point. Similar as the particle counter, the photoelectric turbidimetry method is also based on light scattering theory, and both of them belong to the floating measurement method. The scattering light of single particle is measured in particle counter, while the scattering light of the particle group is measured in the photoelectric turbidimeter. When the intensity of incident light is fixed, the total light scattering of particle group is not only related with the particle size but also related with the scattering particle number. Within a certain range of concentration, the total energy of scattered light is proportional to the concentration of particles. This measured result is represented
by the photoelectric current value. For some aerosol often measured, if the weighing concentration is prepared in advance which is carried out during the concentration calibration of instrument, the equivalent weight concentration corresponding with the photoelectric current value can be directly obtained. If it is used to determine the filter efficiency, concentration calibration is not needed. In the past, the photoelectric turbidimeter for measuring particles has been produced, which will not be described in detail here.

17.1.6 Biological Particle Measurement Method

Measurement of biological particles (mainly bacteria) not only contains the measurement of all the particulate material but also must contain the necessary conditions of biology. The detailed discussion is not the scope of this book, so in this section, there is only a brief introduction.

Pay attention to the following questions when measuring biological particles:

1. Absolute sterilization must be performed on measuring instrument, measuring accessories, and operation appliances.
2. All measures should be taken to prevent the pollution of specimens from occupant.
3. It shall adopt the most suitable sampling method according to the applications. Detailed information about the use condition, culture medium, culture condition, and other parameters should be recorded.
4. In some cases, the contrast specimens must be used.

The commonly used measurement methods will be introduced as follows:

17.1.6.1 Settlement Method

This is the measurement method for sedimentation bacteria, which is the most convenient and simple method. The culture dishes filled with culture medium (diameter is usually 90 mm) are placed on the test locations. They are placed with the prescribed time for exposure, which can also be determined through trial test. Then, they are cultured according to the specified temperature and time, after which the colony number is counted with the naked eye.

In the past, the culture temperature was 37 °C, and the culture time was 48 h in general. The American Aerospace Standard specifies 32 °C and 48 h, respectively. But according to experiment [11], after 48 h of culture, the sequential relationship between the colony count and the temperature is: 25 °C ≥ 31 °C ≥ 37 °C ≥ 20 °C ≥ 43 °C. We can see that both 25 and 31 °C are the suitable culture temperature. Therefore, during the measurement of the general bacteria and the bacterial number, 48 h and 31–32 °C can be used for culture. For measurement of fungi, 96 h and 25 °C can be used for culture [12]. From the bacterial growth curve in Chap. 9, we can know that, 24–48 h corresponds to the stable growth period of bacteria. So, if
the temperature for culture increases from 32 to 37 °C, 24 h can be used as the culture time, which also meets the requirements. For other tested bacteria methods, the data are also available.

17.1.6.2 Impactor Method

This is the method to measure the airborne bacteria.

Dry Method

(a) The Gap Method. Air is drawn through the slit. The air containing bacteria will hit and deposit on the fixed plate with culture medium. Then, the culture and the counting processes are performed. Cascade sampling device is one example of this method.

(b) The Rotation Method. Air is drawn through the slit. The air containing bacteria will hit and deposit on the rotating plate with culture medium. With the rotation of the culture medium, the variation of the concentration of airborne bacteria with time is measured. Rotary sampler is one example of this method.

(c) The Classification Method. It is a porous plate sampler. It is equipped with a multistage orifice plate. After ejected through each orifice, air impacts the plate culture base, where the biological particles deposit onto culture medium. Since the aperture diameters of each plate are different, the sizes of particles deposited on each section of the culture medium are different. So the size distribution of biological particles can be obtained. The Anderson sampler is one example of this method. It is taken as the standard sampler internationally. Table 17.6 shows the characteristics of Anderson sampler [13].

(d) The Centrifugal Method. Sampling head is the volute of an impeller. When it is turned on, air within the distance of 40 cm can be drawn into the sampler with the high rotating speed of the impeller inside the volute. A conical body with high rotating speed is formed after air enters the casing, where particles

| Stage | Aperture size (μm) | Air velocity (m/s) | Lower size limit of capture particle (μm) | Particle size with 100 % capture efficiency | Main capture range (μm) | Average capture efficiency (%) |
|-------|-------------------|-------------------|-------------------------------------------|---------------------------------------------|------------------------|-------------------------------|
| 1     | 1.181             | 1.08              | 3.78                                      | 11.2                                        | Above 7.7              | –                             |
| 2     | 0.914             | 1.79              | 2.76                                      | 8.29                                        | 5.5–7.7                | 60                            |
| 3     | 0.711             | 2.97              | 1.44                                      | 4.32                                        | 3.5–5.5                | 63                            |
| 4     | 0.533             | 5.28              | 1.17                                      | 3.50                                        | 2.3–3.5                | 63                            |
| 5     | 0.343             | 12.79             | 0.61                                      | 1.84                                        | 1.4–2.3                | 66                            |
| 6     | 0.254             | 23.30             | 0.35                                      | 1.06                                        | 0.75–1.4               | 66                            |
17.1.6.3 Filtration Method

When air passes through the filter, which is 0.3 and 0.45 μm microporous membrane, microbial particles are trapped on the membrane. The membrane is placed directly on the culture medium, then counting can be made. Before sampling, membrane should be placed in the boiling water for sterilization. Take it out and then make it dry, after which it can be used. But someone thinks, with the blowing of sampling airflow, the weak microbe on the membrane surface may probably die due to dry. So it should be completed within the 5 min, and then culture it immediately. It is obviously that such a short sampling time for high air cleanliness environment is difficult. But when the sampling is on the culture medium, sampling time may be slightly longer.

Filtration media used in this filtration method include glass fibrous filter paper, gelatin sponge (after sampling, dissolve it in physiological salt water, then fall the water into the culture medium), and powdered glutamic acid alkali tablet (dissolve it in the water after sampling).

It is difficult to find out the regular relationship between different apparatus and methods for measuring the airborne bacteria both from theory and from practice. Results performed by different investigators are different a lot. Therefore, various measurement data will not be cited here. But the Anderson sampler is usually used as the comparison baseline. In addition, many data indicate that the sampling efficiency of filtration method is higher than that of other methods.

Figure 17.15 is the illustration of above methods and measurement of surface microorganisms.
17.2 Air Filter Measurement

17.2.1 Measurement Range

There are usually three aspects for the measurement of air filter, which will be introduced as follows.

17.2.1.1 Measurement of Filter Media

It is aimed to the mechanism study of air filtration, the choice of filter media, the selection and comparison of filtration scheme, and the measurement needed as a reference for understanding the filter performance. It is known as the measurement of small sample. It includes the following items:

1. Efficiency. After the filter media is fixed by clamps, concentrations upstream and downstream are measured. Then, the efficiency can be calculated according to the formula. When the measured efficiency is provided, the corresponding specific velocity should be indicated.

2. Resistance. After the filter media is fixed by clamps, the difference of differential pressures upstream and downstream is measured, which is called the resistance.
When the measured resistance is provided, the corresponding specific velocity should be indicated.

3. Tensile strength. The tensile strength of filter media used in HEPA filter should be not less than 250 g. For the filter with the requirement of pressure resistance, the tensile strength should not be less than 450 g.

4. Content of combustible matter. For the filter with the requirement of fire protection, the combustible content of filter media should be not more than 5%.

5. Heat resistance. After the filter media is heated under specified temperature, the tensile strength should be checked whether it has changed.

6. Water resistance. After the filter media is exposed in the humid steam flow for 5 min, the resistance is measured. For the filter media without the ability of water resistance or without hydrophobic treatment, pores are quickly blocked, which will increase the resistance significantly.

The above test items and related data are from the general literatures abroad, which are not all from domestic standards. All of them are described here only for readers’ reference. The following content is the same.

### 17.2.1.2 Unit Measurement

These are the requirements during the developing and test of air filters, which include the following items:

1. Efficiency. Test is carried out according to the methods shown in Table 17.6. After air filter is tested, it should maintain the original efficiency or can still meet the requirements.

2. Resistance. Initial resistance is measured with rated airflow. The pipe diameters and velocities upstream and downstream of tested filter should be consistent. The measuring position from the local resistance component downstream should be larger than three times of the edge length, and the distance upstream is more than five times of the edge length.

3. Dust holding capacity. It will be described later.

4. Vibration resistance (applicable to HEPA filter). Tested filter is placed on the vibration table with the vibration amplitude below 10 mm and the vibration frequency about 300 times per minute. After vibration for the specified long time, the filter appearance should be checked to find out if it has changed.

5. Pressure resistance (applicable to HEPA filter). With the increased air velocity or increased dust holding capacity, the filter resistance is increased by more than 10 times. When this situation lasts 15 min, the efficiency is measured again. For HEPA filter with special requirements of pressure resistance, the ability to resist shock wave should be tested [13], such as the HEPA filter for breath of occupant.

6. Heat resistance. Filter is placed into an oven for several hours when the temperature increases slowly to the required value. Then, cool the filter till the room temperature. The shapes of the frame, the gasket, and adhesives should be
checked to find out whether there are unusual changes, and then the filter efficiency should be measured again. Or hot air is used to test the filter.

7. Flame resistance (applicable for filters with requirements of flame resistance). Flame should be used to face the windward side of the air filter at the nominal airflow rate for 5 min. Even when the filter is burnt, the filter can be considered to have the flame resistance ability when the combustion with the same degree of the windward side does not appear at the leeward side.

8. Water resistance (applicable to filters with requirements of water resistance). Immerse the filter vertically into 20 °C water for more than 5 min, and then take it out for less than 5 min to remove water. After water is removed, dry the filter with the air of the rated flow rate for 10 min. The resistance is measured, which should not be larger than two times of the initial resistance. The resistance after it is the completely dry should be half of the original value, and the increase of the most penetration should not exceed the requirement (generally it should not be more than two times of the original penetration).

9. Leakage performance (applicable to the sub-high-efficiency and HEPA filters). Test according to the requirement in Sect. 17.4.

17.2.1.3 Field Test

This is to check whether filters have been damaged during the installation process, whether the gasket is well sealed, or whether certain performance is kept during regular examination. There are the following items:

1. Efficiency. Test according to the methods in Table 17.7.
2. Resistance. The specific velocity should be indicated during the measurement of resistance.
3. Leakage performance. Test according to the requirements in Sect. 17.4 of this chapter.

The test items are summarized above. The following sections will mainly discuss the measurement of efficiency and dust holding capacity.

17.2.2 Measurement of Filter Efficiency

17.2.2.1 Measurement Method

Commonly used measurement methods for filter efficiency are listed in Table 17.7. The main difference between various methods is the standard dust source and the disparity of particles. As mentioned in the chapter about the filtration mechanism, according to the property and the application of air filters, standard dust source should be chosen to test the filter efficiency. For example, for study of HEPA filter, monodisperse particles are usually used as the dust source. Because it is difficult to
| Name | Shape | Particle size distribution | Initial concentration (mg/m³) | Test method and detectable efficiency | Application | Nation and region |
|------|-------|----------------------------|-------------------------------|----------------------------------------|-------------|------------------|
| DOP  | Liquid, fog | Monodisperse, mass median diameter 0.3 μm occupies more than 85 % (mass percentage, and this applies below) | 100 | Light scattering method, particle counter for filter efficiency ≤99.9999 % | Sub-HEPA and HEPA filter. Applicable for unit test only | USA, Japan |
| DOP  | Liquid, fog | Polydisperse, mass median diameter 0.8 μm | 100 | Light scattering method, particle counter for filter efficiency ≤99.9999 % | Sub-HEPA and HEPA filter | USA, Japan |
|      |       | 0.3 μm | 24.77 % | | | |
|      |       | 0.4 μm | 19.74 % | | | |
|      |       | 0.5 μm | 15.80 % | | | |
|      |       | 0.6 μm | 14.92 % | | | |
|      |       | 0.8 μm | 13.04 % | | | |
|      |       | 0 μm | 5.44 % | | | |
|      |       | 1.2 μm | 4.13 % | | | |
|      |       | 1.5 μm | 1.48 % | | | |
|      |       | ≥ 2.0 μm | 0.68 % | | | |
| DOS  | Liquid, fog | 0.2 μm | – | Light scattering method, particle counter for filter efficiency ≤99.9999 % | Sub-HEPA and HEPA filter | USA, Japan |
| Paraffin oil | Liquid, fog | Polydisperse, 0.15–1.1 μm, where 0.3–0.5 μm occupies 80 %, mass median diameter 0.4 μm | 10–80 | Light scattering method, Dinter device for filter efficiency ≤99.9995 % | Sub-HEPA and HEPA filter. Applicable for unit test only | Former Federal Germany |
| Turbine oil | Liquid, fog | Close to monodisperse, most are 0.28–0.34 μm. Mass-weighted diameter 0.31 μm | 2,500 | Light scattering method, turbidimeter for filter efficiency ≤99.99999 % | Sub-HEPA and HEPA filter. Applicable for unit test only | Former Soviet Union, China |

