In order to ensure the reliability of the measurement results of particle concentration, except for the reasonable detecting method and the sophisticated detection equipment, the correct sampling principle to minimize the sampling errors must be followed, which requires that people who carry out the measurement should master the correct sampling theory.

16.1 Sampling System

Sampling is generally divided into the planktonic method (the airborne state of sampled particles remains the same) and the capture method (airborne particles are captured).

In the capture method sampling system, there are a few instruments: the sampler (as the clamp of a filter material, it is preferably made of stainless steel with the commonly effective diameter 25 mm, as shown in Fig. 16.1), the sampling tube (usually plastic pipe), flowmeter (the float flowmeter is commonly used; the flow rate is 0–30 L/min), vacuum pump (vacuum degree ≥300 mmHg; the flow rate ≥30 L/min), and valve (the needle valve or other fine-tuned valve).

In the planktonic method sampling system, it is mainly composed of the dust analyzer (such as a particle counter) and the sampling tube.

When the sampling system is designed, there are two problems should be paid attention to. One is the orientation of the sampling probe, and the other is the position of the flowmeter.

16.1.1 Orientation of the Sampling Probe

The opening of the sampler or the sampling pipe should face the airflow direction. Otherwise, if there is an angle, due to the inertia effect some particles will deposit...
onto the inner wall of the tube or the mouth edge, while some cannot enter the sampler or the sampling tube, so that the resultant collected particle number is less than the actual value. Figure 16.2 shows the curve about the effect of the inclination angle between the sampling mouth and the direction of the flow [1]. When the angle is less than 30°, for particles with diameter less than 10 mm, the sampling error is less than 5 %. Figure 16.3 provides a curve which can be used to calculate this kind of error more accurately [2].

One accurate method is to obtain the direction with the maximum dynamic pressure, i.e., the airflow direction, when the pitot tube is used.

When sampling is performed outside, the filter material should be perpendicular to the ground to avoid the deposition of large particles or debris on the filter material.

### 16.1.2 Position of Flowmeter

The essence of this problem is the influence of additional resistance on the flowmeter. The calibration of flowmeter is carried out in the environment with certain resistance (i.e., the additional resistance at the entrance of the flowmeter), pressure, and temperature, but in the actual application period, all these conditions changed,
so it will certainly affect the original calibration value. In particular, the additional resistance caused by sampler, filter, and valve is often neglected, so it is necessary to emphasize this point.

Figure 16.4 shows the experimental system to investigate the influence of additional resistance caused by different installation positions of the flowmeter [3].

For the completely same flowmeters 1 and 2 (after calibration), they are connected in series and \( K_1 \) is placed in between to create resistance. Its value is indicated by 3. Flowmeter 1 reflects the standard flow, and flowmeter 2 reflects the flow under different resistances. When the vacuum pump is turned on, it can be found that the flow rates showed by the flowmeter 1 and 2 are different. The former
is less than the latter. The larger the resistance is, the larger the difference is. If $K_1$ and $K_2$ are adjusted in the way that the value indicated by the flowmeter 2 is fixed while the resistance of $K_1$ varies, the variation of the values indicated by flowmeter 1 is shown in Fig. 16.5.

The main reason for this result is that air pressures inside the two flowmeters are different due to the additional resistance caused by spiral clamp $K_1$. When air enters from the bottom of the flowmeter 1, there is almost no additional resistance (flowmeter calibration is often carried out in this case). When air goes through $K_1$, the resultant air pressure in the flowmeter 2 decreases. According to the principle for orifice flowmeter and float flowmeter, when the same gas under different conditions is measured with a flowmeter, the following relationship about flow rates can be obtained:

$$\frac{q_1}{q_2} = \sqrt{\frac{\rho_2}{\rho_1}}$$ (16.1)

where

$q_1$ and $q_2$ are the indicated flow rates under two kinds of working conditions; $\rho_1$ and $\rho_2$ are gas densities under two kinds of working conditions.