(continued)
| Name                          | Shape                              | Particle size distribution                        | Initial concentration (mg/m³) | Test method and detectable efficiency                                      | Application                                      | Nation and region               |
|-------------------------------|------------------------------------|---------------------------------------------------|-------------------------------|---------------------------------------------------------------------------|-------------------------------------------------|---------------------------------|
| NaCl                          | Solid, dust                        | Polydisperse, 0007–17 μm, Mass median diameter 0.45–0.6 μm | 3–5                          | Sodium flame method, flame photometer for filter efficiency ≤99.9999 %     | Medium-efficiency and HEPA filter                | EU, China                       |
| Atmospheric dust              | Most are solid. Mixture of several shapes | Polydisperse, particle size distribution is shown in Chap. 2 | Undefined                     | Arrestance method                                                          | Coarse and medium-efficiency filter              | China, USA, Japan               |
| Radioactive atmospheric dust  | Most are solid. Mixture of several shapes | Polydisperse, <1 μm                                  | undefined                     | Condensation particle counter ≤99.99 %                                    | Sub-HEPA and HEPA filter                         | USA, Former Federal Germany     |
| Atmospheric condensation nucleus | Most are solid. Mixture of several shapes | Polydisperse, 0.001–0.1 μm                          | undefined                     | Condensation particle counter ≤ 99.99 %                                    | Sub-HEPA and HEPA filter                         | USA, Former Federal Germany     |
| Quartz dust                   | Solid, dust (SiO₂ 72 %, Black carbon 25 %, Cotton fiber 3 %) | Polydisperse, mass median diameter 5 μm 0–5 μm 39 % 5–10 μm 18 % 10–20 μm 16 % 20–40 μm 18 % 40–80 μm 9 % | <70                           | Arrestance method (AFI method), balance for arrestance ≤99 %               | Coarse and medium-efficiency filter. Applicable for unit test only | USA, Japan                      |
| Quartz dust | Solid, dust | **Polydisperse** | **Arrestance method** | Coarse and medium-efficiency filter. Applicable for unit test only. Or sub-HEPA filter and applicable for unit test only | Former Federal Germany |
|-------------|-------------|-------------------|----------------------|---------------------------------------------------------------------------------|----------------------|
|             |             | Group A > 6 µm  0 % | Light scattering method for efficiency >99.5 % |                                                                              |                      |
|             |             | >4 µm  2 % |                      |                                                                                |                      |
|             |             | >2 µm  26 % |                      |                                                                                |                      |
|             |             | <1 µm  40 % |                      |                                                                                |                      |
|             |             | Mass median diameter 1.3 µm |                      |                                                                                |                      |
|             |             | Group B > 10 µm 1 % |                      |                                                                                |                      |
|             |             | >6 µm  10 % |                      |                                                                                |                      |
|             |             | >4 µm  26 % |                      |                                                                                |                      |
|             |             | >2 µm  58 % |                      |                                                                                |                      |
|             |             | <1 µm  21 % |                      |                                                                                |                      |
|             |             | Mass median diameter 2.5 µm |                      |                                                                                |                      |
|             |             | Group C > 10 µm 30 % |                      |                                                                                |                      |
|             |             | >6 µm  65 % |                      |                                                                                |                      |
|             |             | >4 µm  78 % |                      |                                                                                |                      |
|             |             | >2 µm  93 % |                      |                                                                                |                      |
|             |             | <1 µm  2 % |                      |                                                                                |                      |
|             |             | Mass median diameter 8 µm |                      |                                                                                |                      |
| Japan JIS8 dust | Solid, dust | **Polydisperse, mass median diameter 8 µm** | **Arrestance method** | Coarse filter. Applicable for unit test only | Japan |
|             |             | 30 ± 10 |                      |                                                                                |                      |
|             |             | 0–5 µm  39 ± 5 % |                      |                                                                                |                      |
|             |             | 5–10 µm  18 ± 3 % |                      |                                                                                |                      |
|             |             | 10–20 µm  16 ± 3 % |                      |                                                                                |                      |
|             |             | 20–30 µm  12 ± 3 % |                      |                                                                                |                      |
|             |             | 30–40 µm  6 ± 3 % |                      |                                                                                |                      |
|             |             | 40–74 µm  >9 % |                      |                                                                                |                      |
| Name                | Shape          | Particle size distribution                  | Initial concentration (mg/m³) | Test method and detectable efficiency | Application                                                                 | Nation and region |
|---------------------|----------------|---------------------------------------------|-------------------------------|---------------------------------------|------------------------------------------------------------------------------|--------------------|
| Japan JIS11 dust    | Solid, dust    | Polydisperse, mass median diameter 2 μm     | 3 ± 1                         | Dust spot method                      | Medium-efficiency filter. Applicable for unit test only                      | Japan              |
|                     |                | 1 μm 65 ± 5 %                               |                               |                                       |                                                                               |                    |
|                     |                | 2 μm 30 ± 5 %                               |                               |                                       |                                                                               |                    |
|                     |                | 4 μm 22 ± 5 %                               |                               |                                       |                                                                               |                    |
|                     |                | 6 μm 8 ± 3 %                                |                               |                                       |                                                                               |                    |
|                     |                | 8 μm 3 ± 3 %                                |                               |                                       |                                                                               |                    |
| Sodium fluorescein  | Solid, dust    | Polydisperse, average size 0.08 μm, mass median diameter 0.15 μm | 0.01                          | Fluorescence method                   | Sub-HEPA and HEPA filter. Applicable for unit test only                      | France             |
|                     |                |                                             |                               | (fluorimeter is used to test the fluorescence from the scrubbing solution of filter media by ammonia) |                                                                               |                    |
|                     |                |                                             |                               |                                       |                                                                               |                    |
|                     |                |                                             |                               |                                       |                                                                               |                    |
generate monodisperse particles, polydisperse particles are used for the field test of HEPA filter. In terms of penetration, the penetration with polydisperse particles is less than half of that with monodisperse particles. So the field test efficiency should be higher than that measured in factory or laboratory. But due to the leakage during installation, the conclusion is usually opposite.

It should be illustrated for DOP aerosol in the table that it got criticism recently in two aspects. One criticism is that DOP generated with the heating method is easily attached to the filter surface, and the generation device is huge, so it is suggested to change the generation method [14, 15]. The other one is that in some cases after the volatilization, DOP may enter the clean airflow and have the carcinogenic effect [16]. But there is also doubt on this criticism [17]. It is found through experiment under the normal temperature that the volatile DOP concentration from the filter material is only one tenth of the allowable concentration of harmful substances with the most strict control requirement, so it is too early to conclude that it is harmful. Based on the above reasons, attention has been paid on looking for the substitute of DOP recently. DOS in the table is one of the substitutes. DOS with molecular weight 427 is an aromatic colorless oily liquid. Its molecular expression is \((\text{CH}_2)_6(\text{CH}_2\text{COOC}_8\text{H}_{17})_2\). The dispersion characteristic is same as DOP, but it is relatively safer. Similar as DOS, DEHS (di-ethyl-hexyl-sebacat) is also one substitute. Besides, artificial aerosol also includes PAO (polyalphaolefin) and PSL (polystyrene sphere latex). Atmospheric dust can also be used.

As mentioned in Chap. 3, there is the most penetrating particle size (MPPS) \(d_{\text{max}}\). The theoretical requirement is satisfied when particles with this size are used to test the efficiency of air filter during research studies. In European standard EN1822 published in 1998, it was proposed to use MPPS as the particle size to test HEPA filters before delivery from factory. But it did not specify the special aerosol. Under different conditions, \(d_{\text{max}}\) will be different. For glass fibrous HEPA filters, \(d_{\text{max}}\) is about 0.1–0.2 \(\mu\text{m}\), and the difference of this value for different filters of this kind is small. As for the industrial standard, the comparable consistent standard should be found as the precondition. In this aspect, Chinese standard adopts 0.1–0.3 \(\mu\text{m}\) as shown in Table 4.37 to replace \(d_{\text{max}}\), which seems more suitable to meet the requirement of consistent standard.

### 17.2.2.2 Comparison of Results with Several Measurement Methods

In Table 17.7, a simple comparison of results with several measurement methods published in literatures is shown.

Table 17.8 shows the difference of results with the weight method, the dust spot method, and the DOP method. The efficiency with the artificial dust and the weight method is the highest.

Figure 17.16 shows the relationship curve between the particle counting efficiency with atmospheric dust particle diameter \(\geq 0.5 \mu\text{m}\) and the weight efficiency with artificial dust (the BF-2 dust mentioned above) in Ref. [18]. Equation (17.16) is the expression obtained from the curve.
\[ \eta_g \approx 37.8 \ln \eta_d - 68.5 \]  \hspace{1cm} (17.16)\

where

\( \eta_g \) is the weight efficiency with artificial dust;
\( \eta_d \) is the particle counting efficiency for particle diameter \( \geq 0.5 \) \( \mu \text{m} \) with atmospheric dust.

Table 17.9 lists the test data on foreign filter [19].

Figure 17.17 is the comparison of the results among the DOP method, the spot method, and the weight efficiency with artificial dust in Ref. [20].

Table 17.10 shows the compiled data on HEPA filter according to the experimental data in China. Table 17.11 gives the measurement efficiency of coarse and medium-efficiency filters made with nylon and polypropylene.
Table 17.9  Comparison of the sodium flame method and the DOP method (air filter)

| Filter | Flow rate (m³/h) | Penetration Efficiency | Efficiency |
|--------|------------------|------------------------|------------|
|        | NaCl k₁ (%)      | DOP k₂ (%)             | k₂/k₁      | NaCl        | DOP        |
| 1      | 0.0045           | 0.007                  | 1.5        | 0.999954    | 0.99993    |
| 2      | 0.0030           | 0.004                  | 1.34       | 0.999970    | 0.99996    |
| 3      | 0.0040           | 0.004                  | 1          | 0.999960    | 0.99996    |
| 4      | 0.0050           | 0.007                  | 1.4        | 0.999950    | 0.99993    |
| Average|                  |                        |            | 1.31        |            |

Fig. 17.17  Comparison of the efficiencies among the DOP method, the spot method, and the weight efficiency with artificial dust

Table 17.12 is the experimental result with high-efficiency filters [6].
The above relations come from the experience, through which theoretical conclusions cannot be made. But the relationship between several methods with domestic and foreign data is roughly as follows:
Penetration $k_4$ with the particle counting method with atmospheric dust $>$ penetration $k_2$ with the DOP method $>$ penetration $k_1$ with the sodium flame method $>$ penetration $k_3$ with the oil mist method.
The particle counting efficiency with atmospheric dust is slightly more than that with the DOP method, or the penetration of the former is slightly less by 20%. The efficiency with the DOP method is lower than that with the sodium flame method, or the penetration of the former is larger by more than 1.4 times. The efficiency with the sodium flame method is greater than the oil mist method, or the penetration of the former is larger by more than 1 time.

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The efficiency with the DOP method is less than that with the sodium flame method, which is consistent with the conclusions from the general literatures. This

### Table 17.10 Comparison of the sodium flame method and the oil mist method (air filter)

| Sample material                  | NaCl $k_1$ | Oil mist $k_3$ | $k_3/k_1$ |
|----------------------------------|------------|----------------|-----------|
| Asbestos 149                     | 0.000710   | 0.000220       | 0.31      |
| Glass fiber 7001                 | 0.000051   | 0.000031       | 0.61      |
| Glass fiber 6901                 | 0.008600   | 0.008700       | 1         |
| φmm-15 from former USSR          | 0.240000   | 0.170000       | 0.71      |
| Glass fiber (thick)              | 0.003300   | 0.000700       | 0.21      |
| Glass fiber (thin)               | 0.051000   | 0.011000       | 0.27      |
| Average                          |            |                | 0.52      |

### Table 17.11 Comparison of measured efficiency of coarse and medium-efficiency filters between the sodium flame method and the oil mist method

| Filter media | NaCl $\eta_1$ (%) | Oil mist $\eta_2$ (%) | Filter media | NaCl $\eta_1$ (%) | Oil mist $\eta_2$ (%) |
|--------------|-------------------|-----------------------|--------------|-------------------|-----------------------|
| 1            | 2                 | 10                    | 9            | 26                | 28.6                  |
| 2            | 5                 | 10.8                  | 10           | 36                | 36.3                  |
| 3            | 6                 | 16                    | 11           | 38                | 30.5                  |
| 4            | 6                 | 16                    | 12           | 40                | 32.5                  |
| 5            | 7                 | 10                    | 13           | 42                | 44                    |
| 6            | 13                | 16                    | 14           | 47                | 31.6                  |
| 7            | 18                | 12.7                  | 15           | 53                | 47.3                  |
| 8            | 19                | 30.9                  | 16           | 53                | 49.1                  |

### Table 17.12 Comparison of penetrations for several filter media

| Filter media | Polydisperse DOP $k_2$ (%) | Sodium flame method $k_1$ (%) | Atmospheric dust method (laser particle counter) $k_4$ (%) | $k_3/k_1$ | $k_2/k_4$ |
|--------------|----------------------------|-------------------------------|-----------------------------------------------------------|-----------|-----------|
| I-2          | 0.000014                   | undetectable                 | undetectable                                             | –         | –         |
| II-5         | 0.00302                    | 0.0016                       | 0.005                                                    | 1.88      | 0.6       |
| III-1        | 0.00476                    | 0.0029                       | 0.0059                                                   | 1.61      | 0.81      |
| III-2        | 0.0441                     | 0.034                        | 0.048                                                    | 1.80      | 0.92      |
| Average      |                            |                               |                                                          | 1.6       | 0.78      |
is also consistent with the opinion that the efficiency with liquid particles is lower than that with the solid particles. But contradictory results appear when the oil mist method and the sodium flame method are compared. Liquid particle methods are used in both the DOP method and the oil mist method, where the average particle sizes are basically the same. But due to the different particle size distribution, it is possible that the measured efficiencies may not be entirely the same. But there may be other reasons for such big difference. According to the characteristic of the oil mist method, if parameters are not well controlled during the generation process of oil mist, both the dispersity and the average particle size may deviate a lot from the standard values. Furthermore, results are also affected by different filter media. In summary, further study is needed to compare the results with several measurement methods.

For measuring the coarse and medium-efficiency filters, the test efficiency with artificial dust is much higher than that with the atmospheric dust. For the same foam filter, the weight efficiency with atmospheric dust is 45 %, while the weight efficiency with artificial dust reaches 90 %. The reason why the efficiency with artificial dust is so high is that the artificial ground dust particles are angular and particles will be positively charged with the movement of airflow. When the particles are positively charged and the wall surface is negatively charged, the capture efficiency will be improved. Some artificial dust will easily coagulate due to the special ingredients, so it is more easily captured. In the nature, the dust particles formed are generally not angular, and the charged phenomenon is weak.

### 17.2.2.3 Standard Method in China

In national standard GB/T 14295-2008 *Air Filter*, test methods are included, which is suitable for dry air filter (including the electrostatic filter). It is shown in Table 17.1.

In national standard GB/T 13554-2008 *HEPA Filter*, HEPA and sub-high-efficiency air filters should be tested with the sodium flame method. ULPA filters should be tested with the particle counting method. The medium diameter of aerosol is 0.1–0.3 μm. There is no limit for the type of aerosol and its dispersity. This standard is not suitable for the military and nuclear applications. In the military application, the oil mist efficiency can be used.

### 17.2.2.4 Mixed Multi-position Test

For the efficiency test of filters especially HEPA filters, the most common practice at home and abroad in the past is that only one sampling position is placed in the center of both the upwind side and the downwind side, respectively. The measured efficiency in this way is often high. And it is also difficult to find the leakage phenomenon. This is caused by the nonuniform distribution of concentration in the pipe. There are two main reasons that cause the nonuniform distribution of
| Method               | Aerosol type                           | Name                                          | Particle size range | Test method       | Instrument performance | Instrument No. | Reading                                                                 |
|---------------------|----------------------------------------|-----------------------------------------------|---------------------|-------------------|------------------------|----------------|-------------------------------------------------------------------------|
| Particle counting   | Polydisperse solid particles           | Potassium chloride KCl (charge neutralized     | 0.3–10 μm           | Particle counter    | Particle counting      | 50 %           | The reading downstream should be >100. Average concentrations are obtained for sampling three times both upstream and downstream with two instruments, which can be used to calculate the efficiency. In total two times of efficiency should be calculated. The difference between two efficiencies is shown in Table 17.14. For one instrument only, five sampling times are needed while other requirements are the same as above situation |
| method              | 0.3–0.5 μm                             | after spray)                                  |                     |                   | efficiency for 0.3 μm | PSL ≥ 50 %       |                                                                          |
|                     | (65 ± 5)%                              |                                               |                     |                   |                        |                |                                                                          |
|                     | 0.5–1 μm                               |                                               |                     |                   |                        |                |                                                                          |
|                     | (30 ± 3)%                              |                                               |                     |                   |                        |                |                                                                          |
|                     | 1–2 μm                                 |                                               |                     |                   |                        |                |                                                                          |
|                     | (3 ± 1)%                               |                                               |                     |                   |                        |                |                                                                          |
|                     | >2 μm                                  |                                               |                     |                   |                        |                |                                                                          |
|                     | (>1)%                                  |                                               |                     |                   |                        |                |                                                                          |
| Weight method       | Polydisperse solid artificial particles | Artificial dust (see Table 17.15)            |                     |                   | The weighting method   |                |                                                                          |
|                     |                                        |                                               |                     |                   |                        |                |                                                                          |
concentration. First, the test aerosol particles generally come from a point source, so it is difficult to uniformly distribute on the cross section of the pipe. Second, with the effect of air filter, the airflow at the leeward side of the filter is much uniform, which is more significant for HEPA filters. With the characteristics of unidirectional parallel flow, the airflow with nonuniform distribution of concentration at upwind side passes through the filter, which will keep the original distribution. So it is difficult to mix fully at the cross section (see Fig. 17.18). So the result with this method will inevitably incorrect.