It is known that the gas density $\rho$ is proportional to the pressure $P$ and is inversely proportional to temperature $T$. The above expression can be written as

$$\frac{q_1}{q_2} = \sqrt{\frac{P_2}{P_1} \times \frac{273 + t_1}{273 + t_2}}$$ (16.2)
where

\( P_1 \) and \( P_2 \) are the pressures upstream of the flowmeters under two different working conditions (the air pressure in calibration condition is generally one atmospheric pressure or 760 mmHg. The air pressure in measurement condition is the subtraction of the absolute value of the readings of the pressure gauge upstream of the flowmeter from the local atmospheric pressure \( B \) or the subtraction between \( B \) and the known additional total resistance before the flowmeter. Only in the circumstance with the sampler, the total resistance becomes the resistance of the filter media under the sampling velocity.); \( t_1 \) and \( t_2 \) are air temperatures in two different working conditions, which is generally \( 20^\circ C \) in calibration condition.

There are two kinds of consideration methods for the application of this expression.

The first consideration method. Let the indication value \( q_2 \) represent the scale value in calibration condition, \( q_1 \) the indication value to be measured in the actual working condition, \( P_2 \) one atmospheric pressure in calibration conditions, and \( P_1 \) the pressure in the measurement condition; it is obvious that \( P_1 < P_2 \), and \( q_1 > q_2 \) (for the convenience of discussion, it is assumed that there is no difference for the temperature), namely, the actual flow through the flowmeter is greater than the indication value. This is because of the reduced density and the decreased air pressure in the flowmeter.

The second consideration method. Let the indication value \( q_2 \) represent the actual measured indication value, \( P_2 \) the actual measured pressure, and \( q_1 \) the indication value with the calibration pressure \( P_1 \); it is obvious that \( P_2 < P_1 \) and \( q_1 < q_2 \), i.e., the actual indication value \( q_2 \) in actual condition should be reduced to \( q_1 \) in the calibration condition, which is always easily neglected by people. The round dots in Fig. 16.5 are the indication values in the calibration condition after calculation (the temperature difference is ignored), and the value agrees well with the experimental data.

If the above two calculation results should be converted to other conditions, the following equation can be used:

\[
q' = q_1 \frac{P_1}{P'} \frac{T'}{T_1}
\]

(16.3)

where the superscript “‘” in the equation represents the conversion state, such as the calibration state, standard state, sampling state, and special state in the flowmeter. The subscript “1” means the adopted symbol during the application of Eq. (16.2) with one of the two consideration methods.

As for what kind of the destination state of conversion, it depends on the need. For example, in inspection process of product quality or quality accident, the actual local particle concentration should be known, so it should be converted into the sampling state. For the general measurement, for the purpose of comparison, it should be converted to calibration state or standard state. So for the general
measurement, the second method to correct the flow rate should be used, because after correction the result under calibration state is obtained, which no longer needs state conversion.

According to the influence of the additional resistance on the flow rate, the following points in the sampling should be paid attention to:

1. When the particle concentration is measured with the filter method, under the premise of the particle collecting efficiency, the filter material with small resistance should be used, and the resistance of the pipeline should be reduced as much as possible.

2. When the flowmeter is installed at the suction end of a vacuum pump, the valve used to regulate the flow must be installed behind the flowmeter, as shown in Fig. 16.6. It should not be installed between the sampler and the flowmeter. If the flowmeter is installed at the exhaust end of the vacuum pump, there should be a buffer bottle between the flowmeter and the vacuum pump. Particularly for removing large oil drops during the use of mechanical pump, apparatus such as valve and filter cannot be placed outside of the buffer bottle, as shown in Fig. 16.7.

If sampling is performed in the cleanroom, the vacuum pump can only be placed indoors. Because the exhaust of vacuum pump must pass HEPA filter, it is not suitable to place the flowmeter at the exhaust end.

3. When filter paper is used as the media, because the resistance during sampling is not more than 30 mmHg, so its influence can be neglected. When microporous
membrane filter is used for sampling, because its resistance during sampling is often more than 100 mmHg, the influence of this additional resistance on the indication value of flow rate will be more than 10%. Therefore the result must be corrected.

Now examples for calculation will be given as follows:

Example 16.1. During the indoor sampling in a cleanroom, the indication value of the flowmeter is 20 L/min, and the sampling time is 16 min. The resistance of sampling filter material (microporous filter membrane) under the sampling flow rate is 150 mmHg. After calculation, the total number of particles is 102,000 under the air temperature 300 °C and the air pressure 750 mmHg during measurement. What kind of air cleanliness level can be achieved in the room?