In order to improve this situation, experiment was performed to study different dust nozzles and different mixing methods [21]. Ten sampling points were placed along the center line at the cross section of the pipe. Concentrations $N_i$ at each sampling point was measured. The arithmetic average value $\bar{N}$ of the measured concentrations was calculated. The deviation of the measured concentrations is expressed with $\left[ \frac{N_i-\bar{N}}{\bar{N}} \times \frac{100}{100} \right]$. The bigger the deviation is, the worse the mixture effect is. The mixing effect on the upwind side of the filter is summarized in Table 17.16, which indicates that:

1. The mixing effect of the annular perforated nozzle, which is used to spray particles, is the best. The mixing effect of the linear perforated nozzle is almost

| The 1st efficiency $E_1$ | Difference between $E_2$ and $E_1$ |
|--------------------------|-----------------------------------|
| $< 40 \%$                | $< 0.3E_1$                        |
| $40–60 \%$               | $< 0.15E_1$                       |
| $60–80 \%$               | $< 0.08E_1$                       |
| $80–90 \%$               | $< 0.04E_1$                       |
| $90–99 \%$               | $< 0.02E_1$                       |
| $\geq 99 \%$             | $< 0.01E_1$                       |

Fig. 17.18  Airflow state at the leeward side of the filter
### Table 17.15 Properties of artificial dust

| Component | Mass ratio (%) | Specification of raw material | Particle size distribution | Property of raw material |
|-----------|----------------|-------------------------------|---------------------------|--------------------------|
| Coarse particle | 72 | Road dust | | |
| | | | Size range (μm) | Percentage (%) | Chemical ingredients |
| | | | 0–5 | (36 ± 5) | SiO₂ |
| | | | 5–10 | (20 ± 5) | Al₂O₃ |
| | | | 10–20 | (17 ± 5) | Fe₂O₃ |
| | | | 20–40 | (18 ± 3) | CaO |
| | | | 40–80 | (9 ± 3) | MgO |
| Fine particle | 23 | Black carbon | 0.08–0.13 μm | Iodine adsorption 10 mg/g–25 mg/g |
| | | | | Oil absorption 0.4 mg/g–0.7 mg/g |
| Fiber | 5 | Short lint | | Detached cotton fiber after treatment |

### Table 17.16 Comparison of mixing effect with various mixing means at the upwind side of filter

| Generation location | Mixing means | Perforated plate (open ratio 0.2) | Stirring fan | Max. deviation (%) |
|---------------------|--------------|----------------------------------|--------------|-------------------|
| A (5D from filter)  | B (2.5D from filter) | Nozzle shape | Without | With | Without | With | |
| Ring multihole | ○ | ○ | ○ | 20 | |
| ○ | ○ | ○ | 12 | |
| ○ | ○ | ○ | 17 | |
| ○ | ○ | ○ | 4 | |
| ○ | ○ | ○ | 34 | |
| ○ | ○ | ○ | 7 | |
| ○ | ○ | ○ | 5 | |
| Linear multihole | ○ | ○ | ○ | 28 | |
| ○ | ○ | ○ | 11 | |
| ○ | ○ | ○ | 4 | |
| ○ | ○ | ○ | 33 | |
| ○ | ○ | ○ | 19 | |
| ○ | ○ | ○ | 14 | |
| Single hole | ○ | ○ | ○ | 24 | |
| ○ | ○ | ○ | 13 | |
| ○ | ○ | ○ | 10 | |
| ○ | ○ | ○ | 167 | |
| ○ | ○ | ○ | 55 | |
| ○ | ○ | ○ | 32 | |
the same as that of the single-hole nozzle. The shapes of these nozzles are shown in Fig. 17.19.

2. It is better to place the sampling point at the windward side of air filter further. When the distance between this sampling point and the air filter is 5D (3 m, \(D\) is the pipe diameter), the biggest deviation is just 24% even when single-hole nozzle is used without any other mixing means. But when the distance is 2.5D (1.5 m), the deviation reaches up to 167%.

3. No matter what kind of dust nozzle is used and how much is the sampling distance is, the mixing effect improved when orifice plate or a mixing fan is used as the mixing method.

The uniform effect of the stirring fan is self-evident. The uniform effect of orifice plate is that the velocity field becomes uniform, which improves the uniformity of concentration field.

Let \(\Delta u_0\) be the fluctuating velocity of the airflow upstream of the filter at the place far away from the orifice plate and \(\Delta u_1\) the fluctuating velocity of the airflow downstream of the filter at the place far away from the orifice plate:

\[
\frac{\Delta u_1}{\Delta u_0} = f
\]  

(17.17)

Obviously if \(f = 0\), the fluctuation of airflow downstream is completely eliminated. Figure 17.20 is an experimental relationship between the air resistance coefficient \(\xi\) of the orifice plate and \(f\) [22]. Although the data are not concentrated, the curve such as the dotted line can still be plotted. It can be seen that \(\xi\) is about 2.5 when \(f = 0\).

The value of \(\xi\) is closely related to the opening ratio. The differential pressure through the orifice plate is expressed as follows:

\[
\Delta P = P_0 - P_1 = \frac{1}{2} \rho (u_1^2 - u_0^2)
\]  

(17.18)

\[
u_1 = \frac{u_0}{c_s}
\]  

(17.19)
where

\( u_0 \) and \( P_0 \) are the air velocity and the pressure at the windward side of orifice plate;
\( u_1 \) and \( P_1 \) are the air velocity and the pressure at the leeward side of orifice plate;
\( c \) is the contraction coefficient when airflow passes through the orifice plate, which is usually 0.9;
\( \rho \) is the gas density;
\( s \) is the opening ratio.

Substituting Eq. (17.19) into Eq. (17.18) becomes:

\[
\Delta P = P_0 - P_1 = \frac{1}{2} \rho u_0^2 \left( \frac{1 - c^2 s^2}{c^2 s^2} \right)
\]  

(17.20)

Let

\[
\xi = \frac{1 - c^2 s^2}{c^2 s^2}
\]  

(17.21)

It is the drag coefficient. In the above experiment, the opening ratio of the orifice plate is only 20 %, where only one plate was placed. If the opening ratio was increased or multiple orifice plates were placed in series, the effect will be better. Figure 17.21 shows the uniform velocity field with multiple orifice plates in series.
Experimental results of the mixing effect at the leeward side of filter are summarized in Table 17.17. In the experiment, simulated leakage method was used so that leakage was forced from three positions of the cross section on the filter. (Leakage concentration is 0.03 mg/m³. The leakage flow rate is for less than 0.2 % of the rated flow.) The results show that [23]:

1. The maximum deviation of measurement value appears when leakage appears on the edge of the filter and no mixing means was adopted.
2. When no mixing means is used at the leeward side of the filter, the maximum deviation of the measured results is about 65–140 %. By using the mixed means later, it reduces to 40–75 %, which is still not ideal.

### Table 17.17 Comparison of the mixing effect with various means at the leeward side of filter

| Sampler location | Leakage location | Mixing means | Max. deviation (%) |
|------------------|------------------|--------------|--------------------|
|                  | Inner side of filter (close to the pipe center) | Perforated plate (open ratio 0.4) | Stirring fan |                  |
|                  | In the middle of filter | Without | With | Without | With |                  |
|                  | Outer side of filter (close to pipe wall) |          |          |          |          |                  |
| 2.5D from filter | ○                  | ○          | ○          | ○        | ○        | 65                |
| (D is the pipe diameter) | ○                  | ○          | ○          | ○        | ○        | 54                |
|                  | ○                  | ○          | ○          | ○        | ○        | 75                |
|                  | ○                  | ○          | ○          | □        | □        | 66                |
|                  | ○                  | ○          | ○          | □        | □        | 140               |
|                  | ○                  | ○          | ○          | □        | □        | 42                |
|                  | ○                  | ○          | ○          | □        | □        | 58                |
When it is difficult to use any mixing means or the mixing effect is poor, the average method of three sampling positions is shown to be good at the consistent of the measured results [21]. The three sampling positions method is that sampling probes are placed in the central point of the trisection surface on the cross section of the pipeline, and then the mean value is calculated. From the measured data shown in Table 17.18, even if the single-hole nozzle is used, the maximum deviation at the windward side also drops from 167 to 11%. Therefore, three sampling positions method is worthy consideration when filter efficiency is measured.

17.2.2.5 Total Measurement Error

If the measurement errors of air filter with upstream concentration \( N_1 \) and downstream concentration \( N_2 \) are \( \sigma_1 \) and \( \sigma_2 \), respectively, the maximum efficiency \( \eta_{\text{max}} \) and the minimum efficiency \( \eta_{\text{min}} \) can be expressed as:

\[
\eta_{\text{max}} = 1 - \frac{(1 - \sigma_2)N_2}{(1 + \sigma_1)N_1}
\]

\[
\eta_{\text{min}} = 1 - \frac{(1 + \sigma_2)N_2}{(1 - \sigma_1)N_1}
\] (17.22)

So the positive error \( \Delta \eta \) of efficiency and the negative error \(-\Delta \eta\) can be deduced as follows:

\[
\Delta \eta = \eta_{\text{max}} - \eta = \frac{(1 + \sigma_1)N_1 - (1 - \sigma_2)N_2 - (1 + \sigma_1)(N_1 - N_2)}{(1 + \sigma_1)N_1}
\]

\[
= \frac{(\sigma_1 + \sigma_2)N_2}{(1 + \sigma_1)N_1} = \frac{\sigma_1 + \sigma_2}{1 + \sigma_1} \times \frac{N_1 - (N_1 - N_2)}{N_1}
\]

\[
= \frac{\sigma_1 + \sigma_2}{1 + \sigma_1} \times \left( 1 - \frac{N_1 - N_2}{N_1} \right)
\]

\[
= \frac{\sigma_1 + \sigma_2}{1 + \sigma_1} \times (1 - \eta)
\] (17.23)

Also, we can get:

\[
-\Delta \eta = \eta - \eta_{\text{max}} = -\frac{\sigma_1 + \sigma_2}{1 - \sigma_1} (1 - \eta)
\] (17.24)

According to the error theory, both \( \sigma_1 \) and \( \sigma_2 \) in the above formula can be expressed as follows:

\[
\sigma_1 (\text{or} \sigma_2) = \sqrt{\sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \sigma_d^2}
\] (17.25)
### Table 17.18 Effect of three sampling positions method

| Nozzle          | Upstream Distance (Distance from filter) | Max. deviation with the one sampling position method (%) | Max. deviation with the three sampling positions method $a'$ (%) | Downstream | Max. deviation with the one sampling position method (%) | Max. deviation with the three sampling positions method $b'$ (%) | Comprehensive error with the three sampling positions method $(a' + b')$ (%) |
|-----------------|------------------------------------------|-------------------------------------------------------|---------------------------------------------------------------|------------|-------------------------------------------------------|---------------------------------------------------------------|-----------------------------------------------------------------|
| Single hole     | $2.5D$                                   | 167                                                   | 11.3                                                          | $5D$       | 24                                                    | 0.8                                                          |                                                                 |
|                 |                                          |                                                       |                                                               |            |                                                       |                                                               |                                                                 |
| Linear multihole| $2.5D$                                   | 33                                                    | 11.3                                                          | $5D$       | 28                                                    | 4.3                                                          |                                                                 |
|                 |                                          |                                                       |                                                               |            |                                                       |                                                               |                                                                 |
| Ring multihole  | $2.5D$                                   | 34                                                    | 0.3                                                           | $5D$       | 20                                                    | 2.2                                                          |                                                                 |
|                 |                                          |                                                       |                                                               |            |                                                       |                                                               |                                                                 |
where

$\sigma_a$ is the error caused by the variation of the flow rate and the particle concentration through the air filter with time, weather conditions, or other factors. According to the practical experience, during the measurement time, the resultant error for particle concentration can reach 20%. It can generally be considered as 10%;

$\sigma_h$ is the error of the sampling flow rate for instrument such as particle counter. As pointed out before it is about 3%;

$\sigma_c$ is the error caused by non-isokinematic sampling. According to the previous analysis, the average value is 5%;

$\sigma_d$ is the error caused by particle loss in sampling tubes. According to the previous analysis, in general it is not more than 3%.

As for the overlapping error of particle counter, it should be considered under specific condition.

For efficiency test of air filter, we can consider that $\sigma_1 = \sigma_2$ and suppose $\sigma_a = \pm 10\%$, $\sigma_b = \pm 3\%$, $\sigma_c = \pm 5\%$, and $\sigma_d = \pm 3\%$. Substituting them into Eq. (17.25) becomes:

$$
\sigma_1 = \sigma_2 = \sqrt{0.12^2 + 0.03^2 + 0.05^2 + 0.03^2} = \sqrt{0.0143} = 0.12
$$

When it is inserted into Eqs. (17.23) and (17.24) and suppose $\eta = 0.999$, we obtain:

$$
\Delta \eta = \frac{0.12 + 0.12}{1 + 0.12} (1 - 0.999) = 0.00021
$$

$$
- \Delta \eta = \frac{0.12 + 0.12}{1 - 0.12} (1 - 0.999) = -0.00027
$$

So the filter efficiency should be within the range $(0.999 - 0.00027)$–$(0.999 + 0.00021)$, namely, $(0.99873–0.99921)$. If $\sigma_1$ reaches 20%, the efficiency is between 0.99847 and 0.99935. It is clear that even with larger errors for individual measurement item, the total error for efficiency measurement is still acceptable.

### 17.2.3 Measurement of Dust Holding Capacity of Filter

Dust holding capacity $W$ can be calculated by the following formula:

$$
W = W_1 - W_2 (g) \quad (17.26)
$$

where
$W_1$ is the weight of air filter at the end of the test, according to the requirement of dust holding capacity (see Chap. 4) (g);

$W_2$ is the weight of air filter quality (g) before the test for dust holding capacity.

With the value of $W$, we can calculate the dust holding capacity per unit area.

In order to shorten the test time, artificial dust is used as the test dust source for the dust holding capacity measurement, which is mainly the process dust and the simulated atmospheric dust. For the test of air filters in air-conditioning system and air purification technology, the simulated atmospheric dust is used as the test dust source. In terms of the blockage effect on air filter, three main components are contained to simulate the atmospheric dust. The first one is the mineral and the sand particles, which are the main component of atmospheric dust. Because they easily spread into the air, they are used to represent the inorganic noncombustible material, which occupies the most part in the simulated atmospheric dust. The second one is the carbon black. It is used to represent the free carbon in air, which is representative of the pollution effect of atmosphere and is the representative component of the atmospheric dust in industrial and urban region. Usually it occupies about 1/4. Because it is small and easy to coagulate, it is the important reason for the clogging of filter. It is also indispensable for the performance evaluation of the dust holding capacity. It is also essential in the simulated atmospheric dust. The third one is fiber. It represents the organic component in air, which can speed up the clogging of filter. So it should also be included in the simulated atmospheric dust. It only occupies several percentages.

AFI test dust was proposed by NAFA (National Air Filtration Association) in the USA, which is close to the urban atmospheric dust. It mainly contains mineral substances such as silica and others, and carbon black and batting.

Japan Air Cleaning Association specified the performance test method standard for air cleaning device. During the test of the dust holding capacity, the Type 15 dust from Japanese Industrial Standards (JIS) is used, which is made up of Type 8 dust, Type 12 dust, and cotton. Type 8 dust (also Type 7 dust and Type 11 dust) is the burnt East Asian clay which is ground to obtain the specified particle size distribution. The medium diameter is 8 $\mu$m, and the geometric standard deviation is $\sigma_g = 3.63$ (the composition and the real density of Type 7 dust and Type 11 dust are the same as Type 8 dust, and the particle size distributions are different). Type 12 dust is the carbon black. So East Asian clay is used as the test dust, because it does not easily adhere to the surface and easily disperse in the air and not easily coagulate.

The characteristics of the simulated atmospheric dust in the USA and Japan are shown in Table 17.19.

In order to compare the characteristics of the simulated dust and the atmospheric dust, the simulated dust is heated to 300 °C so that the carbon black is burnt off. Then, analysis is carried on. Some agencies in China have tried to use the simulated atmospheric dust which is made of 75% anthracite-pulverized coal and 25% carbon black. From the above analysis, the characteristics of this simulated dust are very different from that of the atmospheric dust. They are more likely to
coagulate than the ordinary atmospheric dust. So filters are easily to be clogged.
During the efficiency test, high value is likely to be obtained.

Before the year 2008, the artificial dust used for measuring the dust holding capacity in China was specified in the national standard *Test Method of Air Filter Performance in General Ventilation*, which is shown in Table 17.20. After 2008, the artificial dust specified in Table 17.15 is used.

Figure 17.22 shows the experimental curve [24], which explains what kind of the dust source can be used as the dust source for measuring the dust holding capacity. From three groups of curves among curves 1, 2, and 3, we can see that:

1. The filter is clogged very quickly by small particles.

| Test aerosol | Composition percentage |
|--------------|------------------------|
| Japan: JIS-15 type | JIS-8 type 72 % JIS-12 type 25 % Cotton fiber 3 % |
| Composition | SiO₂ 34–40 % Fe₂O₃ 17–23 Al₂O₃ 26–32 CaO 0–3 MgO 3–7 TiO₂ 0–4 Scorching hot loss 0–4 |
| Particle size | 0–5 μm 39 ± 5 % 0.03–0.2 μm Smaller than 1.5 μm (diameter) × 1 mm (length) |
| Density | 2.7 |
| USA: AFI | Coarse particle 72 % K-1 type carbon black 25 % 7 type cotton fiber 3 % |
| Composition | SiO₂ 68.47 % Fe₂O₃ 4.58 Al₂O₃ 15.98 CaO 2.91 MgO 0.77 Alkali 4.61 Scorching hot loss 2.68 |
| Particle size | 0–5 μm 39 ± 2 % 5–10 18 ± 3 10–20 16 ± 3 20–40 18 ± 3 40–80 9 ± 3 |
| Density | 2.2 |
2. Carbon black is more likely to clog air filter than atmospheric dust. It shows that filter’s actual lifetime is longer than the experiment value with carbon black. Therefore, the characteristics of simulated atmospheric dust used for measuring the dust holding capacity must be close to that of the true atmospheric dust as much as possible.

17.3 Leakage Detection

17.3.1 Leakage Detection of HEPA Filter

17.3.1.1 Implication of Leakage on Air Filter

When leakage is mentioned for the air filter unit, it includes the leakage on the filter media and the glue between the filter media and the filter frame. When leakage is
mentioned for the air filter which is already installed, except for the above leakage positions, it also includes the leakage between the sealing surface of the filter frame and the installation frame and between the wall board where the installation box is placed and the installation frame.

Leakage on terminal air filter is a fatal quality problem for cleanroom and the air cleaning equipment. So the leakage of air filter is an important topic for the air cleaning technology.

17.3.1.2 Leakage Detection Method

There are usually several methods as follows to detect the leakage of HEPA filters:

Leakage Detection with Light

This method is only suitable for qualitative leak detection of air filter unit (or called initial check).

HEPA filter is installed on the leak detection device with light, which is shown in Fig. 17.23. It is covered with black velvet around. One side of the cover can be lifted so that the inspector can stretch out his head inside for visualization. Airflow with smoke passes through the filter with the velocity of 1 cm/s. If there is a leakage pore, the fume will be seen with the black background. This method is sensitive, and leakage with small flow rate can be detected. Smoke needs to be supplied continuously, so both the cigarette smoke and the incense smoke can be used.

Leakage Detection with Double Flow Rates

This method is also used for the leakage detection of air filter unit. With the condition of good mixture at leeward side of air filter, the efficiencies at both the
rated airflow and partial of the rated airflow are measured. If the latter is lower than the former, there is leakage hole on air filter, or the air filter is unqualified, or the scanning detection for leakage should be performed.

With the rated airflow, the resistance across the small hole is high, and the leakage cannot be detected with the leakage flow rate. The resistance of the filter paper is linearly proportional to the filtration velocity. According to the fluid dynamics, the resistance of the small hole is linearly proportional to the square of the air velocity. Suppose the ratio of air velocities before and after the flow rate is reduced is $m$, the resistance after the flow rate is reduced becomes $1/m^2$ of the original value. The flow rate through the small hole increases by about $m$ times compared with the original value. The concentration at the cross section may increase, which means there is the leakage. Figure 17.24 proves the above reason [25].

For filters with no leakage holes, the lower the air velocity is, the lower the penetration is. The extent of decrease may be different (see the section about paper filter in Chap. 4). For filters with leakage holes, with the lower air velocity, the relative flow rate through the hole, namely, the leakage flow rate, becomes larger, so the penetration increases. In order to detect the leakage easily, it is hoped that two penetration values with these two air velocities differ a lot (because the fluctuation of the measurement data may also be 1 time). So in the US Federal Standard 209B, the flow rate for leakage detection was specified to be 20 % of the rated airflow. If the flow rate cannot be regulated to such low value, a little more flow rate can also be used. It is shown from Fig. 17.24 that if the airflow rate for leakage detection increases to 30 % of the rated airflow (try to extend the curve to the left side), the penetration can be more than 3 times of that with the rated airflow, which can be used to distinguish the leakage without any difficulty. Of course, since the leakage hole sizes are different, it is very difficult to determine the exact flow rate for leakage detection.
Leak Detection with Scanning Method

This method is applicable for the leakage detection of both the filter unit and the mounted filter equipment. During the scanning process on filter unit, the leakage detection device with light can be used without the screen curtain. It is better to turn the device around so that filter is placed vertically to the ground, which facilitates the testing. When the combined equipment of air filter is tested and it is difficult to generate smoke upstream of the whole cross section since the upstream concentration needs to be increased, a smoke generation casing can be used at the back of each filter (see Fig. 17.25). Move it to the other filter when the measurement is finished on this filter.

During the leakage detection, it requires that the sampling probe is placed at 2–3 cm from the leeward-side surface of HEPA filter. Scanning is proceeded along the entire surface, the frame, and frame joint. Scanning speed should be 2–3 cm/s, which should not be larger than 8 cm/s and less than 0.5 cm/s. The scanning trajectory is shown in Fig. 17.26, where the trajectory can be overlapped to a certain extent.

When the leakage position is found, materials including the CPVC adhesive, No. 88 adhesive, No. 703 and No. 704 adhesive can be used to completely stop the leakage in site. However, the silicone rubber adhesive cannot be used in some electronic industrial production workshop, because they contain silicon component. Of course, this is only useful for surface leakage. When it is not allowed to seal the leakage hole, the air filter must be replaced.

One kind of leakage detection device for filter unit in foreign country is shown in Fig. 17.27 [26]. Of course, other aerosol can also be used as the artificial dust. This kind of special device is especially suitable for manufacturers and large project field.

Figure 17.28 shows the shape of automatic (also include the manual type) leakage detection device produced in China.
17.3 Leakage Detection

There are two kinds of leakage detection testers, including the photometer and the discrete particle counter. ISO 14644-3 has already pointed out that:

Fig. 17.26 Scanning trajectory. 1 outside frame, 2 scanning routine, 3 filter media, 4 separator

Fig. 17.27 Example of leakage detection device for HEPA filter. 1 prefiltet, 2 fan, 3 Laskin DOP generator (also called as the cold generator, see page 353 of Ref. [11]), 4 transition section, 5 rectification plate, 6 separator, 7 tested filter, 8 sampling pipe, 9 computer, 10 particle counter

17.3.1.3 Leakage Detection Tester and Aerosol

There are two kinds of leakage detection testers, including the photometer and the discrete particle counter. ISO 14644-3 has already pointed out that:
1. Photometer with DOP can be used to detect leakage for filters with penetration $\geq 0.005\%$, which corresponds with HEPA filters whose MPPS efficiency is not larger than $99.995\%$ (which is equivalent with Type B and C filters in China).
2. Photometer with DOP can be used in the applications where the gas released from the volatile organic test aerosol deposited on filter and pipeline has no harmful effect on the product and the process inside the cleanroom, such as the leakage detection of air filter in nuclear facility.
3. Particle counter with artificial aerosol is suitable for the leakage detection of filter with penetration $\leq 0.0000005\%$, which corresponds with filters whose efficiency is equal or larger than $99.9999995\%$ (with MPPS particles).
4. The method to use particle counter is more sensitive than the photometer. The resultant pollution is smaller. For leakage detection, it is more accurate and fast.
5. There are more than eight kinds of aerosol for leakage detection, such as phthalates, diethyl sebacate, PSL spheres, and atmospheric dust.

In the version published in 2008, it pointed out that when the atmospheric dust concentration is appropriate, particle counter can be used to detect the leakage with atmospheric dust.

17.3.1.4 Leakage Criteria with Penetration

For a long time, the leakage criteria are that when the penetration is larger than several times of the ordinary penetration of the whole filter media. As for the filter media, there is allowable common penetration. Once the penetration is larger than this value, it is considered as abnormal. But there is also fluctuation for common penetration. Therefore, the artificial magnification value is defined, and leakage occurs when the penetration is larger than it.
In the 1960s, the sampling flow rate of particle counter was 700 mL/min. Some foreign company specified that the leakage occurred when the penetration was five times larger.

In the Chinese Industrial Standard GB50591-2010 Code for construction and acceptance of cleanroom, the leakage criteria were also based on several times of the common penetration value.

In ISO 14644-3 published in 1999, the leakage criteria with penetration were specified, which is shown in Table 17.20. The factor in this table is the magnification of the leakage penetration compared with the whole penetration. When the magnification of penetration is larger than this factor, leakage occurs. At the same time, the sampling flow rate is specified as 28.3 L/min. This method is called the penetration method temporarily.

### 17.3.1.5 The Essence of Leakage

For a filter without leakage, no matter how much is the sampling flow rate, the particle number per unit liter of sampled air, namely, the concentration, is almost consistent (including the common fluctuation).

However, the penetration at the leakage position is related to the sampling flow rate. In the sampled airflow, there is the airflow from the leakage position, and there is also clean air through the filter ordinarily which occupies a large proportion. The larger the sample flow rate is, the more the clean air is. Since the number of particles through the leakage position is constant (for the given size of leakage hole and the given filter structure with known damage, when the differential pressure is constant, the leakage flow rate is constant), the penetrated particles will be diluted. In terms of this sample flow rate, when the local particle concentration decreases, the local penetration is correspondingly reduced.

For example, for a HEPA filter with the highest level according EU standard, if the penetration is 0.000005 % and the upstream particle concentration reaches $2 \times 10^7$#/L, the common penetration with the requirement in Table 17.20 is $\leq 1$#/L.

According to ISO standard, the leakage appears when the penetration for the leakage position reaches 301 times of the ordinary penetration for this filter, while there is no leakage when it is 300 times.

Suppose there is a leakage hole with the leakage flow rate 8,490#/min. When the sampling flow rate downstream is 1 L/min, the sampled concentration at the leakage position is 8,490#/L. Since the factor is 8,490, it is of course considered as filter with leakage.

When the sampling flow rate downstream changes to 2.83 L/min, the sampled concentration at the leakage position is 3,000#/L. Since the factor is 3,000, it is of course also considered as filter with leakage.

When the sampling flow rate downstream is 28.3 L/min, the sampled concentration at the leakage position is 300#/L. Since the factor is 300, it is considered as filter without leakage according to the standard.
Since the leakage flow rate is a fixed value, i.e., 8,490#/min, the conclusions of the leakage detection cannot be different when the sampling flow rate is different. It is shown that the leakage conclusion with the penetration is closely related to the sampling flow rate. So it is meaningless when the leakage conclusion is given when only the factor value is mentioned.

The reason is that the final sampled leakage concentration is diluted by the sampling flow rate 2.83 L/min or 28.3 L/min. The dilution factors by different sampling flow rates are of course different.

The most intuitional understanding is that leakage exists objectively. It exists when it is compared with non-leakage.

The essence of leakage is that under the certain differential pressure and the particle concentration upstream, the particle concentrations downstream are basically uniform for a complete air filter without leakage. If apparent nonuniform distribution appears, leakage is likely to exist. For a complete air filter, particles measured locally are almost continuous, and most of the time it is “0.” This is the purpose to use HEPA filter. But if at local position particles can be detected, leakage hole exits at this place which is corresponding to the upstream concentration.

17.3.1.6 Leakage Criteria with the Leakage Flow Rate Through Hole

With the above analysis, we proposed the leakage criteria based on the particle penetration rate based on the flow rate through the leakage hole [27, 28]. This method is termed as the leakage hole method (also called the penetration rate method).

From the electronic microscopic photo of HEPA filter paper in Chap. 3, the grid formed by glass fiber is random with different sizes. But it is shown that the length of single layer of grid can reach 30 \( \mu \)m.

The so-called leakage means the passage or the hole is formed by friction and prick on the fibrous grid. The outflow is formed through the hole, where the flow rate is larger than that through the normal multi-layer fibrous grid.

The outflow \( Q \) through the hole can be expressed with the classical formula as shown in Eq. 17.27:

\[
Q = \mu F \sqrt{\frac{2\Delta \rho}{\rho}}
\]

(17.27)

where

- \( F \) is the hole area, \( A = 0.78d_0^2 \);
- \( d_0 \) is the hole diameter;
- \( \Delta \rho \) is the differential pressure across the air filter (also the leakage hole). For the initial resistance during leakage detection, it is 200 Pa;
- \( \rho \) is the air density, 1.2 kg/m\(^3\);
- \( \mu \) is the flow rate coefficient, which is calculated with the following expression:

\[
\mu = \varepsilon \varphi
\]
where $\varepsilon$ is the contraction coefficient. It is a kind of complete contraction since the surrounding area of the hole is spacious, according to the definition of the fluid dynamics. The value of $\varepsilon$ is the minimum, i.e., 0.62.

$\phi$ is the flow rate coefficient, and the theoretical value is 0.82. The maximum value can be 1. The experimental maximum value is 0.97. For the expansion hole with the expansion angle $5^\circ - 7^\circ$, it is 0.45. For the crack and the hole with complex structure, the average experimental minimum value is 0.29. For the small leakage hole, which is only several times larger than the single layer of fiber grid, the influence of the complex fibrous edge of the hole is large. So the resistance becomes larger, and the flow rate coefficient becomes smaller. With the minimum value of $\phi$, we can obtain that $\mu = \varepsilon \phi = 0.62 \times 0.29 = 0.18$ (in Ref. [27], the value for the hole with diameter larger than 0.1 mm was assumed $\phi = 0.97$).

For the leakage hole shown in Fig. 17.29, it is simplified as a hole perpendicular with the surface of the airflow at the outlet face.

The cross section of the leakage airflow increases gradually, so the concentration is diluted gradually. This airflow is called the polluted airflow. This is caused by the induction of surrounding airflow. But this kind of expansion is not unlimited. When the air velocity at the boundary of the polluted airflow is close to that of the surrounding airflow, the induction effect stops.

Therefore, when the average velocity at the cross section of the polluted airflow decays to the supplied velocity at the outlet of the HEPA filter, expansion and dilution cannot be continued. Since the influence of the leakage airflow on the unidirectional flow is more prominent, the case with the unidirectional flow cleanroom is used as the basis. Suppose the supplied air velocity at the outlet of HEPA filter is 0.5 m/s, a series of parameters can be obtained with the jet flow theory, which is shown in Table 17.21.