Ans:
1. The flow without any corrections
   Total sampling flow rate is \( q = 20 \times 15 = 300 \text{ L} \)
   The average particle concentration is \( N = \frac{102,000}{300} = 340 \# / \text{L} \)
   So the air cleanliness in this room reaches Class 7.

2. Flow rate after correction
   With the first consideration method: (a). The actual flow rate through the flowmeter. The reading value of the flowmeter 20 L/min is the indication value in the calibration condition, so the actual flow rate \( q_1 \) through the flowmeter should be
   \[
   q_1 = q_2 \sqrt{\frac{P_2}{P_1} \times \frac{273 + t_1}{273 + t_2}} = 20 \sqrt{\frac{760}{750 - 150} \times \frac{303}{293}} = 22.891 \text{ L/min}
   \]

   (b). The flow rate after conversion into other states
   - Calibration state \( q' = 22.89 \times \frac{293}{260} \times \frac{600}{303} = 17.47 \text{ L/min} \)
   - Standard state \( q' = 22.89 \times \frac{273}{760} \times \frac{600}{303} = 16.28 \text{ L/min} \)
   - Sampling state \( q' = 22.89 \times \frac{303}{760} \times \frac{600}{303} = 18.31 \text{ L/min} \)

   With the second consideration method: (a) The indication value in calibration condition
   \[
   q_1 = q_2 \sqrt{\frac{P_2}{P_1} \times \frac{273 + t_1}{273 + t_2}} = 20 \sqrt{\frac{750}{760} \times \frac{293}{303}} = 17.47 \text{ L/min}
   \]

   (b) The flow after conversion into other states
Standard state \( q' = 17.47 \times \frac{273}{760} \times \frac{760}{293} = 16.28 \text{ L/min} \)

Sampling state \( q' = 17.47 \times \frac{303}{750} \times \frac{760}{293} = 18.31 \text{ L/min} \)

Inner flowmeter state \( q' = 17.47 \times \frac{303}{600} \times \frac{760}{293} = 22.89 \text{ L/min} \)

3. Particle concentration

Now the particle concentration in sampling state becomes

\[ N = 340 \times \frac{20}{18.31} = 371.4 \# / \text{L} \]

According to the actual collected particle concentration 18.31 L/min after correction, the calculated indoor particle concentration is 371.4#/L, so the indoor air cleanliness level does not reach Class 7.

From the above calculation result, it is found that the influence of additional resistance cannot be overlooked.

### 16.2 Isokinetic Sampling

#### 16.2.1 Sampling in Flowing Air

**16.2.1.1 Principle of Isokinetic Sampling**

When sampling is taken in the flowing air (especially when in the pipeline), the plane of the sampling mouth should be vertical to the direction of the air flow (namely, the axis of the sampling pipe and the direction of flow are the same), and the sampling velocity must be equal to the air flow velocity. Otherwise, the sampled concentration (i.e., the measured concentration) will be greater than or less than the true concentration, which will cause an error. This is the principle of the isokinetic sampling.

On the left of Fig. 16.8, the airflow velocity \( u_0 \) is greater than the sampling velocity \( u \). In this case, the boundary limit of flow inhaled into the sampling tube is less than the diameter \( d \) of the sampling tube. If there are large particles outside the boundary limit of the inhaled flow or outside of the streamline with diameter \( D_0 \), it will not follow the streamline to flow along the tube wall when it approaches to the tube mouth; instead it will enter the tube due to the inertial effect. Small particles on this boundary limit will not enter the tube. In this way, in the same sampling air volume, particles outside this air volume will be carried to enter the tube, especially
the large particles. So the sampled concentration of large particles increases, which means the whole sampled concentration will be higher than the actual concentration.