In the table, $Q_0$ is the leakage flow rate; $S$ is the air supply range, which is the distance when the boundary of jet flow does not expand; $D$ is the diameter of the cross section when the boundary of jet flow does not expand; and $Q$ is the flow rate of the polluted airflow at the place $S$ after the leakage airflow expands and dilutes gradually.
Reference [27] presented three types of situations for the sampling probe during leakage detection process. The most common situation is the place 1 mm from the leakage hole, which is shown in Fig. 17.30.

When the sampling flow rate is larger than the dilution flow rate during the arrival of the polluted airflow to the sampling probe, all the penetrated particles will enter the sampling probe. Since the leakage flow rate $Q_0$ is very small, most of the sampling flow rate is the clean airflow from the surrounding area, so the sampled concentration will be reduced greatly. Suppose the sampling flow rate is $W$ L/min, the sampled concentration is

$$N_s = \frac{(W - Q)N_0K + N_x}{W}$$

(17.28)
where

\( N_x \) is the sampling concentration, \#/L;

\( N_x \) is the penetrated particle number, \( N_x = Q_0 N_0 \), 

\( W \) is the sampling flow rate, L/min.

According to the nonzero test principle for the minimum measuring volume introduced in previous chapter, the average concentration in each sampling volume should reach 3, and 95% of the readings are nonzero values, which can be determined as leakage. This is the essence of the leakage hole method (also called the penetration method).

### 17.3.1.7 Leakage Detection with the Scanning Method

It is obvious that it is quite difficult to detect the real leakage position during the scanning process which goes on quickly. As mentioned before, most readings at the place without leakage are “0.” When nonzero reading is found, the value is at least 1, which may be the possible leakage position. Reference [27] gives the characteristic parameter of the leakage, which is basically the same as ISO standard. The necessary upstream concentration \( N_0 \) for sampling particles \( \geq 1 \# \) during the scanning process is calculated with the following formula:

\[
N_0 K t \left( W - Q_0 \frac{Q}{Q_0} \right) + Q_0 N_0 t \geq 1
\]

where

\( t \) is the scanning time, min. \( t = B/(60v) \);

\( W \) is the sampling flowrate, L/min, which is usually 2.83 or 28.3;

\( B \) is the side length of the sampling probe along the scanning direction, cm;

\( v \) is the scanning velocity, cm/s.

So we obtain:

\[
N_0 \geq \left[ K \left( W - Q_0 \frac{Q}{Q_0} \right) + Q_0 N_0 \right] \frac{B}{60v} = \frac{Q_0 N_0}{Q_0 B} = \frac{60v}{Q_0 B} \quad (17.29)
\]

It is shown from the above equation that when the leakage hole is smaller, \( Q_0 \) becomes larger and the value of \( N_0 \) needed is larger.

Only when \( K > 0.0001 \), \( K \left( W - Q_0 \frac{Q}{Q_0} \right) \) is meaningful relative to \( Q_0 \). From HEPA filters, \( K \) decreases from 0.00001 (similar as Type A filter in China). So in above formula, \( K \left( W - Q_0 \frac{Q}{Q_0} \right) \) can be omitted.

The upper limit of upstream concentration is related to the whole penetration of air filter. With this upstream concentration, the common penetration should be significantly different from the possible leakage value 1#, such as 0.1–0.2#. In this way, particles can be detected in all the leakage positions, while in other places, no particles will be detected.
According to the analysis of Sect. 4.7, HEPA filter is defined as those with particle counting efficiency larger than 99.9 % for 0.3 μm particles, which is the so-called three 9 filter. The efficiency for particles ≥0.5 μm can be approximated as 99.999 % (five 9 filter). (The three 9 filter has efficiency 99.9975 %.)

Therefore, the upstream concentration of HEPA filter should not be >20,000#/L, while the upper limit for the UPLA filter with eight 9 efficiency (for particles ≥0.5 μm) is extremely large, so no limit is made for this kind of filter.

### 17.3.1.8 Leakage Detection at Fixed Position

After possible leakage position is found, leakage detection at fixed position must be performed with Fig. 17.30. The sampling concentration at fixed position should be calculated with Eq. (17.29).

For example, when it is just determined as leakage with the leakage hole method, will it also be determined as leakage with the penetration method?

For a ULPA filter with $K = 0.000005 \%$, when the sampling flow rate is 28.3 L/min according to ISO standard, the sampling concentration for the 0.5 mm leakage hole is

$$N_s = \frac{(28.3 - Q)N_0K + Q_0N_0}{28.3}$$
$$= \frac{(28.3 - 0.00038 \times 4.57) \times 8000 \times 5 \times 10^{-8} + 0.00038 \times 8,000}{28.3}$$
$$= 0.107#/L$$

So according to the penetration method, it is determined that the leakage penetration is $0.107/8,000 = 0.0013 \% < 0.0015 \%$, which can be used to judge that there is no leakage.

But according to the leakage hole method in this section, when the upstream concentration is 8,000#/L, the sampled particle number is 3.42# when the particle counter with the sampling flow rate 28.3 L is used, which is ≥3#. It is judged as leakage.

When the size of the leakage hole increases to 0.053 mm, the sampling concentration becomes:

$$N_s = \frac{(28.3 - 0.00427 \times 4.37) \times 8,000 \times 5 \times 10^{-8} + 0.00427 \times 8,000}{28.3} = 0.121#/L$$

According to the penetration method, the leakage penetration is $0.121/8,000 = 0.00151 \%$, which is >0.0015 %. It is determined as leakage.

When the upstream concentration becomes 9,000#/L or 10,000#/L, the leakage penetration is still 0.00151 %. In the above examples, the upstream concentration changes while the leakage penetration remains the same.

For a ULPA filter with $K \leq 0.00005 \%$, when the leakage hole size is 0.075 mm, it is determined as leakage with the leakage hole method. While the penetration is 0.003 %, which is <0.005 %, so it is without leakage with the penetration method.
When the leakage hole size increases to 0.97 mm, it is judged as leakage with the leakage hole method, and it is also determined leakage with the penetration method since the penetration is 0.0051 %, which is >0.005 %.

For a ULPA filter with $K \leq 0.0005 \%$, when the leakage hole size is 0.1 mm, it is determined as leakage with the leakage hole method. While the penetration is 0.0053 %, which is <0.015 %, it is without leakage with the penetration method. When the leakage hole size increases to 0.17 mm, it is judged as leakage with the leakage hole method, and it is also determined leakage with the penetration method since the penetration is 0.0155 %, which is >0.015 %.

For a HEPA filter with $K \leq 0.005 \%$, when the equivalent diameter of the leakage hole is 0.25 mm, the sampling concentration is:

$$N_s = \frac{(28.3 - 0.0094 \times 4.37) \times 400 \times 5 \times 10^{-5} + 0.0094 \times 400}{28.3} = 0.152\#/L$$

With the leakage hole method, when the upstream concentration is 400#/L and the sampled particle number is 4.32# with the sampling flow rate 28.3 L/min, it is $\geq 3\#$, which can be determined as leakage.

According to the penetration method, the leakage penetration is 0.15/400 = 0.038 %, which is smaller than 0.05 %. So it is without leakage.

When the leakage hole size increases to 0.3 mm, we obtain:

$$N_s = \frac{(28.3 - 0.0135 \times 4.37) \times 300 \times 5 \times 10^{-5} + 0.0135 \times 300}{28.3} = 0.158\#/L$$

With the leakage hole method, when the upstream concentration is 300#/L and the sampled particle number is 4.47# with the sampling flow rate 28.3 L/min, it is $\geq 3\#$, which can be determined as leakage.

According to the penetration method, the leakage penetration is 0.158/300 = 0.052 %, which is larger than 0.05 %. So it is also judged as leakage.

Although the penetration value changes, by the calculation of HEPA filter with $K \leq 0.05 \%$, the conclusions with both methods for the leakage hole with diameter 0.93 mm are that there is leakage on the filter. When the upstream concentration is 30#/L and the penetrated particle number is 4.3# in the sampling air volume, the penetration is 0.51 %, which is >0.5 %, so it is judged as leakage. From the above calculation examples, we know that as only as the leakage flow rate remains the same, the penetration calculated with the penetration method is the same, no matter how much is the upstream concentration. This means the penetration is only related to the leakage flow rate. This also means it is the essence of leakage when the leakage flow rate through the leakage hole is used for determination.

According to the result from past research, no matter what the penetration is, the conclusion of leakage occurrence can be made when the detected particle number is $\geq 3\#$ with the fixed detection position. It is of course the strictest requirement. But in order to be equivalent with ISO standard, the equivalent diameter of the leakage hole is specified for various HEPA filters when they are judged to have leakage, which is shown in Table 17.22.
Both $v$ and $B$ should be determined according to the specific condition and may be adjusted with Eq. (17.29), and the value of $Q_{0\text{min}}$ should remain the same for this kind of air filters. The maximum value of $B$ can be adjusted to 4 cm, and the minimum value of $v$ can be adjusted to 0.5 cm/s. When values of $Q_{0\text{min}}$ for various HEPA filters are inserted into Eq. (17.29), the minimum upstream concentrations can be obtained, which is shown in Table 17.23.

With the minimum upstream concentration, all the leakage particle numbers for various filters are $60 \times 0.5/4 = 7.5#$ in the sampled air volume.

Under the condition of the minimum sampling concentrations, when the leakage detection with the scanning method is used for the above leakage hole size, the detected particles will be $\geq 1#$, which may indicate the leakage position.

From the above analysis, we can know that:

1. For the particle counting concentration in the leakage hole method, the requirement for the upstream concentration is not high. According to ISO standard, atmospheric dust can also be used as one of the upstream dust sources. When atmospheric dust is used in the upstream, pollutions on the environment, test personnel and air filters can be avoided. When the atmospheric dust concentration is suitable according to 2008 version of ISO standard, it is recommended to use atmospheric dust as the upstream dust source. Usually the upstream concentration of HEPA filter in the general air cleaning system meets the above condition. Or measures can be taken to meet this condition. Before leakage detection, the upstream concentration should be checked.

Since for most HEPA filters $K > 0.000005 \%$, the least upstream concentration of channel 3 in Table 17.23, which is 5,208#/L, meets the requirement for most HEPA filters.

If the upstream concentration is too big, which is not adjustable, particle sizes of $\geq 0.7 \mu m$, $\geq 0.8 \mu m$, $\geq 1\mu m$ and so on can be used. Contrarily, particle size of $\geq 0.3 \mu m$ can be chosen. Or the following measures can be taken:

(a) Open the maintenance door at the downstream of air filter for fresh air in the air handling unit. Bypass the air filter for fresh air and draw the indoor air of the machine room.
(b) With the replacement method of air filter, uninstall one or two air filters for fresh air at one certain stage, or uninstall one or two air filters for fresh air at each stage.

2. The sampling flow rate of the instrument should not be specified for the leakage hole method. Results are the same no matter what kind of sampler is used.

3. Among the criteria, the leakage hole method is the most strictest. When three particles are detected in the sampling air volume, it is judged as leakage. It can be used to detect smaller leakage hole than the penetration method. When ISO standard should be followed as much as possible, criteria can be determined through simple calculation for any kind of HEPA filter or can be determined through negotiation (a certain amount of negative or positive deviation can be added on the equivalent diameter of the leakage hole).

4. It is not necessarily to choose particles with diameter \( \geq 0.5 \ \mu m \) for measurement. According to the concentration, particles with diameter \( \geq \) a certain value can be used.

Since for most HEPA filters, \( K > 0.000005 \ % \), the minimum upstream concentration 5,208#/L in Table 17.23 can meet the requirement of most HEPA filters.

If the upstream concentration is too large, which cannot be adjusted, particles with diameter \( \geq 0.7, \geq 0.8, \) and \( \geq 0.9 \ \mu m \) can be used. On the contrary, particles with diameter \( \geq 0.3 \ \mu m \) can be used. Or the following methods can be used:

(a) Open the repair door after the fresh air filter in the air handling unit. Bypass the air from the fresh air filter. Air from the equipment room can be extracted.

(b) Similar to the replacement of air filter, one or two filters in the certain stage of fresh air filters are uninstalled, or one or two filters are uninstalled at each stage.

17.3.2 Leakage Detection of Isolation Bioclean Cabinet

Because dangerous biological particles are dealt with in the isolation bioclean cabinet, the requirement for its sealing performance is very high, which includes the sealing and the negative pressure maintenance ability of the device (containers). There are the following methods to detect leakage for these two aspects.

17.3.2.1 Leakage Detection of the Sealing

Pressure Decay Method

The test system is introduced in Chinese national standard Code for construction and acceptance of cleanroom (GB 50591-2010), which is shown in Fig. 17.31.

The test steps with this method are as follows:

(a) The cleanroom temperature is controlled in the design range and kept constant. The variation of room temperature during the pressure decay test process is
recorded (the minimum indication value on the thermometer or temperature sensor should not be larger than 0.1 °C).

(b) Close all the doors and the delivery windows on the envelope of the cleanroom. Switch off the sealing valve on the return air (or exhaust air) pipeline. Other sealing measures are not allowed to take at the air outlet. The sealing status of various apertures and cracks is maintained.

(c) Turn on the air supply system so that the room pressure increases to the specified test pressure. (The test range of pressure should be at least 1.5 times of the test pressure. The minimum indication value should not be larger than 10 Pa.) When the pressure is stable, stop the air supply fan and then close the air supply valve.

(d) Or close the valve on air supply pipeline. If there is no valve on the air supply pipeline or the valve is not sealed well, the air supply outlet should be sealed with the plastic membrane and the plate, then turn on the exhaust air system. When the room pressure decreases to the specified test pressure, which keeps stable, stop the exhaust system and then switch off the sealing valve on the exhaust air pipeline.

(e) Since the stop of air supply (exhaust), the variation of pressure decay with time is recorded. The differential pressure and the temperature are recorded once every minute. It continues till the room pressure decreases to half of the initial pressure.

(f) When test completes, switch on the valve slowly till the room pressure recovers to the common state.

(g) If repeated test is needed, it should restart in 20 min.

Cao Guoqing, author, and others performed measurement with this method [29]. The laboratory dimension is 4.5 × 4.5 × 2 m. It is the assembly structure. The floor is the field pouring concrete. The door is sealed. All the visible cracks are sealed with the sealing glue.

Experimental results are shown in Fig. 17.32.

At the same time, the theoretical calculation (with the same volume of the room) was performed. The result is shown in Fig. 17.33.
It is shown that the experimental data with the model is basically consistent with the decay curve of the pressure with the theoretical calculation. But the decay velocity of pressure with the model experiment is obviously larger than the theoretical value. The reason may be that when the differential pressure is relative large, the sealing performance of the envelope structure may be damaged. This also means that it is very difficult to maintain the pressure.

Constant Pressure Method

In the Chinese standard GB50591-2010 *Code for construction and acceptance of cleanroom*, the test system with this method is shown in Fig. 17.34.

The test procedures with this method are as follows:

(a) The cleanroom temperature is controlled in the design range and kept constant. The variation of room temperature during the pressure decay test process is recorded (the minimum indication value on the thermometer or temperature sensor should not be larger than 0.1 °C).

(b) Close all the doors and the delivery windows on the envelope of the cleanroom. Switch off the sealing valve on the return air (or exhaust air) pipeline. If there is no valve on the air supply pipeline or the valve is not sealed well, the air return
grille should be sealed with the plastic membrane and the plate on the return air (or exhaust air) system.

(c) Turn on the air supply system so that the room pressure increases to 500 Pa. Then stop the air supply fan, and close the air supply valve.

The makeup air is supplied into the room with the air supply fan and the air compressor by the aperture and the pipe on the envelope. The flow rate of the makeup air is varied with the adjustment value on the pipe so that the pressure inside the cleanroom is maintained constant and does not reduce. The readings on the floating flowmeter are recorded every 1 min. This value means the leakage airflow rate. The test should last less than 5 min. Average value should be calculated.

(d) On the contrary, close the air supply valve, and then turn on the exhaust air system. When the indoor pressure reduces to \(-500\) Pa, close the exhaust air system. The vacuum pump is open to keep the indoor pressure. The leakage flow rate is recorded.

(e) When the test is finished, switch on the valve slowly so that the room pressure recovers to the common state.

(f) If needed, test can be repeated in 20 min.

The measured leakage ratios with above models are shown in Table 17.24. The relationship between the leakage ratio and the pressure is thus obtained, which is shown in Fig. 17.35.

It is shown that the larger the test pressure is, the quicker the increase of the leakage ratio becomes. This is consistent with the pressure decay method.

The converted leakage flow rates in the above table are the corrected values with the readings of the leakage flow rates. The correction expression is shown in Eq. (16.2).

In the Chinese standard GB50591-2010 Code for construction and acceptance of cleanroom, it is suggested to distinguish the sealing extent according to the half-life time of pressure with the pressure decay method. It is shown in Table 17.25.
With the constant pressure method, it is also suggest in the above standard that the sealing extent is classified with the leakage ratio, which is presented in Table 17.26.

In the table, $\alpha = Q/V$, where $V$ is the net volume of tested cleanroom (usually it is the room volume) (m$^3$); $Q$ is the hourly leakage flow rate from the readings in the previous 5 min with the tested pressure (m$^3$/h).

For the industrial cleanroom, the requirement of the sealing is not so strict. The usual methods are as follows:

(a) For small apparatus, after it is pressurized, kerosene or soap liquid can be coated on various cracks. Bubble will appear at the place where leakage exists.

(b) After the pressurization system stops, the pressure decay within the specified time period should be observed to determine whether it is larger than the specified value. For example, in the American Aerospace Standard, when the large space is pressurized to 25 Pa, the pressurization system stops. If the pressure does not recover to the original value within 1 h, it is considered as sealed.

---

**Table 17.24** Experimental relationship between the test pressure and the leakage ratio

| Test pressure Pa | Leakage flow rate reading (m$^3$/h) | Converted leakage flow rates (m$^3$/h) | Leakage ratio (%) |
|-----------------|------------------------------------|----------------------------------------|-------------------|
| 150             | 1.61                               | 2.79                                   | 4.92              |
| 250             | 1.80                               | 3.12                                   | 5.50              |
| 360             | 2.00                               | 3.46                                   | 6.11              |
| 500             | 3.20                               | 5.54                                   | 9.78              |
| 660             | 4.95                               | 8.57                                   | 15.12             |

Note: the room volume is 56.7 m$^3$

**Table 17.25** Classification of the sealing extents with the half-life time of pressure

| Sealing extent | Half-life time of pressure $T$ (the time when test pressure decays to half) (min) |
|----------------|----------------------------------------------------------------------------------|
| 1              | $\geq 30$                                                                        |
| 2              | $\geq 20$                                                                        |
| 3              | $\geq 10$                                                                        |
| 4              | $\geq 5$                                                                         |

---

**Fig. 17.35** Polynomial regression curve for the relationship between the test pressure and the leakage ratio
Halogen Method

The leakage detector made by the halogen effect can be used to detect the container filled with the halogen gas or the space with volume less than 30 m³. Common halogen gases used include Freon 12 (or 22) and chloroform. The former is nontoxic, incombustible, and especially sensitive (the sensitivity of domestic-made halogen leak detector is 0.5 g/year). During the leakage detection process, the instrument is powered on at first, and then the end of the receiver probe is aligned with the gap and moved slowly. If there is leakage, the sound of the instrument increases and the pointer will also move with a larger magnitude. When leakage detection is performed on a certain device, the room air where the device is placed should be checked at first. Leakage detection starts when it is sure that there is no halogen pollution indoors.

The smelt copper wire can also be used, which moves near the gap. If any fluorine steam seeps and comes into contact with the copper wire, the copper wire will become dark green, which can be used as a qualitative check.

Sulfur Hexafluoride Method

SF₆ gas is injected into the container or the device, the leakage detector corresponding with this gas is used to check. This instrument is made according to the mechanism that the degrees of ionization are different for SF₆ gas in high-frequency electromagnetic field. The lower detection limit is higher than the halogen method.

Ammonia Method

Fill the container with ammonia. Phenolphthalein test paper is used to check the possible leakage place. If the leakage gas contacts the test paper, the test paper will be pink immediately. Ammonia method is more sensitive than the halogen method, but the risk is big. The safety operation manuals with ammonia must be followed.

17.3.2.2 Leakage Detection for the Maintenance Stability of Negative Pressure

In order to check whether there is airflow spillover at the opening position of the biological cleaning device in operation, leakage detection for the maintenance
stability of negative pressure is needed. High-concentration aerosol (smoke, spore fog, or other gas) is released in the interior of the instrument; detection is performed in the external of the device for leakage check. (According to the relevant standards in the USA, when Bacillus subtilis aerosol is used in the test, the total number of bacillus generated is hundreds of millions to billions. The sampling dish with narrow seam is used for the external sampling of the device. The colony should not be more than 5# in each sampling dish.)

17.4 Cleanroom Measurement

17.4.1 Measurement Types of Cleanroom

17.4.1.1 Acceptance Measurement (Characteristics Measurement)

This is aimed to find out whether the performance of the cleanroom meets the requirements of the design or to study the characteristics of the cleanroom. Through this kind of measurement, reasons for the failure of the requirement can be found whether problems exist in the design, construction or process. In addition, this kind of measurement can also be the foundation to establish reasonable maintenance management system.

Before the measurement, full preparation must be made. The general condition of cleanroom should be fully understood, which includes the following: various related drawings, the requirement of the designed air parameters, the air handling scheme, the flow rate and the air distribution method, cleaning schemes for human and object, the operational condition of cleanroom, and the surrounding environment of the cleanroom.

This kind of measurement is the most comprehensive, which includes the following items:

1. Leakage detection. It is performed according to the requirements in the previous section.
2. Air volume. It includes the supply air volume, the return air volume, the fresh air volume, and the exhaust air volume.
3. Velocity field. It includes the velocity field along the longitudinal cross section through the center of ventilation opening, the planar velocity field on the working area, and other velocity field at any cross section where it is required. The sampling positions for the velocity field are the same as that for the concentration field.

For unidirectional flow cleanroom, requirements are made for not only the average velocity on the working area but also the turbidity (namely, the nonuniformity of velocity).
4. Airflow pattern. The most commonly used method is that several filaments are fastened on different positions of the rod. During observation, the plate with black background and white lines is placed at the back of the filaments. The angles of the filaments are recorded point by point. It is shown in Fig. 17.36. Then, the flow directions are plotted on the paper point by point. The plotted cross section is the same as the velocity field.

When it is possible, tracer particles can be released to show the streamline, which can be recorded by taking photos. Tracer particles are commonly used in the visualization technology for airflow. Continuous tracer particles include smoke and fog generated by some liquid. Discontinuous tracer particles include feathers from some animals, plant seeds, and chemical crystals such as metaldehyde, foam plastic particles, the floccule by heating the solid alcohol, and bubbles produced by some foaming agent.

Figure 17.37 is the schematic diagram of the smoke generator with the smoke particles as the tracer particles, which is used for streamline measurement. The power supply for the smoke generator can be a blower or a handheld pinched ball. Observation of the streamlines with smoke generator is often performed with the velocity field measurement simultaneously.

Figure 17.38 shows a bubble generator. This is the first time that this kind of bubble generator is used in air cleaning technology in China for streamline visualization experiment [30]. The foaming agent is the Type 1227 surfactant produced in the detergent factory, which is diluted to the concentration 20% and mixed with a small amount of foam stabilizer. The mixture gas with air and helium from the foam generator can produce many small bubbles with diameter 4 mm. When proper proportion of helium and air is kept, the bubble density can be equivalent with that of air.
If the parallelism of the streamline is needed, it is measured with the concept of parallelism. The distance of lateral diffusion at the leeward side is measured, and the smoke is generated upstream.

5. Static pressure. The differential pressure between indoors and outdoors should be measured when the door is closed. Besides, according to the requirements for the positive pressure, the airflow direction should be inspected to find out if it can be kept in the outward flow when the door is open. Moreover, the particle concentration at the height of working area 0.6 m inside the door (this is also required in *Code for construction and acceptance of cleanroom* and related standard abroad [31]) should be checked whether it is higher than the required value corresponding to the air cleanliness level of cleanroom.

6. Filter efficiency at various stages. Measurement methods listed in Table 17.6 should be used.

7. Concentration field (including dust concentration and bacteria concentration). The sampling locations can be the same as that for measuring velocity field. For
cleanrooms with different cleanliness levels, the number of measuring positions is different, which should be determined with the relevant requirements introduced later. The measurement positions are placed in the cell centers which divide the measuring plane uniformly.

8. Self-cleaning time. Before the operation of the air cleaning system, the original concentration in the cleanroom is measured at first. Then, operate the system immediately. The variations of concentrations are measured with time during each sampling step. It continues until the concentration is obviously stable. If the original concentration is too low, smoke can be generated indoors at first. When particles are accumulated to a certain concentration, stop generating smoke and measure the concentration (usually in the center of the room) as the original value. Then, start up the system immediately, and measure the decay of concentration with time. The time from the starting up to the appearance of stable concentration is called self-cleaning time. The self-cleaning process curve can be plotted. Recently, in some standards for the application of air cleaning system in operating rooms, the time needed to remove 90 % or 99 % of the pollutant concentration is termed as the self-purification time.

9. Others. This includes temperature, humidity, air distribution and streamline, noise, illumination intensity, vibration, and other parameters, which can be referred to Ref. [11].

For the above items, some are compulsory, which are included in the content of “evaluation of comprehensive performance” and specified in detail in Code for construction and acceptance of cleanroom (GB50591-2010). It is the first time that formaldehyde is listed as the compulsory test item.

17.4.1.2 Monitoring Measurement (Daily Measurement)

This is aimed to determine whether the performance of the cleanroom can be kept. It also provides the basis for the parameter adjustment of the system. The measurement should be performed with the purpose of understanding the performance of cleanroom correctly. With the daily test data from several sampling positions, the whole indoor environment can be correctly derived. Otherwise, even if the measured data at certain places are obtained, it is hard to solve the problem with this kind of measurement, when the nonuniform distribution indoors is not understood, the daily variation data are not obtained, the limits of these main parameters (such as the design condition, the load condition, the operational condition of equipment) are unknown, and the influences of these basic factors are unclear.

As the sampling position for monitoring measurement, the controlling points should be chosen according to the performance of cleanroom or placed near the operating site. Usually sampling places can be arranged with the diagonal five-point layout method, which is shown in Fig. 17.39. The number of sampling points can be increased appropriately when the area of cleanroom is more than 40 m². For the turbulent flow cleanroom, sampling probe should not be placed right under the filter.
In order to reflect the characteristic and monitor the system, this kind of measurement should be performed in accordance to a predetermined plan. The representative sampling points or fixed points should be chosen during a regular time interval.

The monitoring measurement items should include the air volume or air velocity, the static pressure, the dust concentration, or bacteria concentration. The specific practice can be referred to the acceptance test. Other items can be measured according to the need.

17.4.1.3 Special Measurement (Temporary Measurement)

This is aimed to find out the temporary and local reason for problems. For example, when the production yield declines, in order to find out if there is a local pollution source, it is measured temporarily.

The main measurement items include the dust concentration and the air velocity. Sometimes the static pressure and the local streamline should also be measured.

17.4.2 Test Status of Cleanroom

In 1973, the test status of the cleanroom was first proposed [31]. It is the so-called empty status when the air cleaning system is already operated, when the process equipment is not installed. It is the so-called static status, once the process equipment is installed and put into operation, but there is no working staff indoors. It is the so-called dynamic status when the air-conditioning system and the process equipment are in operation with the presence of staff indoors. This classification method for the status was brought in the US Federal Standards 209C and 209D since 1987. It is also adopted in ISO 14644-1 EU GMP and GB50073-2001 “Code for Design of Clean Room” in China, which are shown in Tables 17.27, 17.28 and 17.29 [32].

It is obvious that any activity should exist in at-rest status. The implication of “at-rest” include “rest” and “still”. If there is no personnel inside but there is production machine in operating condition, this is not the essence of “static”.

![Five sampling positions method](image)
Therefore, it is suitable to call “empty status”, “static status” and “dynamic status” as “completion status”, “shutdown status” and “operational status”, respectively.

It is quite common during the actual test process for cleanroom project that HAVC system runs normally while the installed process production equipment is not operating. The condition with operating equipment inside and without personnel can only be found in mechanized, automatic, and closed production cleanroom. It is ubiquitous in the workshop for semiconductors. But it is rare in other kinds of cleanrooms. GMP cleanroom workshop is one example.

In order to include several conditions, GB50591 “Code for Construction and Acceptance of Cleanroom” specifies three statuses, which are:

- Process equipment is not operating and there are no personnel inside;
- Process equipment operates with the mode agreed upon by the custom and the supplier, and there are no personnel inside;
- Operation stops and steady state is reached after self-purification process.

| Table 17.27 Definition of occupancy status in cleanroom by US federal standard |
|-----------------------------------------------|------------------|------------------|------------------ |
| Fed-Std-209C  | Fed-Std-209D  | Fed-Std-209E  |
| At-rest cleanroom (facility) | A cleanroom (facility) that is complete and has the production equipment installed and operating, but without personnel within the facility. | A cleanroom (facility) that is complete and has the production equipment installed and operating, but without personnel within the facility. | A cleanroom (facility) that is complete with all services functioning and with equipment installed and operable or operating, as specified, but without operating personnel in the facility. |

| Table 17.28 Definition of occupancy status in cleanroom by ISO standard |
|-----------------------------------------------|------------------ |
| ISO 14644-1-1999 and ISO 14698-1-2003 |
| At-rest | Condition where the installation is complete with equipment installed and operating in a manner agreed upon by the customer and supplier, but with no personnel present. |

| Table 17.29 Definition of occupancy status in cleanroom by EU standard |
|-----------------------------------------------|------------------ |
| EU GMP |
| At-rest | The “at-rest” state is the condition where the installation is installed and operating, complete with production equipment but with no operating personnel present. “at-rest” state should be achieved after a short “clean up” period of 15–20 minutes (guidance value) in an unmanned state after completion of operations. |
17.4.3 Necessary Sampling Points

During the measurement of large clean space such as the cleanroom, because of the random particle distribution, coincidence rate is very large if the air cleanliness level was determined only with one sampling position. Obviously, the more the sampling positions are, the better it is. But there is a problem of economy and possibility, so the number of necessary sampling points should be found.

17.4.3.1 20 Points Reference Method [33]

It is already known that indoor dust distribution has some characteristics. The concentration of each sampling which contains more than ten particles in the sampling volume basically obeys the normal distribution. So 95 % of the measured data should fall in the range of $\frac{X}{C_6} = \sqrt[2]{\frac{1}{C_6}}$, where $\sigma$ is the standard deviation. Based on the statistics of measured data, for applications with air cleanliness level between Class 100000 to Class 10000, $\frac{X}{C_6}$ is between 1.6 and 1.8 (here only the upper limit of the concentration deviation is used). As for the concentration of each sampling which contains more than 3.5 particles, 95 % of measured data are likely to be within the range of $2X$. As for the concentration of each sampling which contains more than 1 particles, 94 % of measured data are likely to be within the range of $2X$.

In addition, from the nonuniform distribution calculation theory of cleanroom introduced above, the biggest difference between the measured concentration and the room average concentration is about $2X$ in cleanroom with air cleanliness levels Class 6 and higher, where $X$ is the room average concentration. For cleanroom with air cleanliness levels Class 7 and Class 8, the difference is about $1.5X \sim 1.8X$. These theoretical conclusions are very close to the previous measurement results.

Therefore, for the normal measurement, it is allowable that 5 % of the data are more than the required values. If more than 5 % of the tested data are larger than the requirement, this measurement can be considered as abnormal and the reliability of the data is doubtful.

Since the number of measuring points is only an integer, when it should be assured that less than 5 % of the measured data are larger than the required value, the total number of measuring points should be 20 at least. If at each sampling place, it is required to sample at least two times, so there should be at least 10 test points. And in all the measured data, the frequency of the measured value which is more than $2X$ should be at most once. So the method can be called 20 points reference method.

It is still not comprehensive to perform measurement with the number of measuring points determined in this way. For high cleanliness occasions, the second type of error may also easily appear because of less measuring points.

If the air cleanliness of the cleanroom has not reached a certain level, but a group of data within this air cleanliness level may be obtained as a result of randomness of dust distribution and shortage of the measurement times, it is possible to judge that
this cleanroom has reached this level. In this way, the unqualified cleanroom will be
misjudged as qualified. This kind of error is the second type of error, whose
probability is set as $\beta$. In project $\beta$ is generally set less than 10–15 %. In order to
make $\beta$ smaller, there must be enough sampling points or sampling times. The
probability is $\beta$ for the occurrence of more than $k$ times which is qualified ($k/m \geq 0.95$) for the unqualified cleanroom during the total sampling $m$ times.

The probability of the appearance of $k$ times with qualified conclusion and $(m-k)$
times with unqualified conclusion can be described with binomial distribution, namely,

$$P(\xi = k) = C_m^k P^k (1 - P)^{m-k} \quad (17.30)$$

$$C_m^k = \frac{m(m-1) \cdots (m-k+1)}{k!} \quad (17.31)$$

where $P$ is the probability for the incident when it is not more than a fixed value.

Then the probability $\beta$ of no less than $k$ qualified samples in the total $m$ samplers
in the unqualified cleanroom is:

$$\beta = P(\xi \geq k) = C_m^k P^k (1 - P)^{m-k} + C_m^{k+1} P^{k+1} (1 - P)^{m-k-1} + \cdots + C_m^m P^m (1 - P)^0 \quad (17.32)$$

If $\beta$ is very small, it means that the probability of the qualified conclusion from
measurement is still very small, since the parent sample is unqualified. As we know,
when the sampling positions are not enough, it is still very likely to obtain the
qualified conclusion, which is out of our expectation. This also means that for a little
qualified cleanroom, it is very likely that the measurement results show the qualified
conclusion with great possibility and the probability to obtain qualified conclusion is
very small.

In engineering, $\beta$ is generally taken less than 10–15 %.

For example, in a clean space where the concentration is allowed to be 0.04#/L,
when every sampling volume is 75 L, the detected particle number should not
exceed 3#, which can be judged as qualified. According to the given formula in
Chap. 1, the probability to obtain particles with number less than 3 in this clean
space can be calculated, i.e., $P(\xi \leq 3) = 0.646$.

If the actual concentration is greater than 0.04 grains/L, the actual probability is
$P < 0.64$, which can be assumed $P = 0.63$. However, in this occasion with unqual-
ified cleanroom, even if the number of sampling points is not enough, samplers with
the above probability can also be measured. With the above formula, trial calculation
can be performed with the above 20 points (times) as the basis. The probability
with $k$ subsamples that are qualified is:

$$\beta = C_{20}^{16} \times 0.63^{16} \times 0.37^4 + C_{20}^{17} \times 0.63^{17} \times 0.37^3 + C_{20}^{18} \times 0.63^{18} \times 0.37^2$$
$$+ C_{20}^{19} \times 0.63^{19} \times 0.37^1 + C_{20}^{20} \times 0.63^{20} \times 0.37^0 = 0.086$$

If $k = 15$, then $\beta = 0.18$.
If $m = 20, k = 8$, then $\beta = 0.18$. 

$854$ 17 Measurement and Evaluation
This suggests that in 20 sampling points (times), if there are at least 16 sampling points (times) which contain no more than 3# and there is at most 1 sampling point (time) which contains more than $2 \times 3 = 6$#, then we can confirm that in the detection volume, there is less than 3#, so misjudgment will not be made. If in 20 sampling points (times), there are only 15 sampling points (times) which contain less than 3#, the possibility of appearance of the average concentration larger than 0.04#/L is large. If the number of sampling points decreases to 10 points (times), even if there are less than 3# in the sampling volumes of 80% points, the possibility is still greater for the concentration larger than this value, so it is likely to make misjudgment for the unqualified cleanroom.

So, if both kinds of errors are required to be decreased or when one kind of error decreases at one place while the other kind does not increase, the number of samplers, namely, the sampling points (times) $n$, should be increased. The greater the number of sampler is, the more concentrated the average sampled distribution is.

If the concentration is as small as 0.02#/L, when the sampling volume 0.1 L is used, it contains 0.002# in each sampling volume. So more than hundreds of sampling points (times) may be needed. This is why cleanroom with high air cleanliness level cannot be measured with the sampling volume 0.1 L even when dozens of minutes or dozens of hours have been taken.

According to the above principle, the calculation results are shown in Table 17.30.

Before the test, $\lambda$ is not given, so the number of necessary sampling points should be determined according to the estimated value of $\lambda$. If the measured $\lambda$ is much smaller than the estimated $\lambda$, the number of necessary sampling points should be reconsidered according to the measured $\lambda$.

With the development of particle counter, $\lambda$ will not be less than 1. So for general situation, it is most appropriate to place 20 points. If the space is small, the number of sampling times can be used to replace the number of sampling points. Suppose at least two times of sampling are performed for each point, the total sampling points can be 10. On contrary, when the space is very big, more sampling points can also be added on the basis of 20 points. This is all considered for engineering in the practical point of view.

Later, the number of sampling points proposed in Japanese standard is similar to the calculated value with the above method, which is shown in Table 17.31.

### 17.4.3.2 $t$ Test Method

Detailed description is presented in Sect. 17.5 of this chapter.

### 17.4.3.3 Compromised Method in 209C

It is troublesome to determine the number of sampling points with the above statistic methods, and it is obviously not so convenient to place more than 20 sampling points. Therefore, two contradictory claims were put forward by revisers for the US Federal Standard 209B [5, 34]. One opinion is that the number
of air cleanliness level should have the inverse relationship with the sampling points, so the numbers of sampling points between high and low air cleanliness levels are quite different. The other opinion is that sampling points has nothing to do with the air cleanliness level, and each sampling point corresponds with the air supply area 25 ft² or the number of area expressed in ft² is equal to the square root
of the air cleanliness level. No matter which kind of opinions, the number of sampling points is far less than the number of the above 20 points. Finally, 209C adopted a compromised plan:

1. The number of sampling points should not be less than 2 (for any clean areas). At least one sampling time is needed at each point. In a zone, at least 5 times of sampling are needed.

2. According to the air supply area or the room area, the smaller value of the following results should be chosen as the number of sampling points (M is the number of air cleanliness level with the international unit system):

   For unidirectional flow
   
   \[
   (a) \quad \frac{\text{Air supply area (ft}^2\text{)}}{25} \quad \text{or} \quad \frac{\text{Air supply area (m}^2\text{)}}{2.32}
   \]

   \[
   (b) \quad \frac{\text{Air supply area (ft}^2\text{)}}{\sqrt{\text{Air cleanliness level (English unit)}}} \quad \text{or} \quad \frac{\text{Air supply area (m}^2\text{)}}{\sqrt{10^M}}
   \]

   For turbulence flow
   
   \[
   \frac{\text{Room area (ft}^2\text{)}}{\sqrt{\text{Air cleanliness level (English unit)}}} \quad \text{or} \quad \frac{\text{Room area (m}^2\text{)}}{\sqrt{10^M}}
   \]

Table 17.32 shows the number of sampling points calculated with the above method.

From the above explanation, we can see that the specification of the necessary sampling points number between 209C and 209E is based on a kind of compromised
way [34]. In ISO 14646-1 published in 1999, the method to calculate the number of sampling points can be further simplified as:

\[
\text{Minimum number of sampling points} = \sqrt{\text{Area of cleanroom}}
\]

There is no specific statistical significance with these methods. Although they are convenient for use, the disadvantage is also obvious.

### 17.4.4 Continuous Sampling Method

For cleanrooms with air cleanliness level higher than Class 100, the dust concentration is extremely low. If the principle introduced in the previous chapter must be followed that 20 particles must be sampled, the sampling time must be very long. In order to shorten the sampling time, the US Federal Standard 209E put forward the “continuous sampling method.” The essence of this approach is that the conclusion about the qualification of air cleanliness level is made with the appearance speed of particles (namely, the length of appearance time). Then, we can write as follows:

\[
T = \frac{Q}{L}
\]  

(17.33)

where

- \(T\) is the required sampling time (when 20 particles are detected) (s);
- \(Q\) is the minimum sampling volume (m\(^3\));
- \(L\) is the sampling flow rate of the instrument (m\(^3\)/s).

Because

\[
Q = \frac{20 \, (#)}{\text{upper limit of concentration with the corresponding air cleanliness level (#/m}^3\text{)}}
\]

So we know:

\[
T = \frac{20}{NL}
\]  

(17.34)

Assume that the possibility with the time that particles are measured is uniform, the number of particles measured in unit time is:

\[
\Delta N = \frac{20}{T} \leq \frac{20NL}{T20} = NL(#/s)
\]  

(17.35)
Then, the time that every particle is measured in turn is:

\[ T = \Delta N \cdot E = NLE \quad (17.36) \]

where \( E \) is the measured particle number in turn (#).

Based on the relationship between the expected sampling time \( t \) and the measured particle number \( E \), the judgment diagram given in 209E (see Fig. 17.40) can be used to judge whether the sampling is qualified.

Now let’s take an example as follows [35]:

For the measurement of cleanroom with air cleanliness level Class M2.5 (the former Class 10 in 209E), the upper-limit concentration for \( \geq 0.5 \) \( \mu \)m particles is 353#/m\(^3\). Since the number of sampled particles should not be less than 20, the sampling flow rate is 20/353 = 0.056 m\(^3\). If the flow rate of the instrument is 5.66 L (0.2 ft\(^3\)), it takes 1 min. When \( E = 20 \), the total sampling time is 10 min, so the total sampling volume needed should be 56.6 L. In the measurement:

1. When the sampling flow of the instrument is 5.66 L, if the counting numbers appeared in order are 1, 2, 0, and 0, four consecutive samplings are qualified. The qualification test purpose is obtained when the total sampled air volume is only 5.56 L = 22.64 L. So the measurement time is shortened.
2. With the same condition, if the numbers of sampled particles in order are 2, 3, 3, 2, and 5, the five consecutive samplings are unqualified. The total sampling flow rate is 5.66 L \( \times \) 5 = 28.3 L. So when the sampling flow rate is less than the
predetermined value 56.6 L, it is concluded that the air cleanliness level has not reached Class M2.5.

3. If the cumulative counted particle number does not intersect with the upper and the lower boundaries when the total sampling volume has reached 56.6 L and the cumulative counted particle number is still less than 20, this cleanliness level can be reached.

Although continuous sampling method was given in 209E, the limitations of this approach were also pointed out, mainly:

1. The method is only valid when the number of each sampled particles is 20#.
2. During each measurement, the monitored data and data analysis are required as appendix (although it can be done by computer).
3. The average dust concentration calculated with the measured results is not very accurate, mainly because the sampling volume is too small.
4. When the sampling points are less than 10, the requirement with 95 % upper confidence limit is not generally easily achieved.

### 17.4.5 Factors Influencing Measurement Result

There are many factors affecting the measurement result of particle concentration in cleanroom, which mainly include the following: whether people wear clean clothes, whether people are at rest indoors and less active, whether it is located in the downwind, and whether people enter in and out. In addition, there are reports that the printer on the particle counter has a great influence on the measurement results [36], especially for high-grade cleanroom. Unqualified results are easily produced if the printer is used. The related experimental data are shown below.

Table 17.33 shows the concentration in the cover when both the printer and its printing paper were covered by clean covers, while only wires are connected to the instrument.

Table 17.34 shows the effect of two locations for the printer.

The above results indicate that if the printer is used, these printer and printing paper with less particle generation must be used or the printer should be kept away
from the sampling position. For cleanroom with higher air cleanliness level, it should be more careful with the application of printers. Of course, this should be noticed especially by the particle counter manufacturers.

17.5 Evaluation of Air Cleanliness in Cleanroom

17.5.1 Evaluation Standard of Air Cleanliness in Cleanroom

The air cleanliness level is evaluated with the particle concentration. So the evaluation of the air cleanliness level is the evaluation of the particle concentration.

17.5.1.1 Estimation Method with Fixed Value

The so-called estimation method with fixed value is the method to estimate the total average concentration $N$ with the randomly sampled particle concentration values $N_1, N_2, \ldots, N_n$. This parameter in the axis is a single position, so in the statistics it is called the estimation method with fixed value or the estimation method with fixed point.

| Printer location | Sampling No. | Printer turned off (measure 3 or 4 times after steady state is reached) | Printer turned on (measure 3 or 4 times after steady state is reached) | Ratio of concentration between printer turned on and turned off | Size of printing paper (length × width) (mm × mm) |
|------------------|--------------|---------------------------------------------------------------------|---------------------------------------------------------------------|----------------------------------------------------------------|-----------------------------------------------|
| Above the device | 1            | 2 3 2 1 3 3 1 0                                                   |                                                                     |                                                                  |                                               |
|                  | 2            | 4 2 4 6 2 4 1 1.2 160 × 44                                        |                                                                     |                                                                  |                                               |
|                  | 3            | 2 7 5 18 18 11 3.4 270 × 44                                       |                                                                     |                                                                  |                                               |
|                  | 4            | 6 6 10 12 11 15 1.7 500 × 44                                      |                                                                     |                                                                  |                                               |
|                  | 5            | 4 3 3 7 7 10 2.4 710 × 44                                         |                                                                     |                                                                  |                                               |
| Near the device  | 1            | 2 2 1 8 5 2 3 3.6 1,030 × 44                                      |                                                                     |                                                                  |                                               |
| Clean cover is used to mantle the printer and printing paper, except the electric line which connects with the device | 1 | 3 0 2 0 0 1 1 5 1.4 1,220 × 44 | | | |
Evaluation with the Sampled Mean Value

Estimation is performed with the sampled mean value, namely, the average particle concentration:

\[ N = \frac{1}{n} \sum_{i=1}^{n} N_i \]  

(17.37)

where \( N_i \) is the mean value at each point.

The standard deviation of the average value \( \bar{N} \) is smaller than that of individual measured value. Only when the former is only \( \frac{1}{\sqrt{n}} \) of the latter, it is closer to the true particle concentration \( N \).

In order to obtain mean values at each position with greater credibility, the requirements in Table 17.18 should be satisfied. The purpose is to show that the distribution of concentration field has a certain pattern, which is not accidental.

If both the sampling volume and the number of measurements meet the requirement, but the number of the controlled value is larger than the required number, it is necessary to increase the average concentration. For example, there are some measurement data in a cleanroom (detection volume 1 L):

\[ \ldots \# / \text{L}, \ldots 6\# / \text{L}, 7\# / \text{L}, 8\# / \text{L} \]

There are 20 times of measurement (10 points) in total, and the average concentration \( \bar{N} = 3\# / \text{L} \). For concentration larger than 2 \( \bar{N} \), there are only two times including 7#/L and 8#/L, which does not meet the requirement of the allowable number 1. So the average concentration should be increased to 3.5#/L, and the number of particle concentration larger than 2 \( \bar{N} \) is only one time, which is 8#/L.

Evaluation with the Maximum Value of the Sample

With this method, any concentration in the cleanroom is not allowed to be larger than the required particle concentration with the corresponding air cleanliness level. This is specified in some foreign standards. But the necessary sampling points are not specified, so this method is also not strict, and sometimes larger error may be obtained.

17.5.1.2 Evaluation with Interval Estimation

Single-Side \( t \) Distribution Test

The so-called interval estimation is to estimate the overall average concentration \( N \) based on a random concentration interval. This interval is called the confidence interval or the confidence limits (upper or lower). It means the probability of the
overall $N$ falling in a certain range. This probability is called the confidence probability, which is expressed as $P$.

In practice, they can be considered as continuous variables, whose average concentration $\overline{N}$ can be used to estimate the overall mean concentration $N$. According to the theory of mathematical statistics, there are two conclusions as follows:

(a) If the whole population is normally distributed, $\overline{N}$ is also normally distributed.
(b) If the whole population does not completely follow the normal distribution, as long as the number of samples (measured points) increases, which reached $n \geq 30$ in general, the distribution of $N$ can be approximately considered as normal distribution. From Chap. 1, the characteristics of the normal distribution depend on its total average value $\overline{N}$ and the total standard deviation $\sigma$ (or $\sigma^2$), that is,

$$\phi(N) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(N-\overline{N})^2}{2\sigma^2}}$$  \hspace{1cm} (17.38)

If $\overline{N}$ can be approximately described with the normal distribution, the standard deviation of the large samplers can be used to replace the total standard deviation $\sigma$ (or $\sigma^2$). But in the actual test of dust concentration, the number of measurement points are rarely more than 30, which are all small samplers. In this case, it is the deduction with small samplers, where the value of $\sigma$ is unknown. If the estimated value $S$ of the standard deviation (in fact, it is the standard deviation of average value) is used to replace $\sigma$, it has been proved with mathematical statistics theory that the statistical variable $\mu = \frac{N-\overline{N}}{\sigma}$ in above expression will change to $t = \frac{N-\overline{N}}{S/\sqrt{n}}$, and it becomes $t$ distribution instead of normal distribution.

According to the Bessel correction, we know for small samplers:

$$S = \sqrt{\frac{\sum (N-\overline{N})^2}{n-1}}$$

It can be used to replace

$$\sigma = \sqrt{\frac{\sum (N-\overline{N})^2}{n}}$$

Let

$$\frac{S}{\sqrt{n}} = \frac{\sigma}{\sigma_N}$$

It is called the error of the average value, then:

$$t(\alpha,f) = \frac{N-\overline{N}}{\sigma_N}$$  \hspace{1cm} (17.39)
When $\bar{N}$ is bigger or smaller than $N$, we can get

$$N = \bar{N} \pm t_{(\alpha, f)} \sigma_N$$  \hspace{1cm} (17.40)

where

- $t$ is the confidence factor, which can be found from the $t$ distribution table (see Table 17.35). It varies with the significance level $\alpha$ and the degree of freedom $f = (n - 1)$. It is also called the $t$ distribution coefficient;
- $\alpha$ is the significance level and also called the risk factor. It is the possibility of the estimated value falling out of the specified interval:

$$\alpha = 1 - P$$

$P$ is the degree of confidence or the confidence coefficient, which reflects the reliability degree.

- $t$ distribution curve is not a curve; instead it is a group of curves with the change of $f$, which are symmetrical to the ordinate. When $n - 1 < 10$, the curve is low and flat, which is greatly different from the normal distribution curve. When $n - 1 > 30$, $t$ distribution curve is similar with the normal distribution curve. When $n - 1 > 100$, $t$ distribution curve can be replaced with the normal distribution curve directly. When $t \to \infty$, they are strictly consistent with each other.

What should be noticed is that there are two forms of $t$ distributions including the unilateral and the bilateral distributions. Bilateral distribution is used when both

| $n - 1$ | 0.2 | 0.1 | 0.05 | 0.02 | 0.01 |
|--------|-----|-----|------|------|------|
| 1      | 3.078 | 6.314 | 12.706 | 31.821 | 63.657 |
| 2      | 1.886 | 2.920 | 4.303   | 6.956 | 9.925 |
| 3      | 1.638 | 2.353 | 3.182   | 4.541 | 5.841 |
| 4      | 1.533 | 2.123 | 2.776   | 3.747 | 4.604 |
| 5      | 1.476 | 2.015 | 2.571   | 3.365 | 4.032 |
| 6      | 1.440 | 1.943 | 2.447   | 3.143 | 3.707 |
| 7      | 1.415 | 1.895 | 2.365   | 2.998 | 3.499 |
| 8      | 1.397 | 1.860 | 2.306   | 2.896 | 3.355 |
| 9      | 1.383 | 1.833 | 2.262   | 2.821 | 3.250 |
| 10     | 1.372 | 1.812 | 2.228   | 2.764 | 3.169 |
| 15     | 1.341 | 1.753 | 2.131   | 2.602 | 2.947 |
| 20     | 1.325 | 1.725 | 2.086   | 2.528 | 2.845 |
| 30     | 1.310 | 1.697 | 2.042   | 2.457 | 2.750 |
| 40     | 1.303 | 1.684 | 2.021   | 2.423 | 2.704 |
| $\infty$ | 1.282 | 1.645 | 1.960   | 2.326 | 2.576 |
| $n - 1$ | 0.1 | 0.05 | 0.025  | 0.01  | 0.005 |

Probability of $t$ value larger than the indicated value in the table (bilateral side)

Table 17.35 $t$ distribution coefficient

Probability of $t$ value larger than the indicated value in the table (single side)
upper and lower limits are required, which is shown in the Fig. 17.41. If it is assumed $\alpha = 0.05$, it occupies 0.025 at each side.

For the particle distribution in cleanroom, people only care about whether the highest concentration is more than the concentration limit corresponding with the air cleanliness level, while the lowest concentration does not affect. So unilateral $t$ distribution should be used for the test. For example, in 209E the upper limit of confidence is 95%; as shown in Fig. 17.42, $\alpha = 0.05$ for unilateral distribution. By comparing two figures, we can see that $t_{0.05}$ for unilateral distribution equals with $t_{0.1}$ for bilateral distribution and $t_{0.025}$ for unilateral distribution equals with $t_{0.05}$ for bilateral distribution.

As introduced before, when $n / \bar{C} \geq 30$, $t$ distribution should be used for the test. But when $t$ distribution is used, the value of $n$ can be different. The necessary measurement points can be calculated according to the calculation method about $t$ distribution [37]. Here only the result derived by statistical methods is given. For normal distribution,

$$n \geq 8 \left( \frac{t_{\infty, \alpha}}{K} \right)^2$$  \hspace{1cm} (17.41)
where

$n$ is the necessary measurement points;

$K$ is constant, which is the $1/\sigma$ of the estimated data distribution interval length,

\[ K = 1/\sigma. \]  Usually it is 1;

$t$ is the $t$ distribution coefficient determined with the value of $\alpha$ and $f \to \infty$.

When the calculated $n$ is a big value which corresponds with a big sample, $t$ is close to normal distribution when $n \to \infty$, which does not need correction. If $n$ is a small sample, $t$ is close to the $t$ distribution, which needs correction. The calculated value of $n$ is used to obtain $t_{2n-2, \alpha}$, which is then substituted into the above formula to get the new value of $n$. The difference is usually small.

**Example 17.1.** When 95% of the data for the unilateral $t$ distribution are required to fall into the interval of one time of $\sigma$, how many measurement points are needed?

**Solution.** From the question, we know $1 - \alpha$ (unilateral) = 0.95. Looking up Table 17.35, we can get $t_{1, \alpha} = 1.645$. Since $K = 1$, so we get

\[ n \geq 8\left(\frac{1.645}{1}\right)^2 = 21.6 \]  (which can be taken as 22)

Because the number of samplers is small, correction is needed. Because $f = 2$

\[ n - 2 = 42, \]  we can look up the table and get $t_{42, 0.05} = 1.684$:

\[ n \geq 8\left(\frac{1.684}{1}\right)^2 = 23 \]

It can also be seen from the results that both the former 20 points standard method and Japanese standards which require the number of measurement points to be between 20 and 30 are in accordance with the statistics, while the required number of measurement points and the total sampling times in 209C–209E are less. Even Mr. Peck, the committee chairman of IES-RP-50 who modified 209B, also pointed out that [5], “this will not reach the statistical qualified 95% confidence. So there is no reason to make 95% as a requirement. In these areas, a series of evaluation should be carried out.” This comment should draw attention.

**Assessment Standards**

US Federal Standard 209C proposed two indispensable criteria with the interval estimation method to assess the air cleanliness. These two criteria are:

(a) The average concentration at each sample point with $n$ sampling times $\leq$ upper limit of concentration corresponding with the air cleanliness level.

(b) 95% upper confidence limit of the average concentration of all sampling points, namely, the room average concentration (i.e., the room average statistical value) $\leq$ upper limit of concentration corresponding with the air cleanliness level.
When these two criteria are met, the air cleanliness has reached that level. ISO 14644-1 also made the same specification, which corresponds to the test with maximum concentration plus statistical test in fact.

The first criterion requires the existence of more than one measuring point. The number of sampling points specified in standard is a function of the measured area. As mentioned earlier, in fact, both the number of the measurement points and the total number of sampling times specified in 209C–209E are less than normal. Given the possible accidental error, the average concentration at one sampling point instead of one sampled concentration is used in this standard.

The second criterion requires the uniformity of measurement results (namely, the variation rate of concentrations at the measurement point is small). According to the specification in 209E, this has influence only for the application with less than 10 sampling points (209E has no limit for sampling points), because it is more difficult to reach the standard specified value. By this criterion, it shows that time is saved if the number of measuring points is less but at the expense of the air cleanliness. The statistic value with less point is higher than that with more points. In addition, if the measurement data is close to the upper limit of concentration corresponding with the air cleanliness level, or although there is a very low concentration data, the difference between the data is big; the statistic measurement result may be larger than the value specified in the standard. In this case, the number of measuring points should be appropriately increased.

According to 209E, \( t \) distribution will not be used when the number of measuring points is less than 10, so it is simplified to the test with maximum concentration.

### 17.5.2 Dynamic-to-Static Ratio

The particle concentration specified with the corresponding air cleanliness level is independent with the test state. But when the particle concentration under the as-built and at-rest status is compared with that under the operational status, the average concept should be introduced, namely,

\[
\frac{\text{Particle concentration at operational status}}{\text{Particle concentration at at-rest status}}
\]

It is called the dynamic-to-static ratio \([38]\).

As mentioned before, the indoor particles in the cleanroom are mainly from the human activities. The ratio of the particle generation rate per unit volume (including the amount of surface particle generation) between the human activity and the human rest can be calculated. For a cleanroom with area larger than 1 m\(^2\), it can be assumed two people inside for test, so the maximum occupant density during measurement is 0.2 p/m\(^2\). According to the available information at home and
abroad, for turbulent flow cleanroom, the occupant density during work period is generally not more than 0.3; then we can obtain:

$$\frac{G_{n0.3}}{G_{m0.2}} = \frac{6.5 \times 10^4}{1.3 \times 10^4} = 5$$

If the area of cleanroom is more than 10 m², the ratio will be less than 5. When the staff density is greater than 0.3, the ratio will be greater than 5, but this is in a few situations. That means 5 is a relatively big number. Is it suitable to use the expression of $G_n/G_m$ to represent the dynamic-to-static ratio of the particle concentration? First, $N$ is proportional to $G$. Second, some experimental data also shows that most of the dynamic-to-static ratios are less than 5 [35]. Figure 17.43 shows the relationship summarized based on the operation experience of cleanroom with the published papers at both home and abroad [39]. It indicates that the difference of particle concentration is about 5 times between working and non-working periods.

In short, the operational particle concentration in general can be obtained when the as-built particle concentration measured for the acceptance test is multiplied by 5.

The above is about turbulent flow cleanroom. In the US Air Force Standard T.O.00-25-203, the ratio between the design standard and the operating standard for turbulent flow cleanroom is also 5 times.

For unidirectional flow cleanroom, there is no any foreign national standards which specify the dynamic-to-static ratio. In the US Air Force Standard above, the difference between the design standard and the operating standard for the unidirectional flow clean bench was stipulated with 10 times. But with the technical requirements for acceptance test in the USA for cleanroom with air cleanliness level Class 100 (ISO Class 5) [35], regardless of the as-built state or the at-rest state, the number of particles equal to and bigger than 0.5 μm per cubic foot is less than 10, and the number of the particles equal to and bigger than 1 μm is 0. This means the dynamic-to-static ratio for particle concentration in unidirectional flow cleanroom should be 10.
In China, there are two views on this issue. One view is that due to the characteristics of unidirectional flow, the particles generated can be removed immediately, so the dynamic-to-static ratio can be 1. Another point of view is that since the particle concentration for unidirectional flow cleanroom is very low, the concentration will change immediately once disturbance occurs. So for the safety reason, there should be a value for the dynamic-to-static ratio. As discussed before in the section about the lower limit of the air velocity, the pollution control ability of unidirectional flow cleanroom is really strong, which supports the first view. However, occasional factors cannot be excluded. For safety, it is also appropriate to define the dynamic-to-static ratio with a small value (such as 1 or 2 times). This value specified in “Air Cleaning Technical Measures” was 3, but now it seems that it is also feasible to set the value 2.

Here the example presented in Chap. 13 will be illustrated. The designed particle concentration cannot choose the maximum value corresponding with the air cleanliness level. For the cleanroom with air cleanliness level Class 7, the designed particle concentration cannot be 350#/L. As mentioned in Chap. 11, when other factors are taken into consideration, it is better to choose the upper limit of concentration with 1/2–1/3, namely, 175–120#/L.

### 17.5.3 Correction to Atmospheric Dust Concentration

For the cleanroom with air cleanliness level Class 5 or lower than Class 5, no matter how much is the atmospheric dust concentration during the test, the test results can be applied to all the conditions. While for cleanroom with air cleanliness higher than Class 5, it is necessary to make correction for the atmospheric dust concentration [40], namely,

\[
\bar{N}' = AN_s + \bar{N}
\]  

(17.42)

where

- \(\bar{N}'\) is the average concentration in the cleanroom after correction (#/L);
- \(\bar{N}\) is the average concentration measured by normal methods before correction (#/L);
- \(N_s\) is the particle concentration of the supplied air (#/L);
- \(A\) is the atmospheric dust correction coefficient:

\[
A = \frac{10^6 \# / L - M \# / L}{10^6 \# / L}
\]  

(17.43)

\(M\) is the atmospheric dust concentration during measurement.
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