On the right in Fig. 16.8, the airflow velocity $u_0$ is less than the sampling velocity $u$. In this case, the boundary limit of the flow inhaled into the sampling tube is bigger than the diameter $d$ of the sampling tube. Even if there are big particles within the boundary limit of the inhaled flow or within the streamline range with diameter $D_0$, when it approaches the tube mouth, it will not enter into the tube but instead flow away along the tube wall, and only small particles in the streamline can enter into the tube. So in the same volume of airflow entering into the tube, particles especially big particles will be lost. So the total sampled concentration will be less than the actual one.

Therefore, factors that affect the sampling concentrations mainly include the difference between the air flow velocity $u_0$ and the sampling velocity $u$ (i.e., the velocity at the sampling mouth), the dimensionless inertial parameter describing the inertial effect (Stokes parameter) $St$. The form of the expression is

$$\frac{N}{N_0} = f\left(\frac{u_0}{u}, St\right)$$

(16.4)

where

$N$ is the sampled concentration;

$N_0$ is the real concentration.
As for the error caused by non-isokinetic sampling, the following semi-theoretical formula [4–6] is now widely used:

\[
\frac{N}{N_0} = 1 + \left[ \frac{u_0}{(u - 1)} \right] \alpha \tag{16.5}
\]

In Refs. [4, 5] it provides:

\[
\alpha = -\left( \frac{2 + 0.617 u}{u_0} \right) St \frac{1}{1 + \left( 2 + \frac{0.617 u}{u_0} \right) St} \tag{16.6}
\]

In Ref. [6] it provides:

\[
\alpha = -\left( \frac{2 + 0.617 u}{u_0} \right) St \frac{1}{1 + \left( 2 + \frac{0.617 u}{u_0} \right) St} \tag{16.7}
\]

It is shown that the relationship between \( \frac{N}{N_0} \) and \( \frac{u_0}{u} \) is more obviously demonstrated directly in Eq. (16.6) (published in 1980) than Eq. (16.7) (published in 1994), so Eq. (16.6) was referred by 209E. The difference of the results with the two formulas is little, and the latter is slightly larger.

From Eq. (16.5), it is shown that the general characteristic is:

\[
\frac{u_0}{u} = 1 \quad \frac{N}{N_0} = 1 \quad St = 0 \quad \frac{N}{N_0} = 1
\]

\( St >> 1 \frac{N}{N_0} \approx \frac{u_0}{u} \) (for the situation when particles are very big, and the flow rate is large, and the diameter of the sampling tube is very small);

\( St = \text{const} \) (the larger the difference between \( u_0 \) and \( u \) is, the greater the concentration difference is)

\( u_0/u = \text{const} \) (the larger \( St \) is, the bigger the concentration difference is)

When both Eqs. (16.5) and (16.6) are plotted in Fig. 16.9 [7], the above feature can be vividly demonstrated.

It is shown that:

1. In the conditions of non-isokinetic sampling in the wide range \( u_0/u = 0.012–25.76 \), as long as \( St \neq 0.001 \), or \( u_0/u = 0.15–3 \) and \( St \neq 0.01 \), the sampling error \( \neq 5\% \).

Because large particles are the sampled object in the field of dust removal technology, the requirement for the velocity deviation is less strict when error
is $\neq 5\%$. For example, in Japanese standard JIS Z8808, the sampling error for non-isokinetic sampling is within $\pm 5\%$ when the error of non-isokinetic velocity is between $-5\% \sim +10\%$.

2. The influence at the situation $u_0/u > 1$ which has slower sampling velocity (as on the right of Fig. 16.9) is much larger than that at the situation $u_0/u < 1$ which has faster sampling velocity (as on the left of Fig. 16.9). This is also the reason why the negative deviation is less than the positive deviation specified in JIS Z88-8.

Professor Hinds (W.C. Hinds) at Harvard University of USA also obtained similar relationship diagram as Fig. 16.9 [2] based on Eq. (16.6). US Federal Standard 209E also gives the relationship between $u_0/u$ and the error. The comparison is shown in Table 16.1.

Now one example is given as follows:
Suppose $d_p = 0.5$ and $5\,\mu m$, $u_0 = 0.5\,m/s$, $D_0 = 6.5\,mm$, $u = 1.42\,m/s$ (the sampling flow rate is $2.83\,L/min$) or $14.2\,m/s$ (the sampling flow rate is $28.3\,L/min$), and $\rho_p = 1 \times 10^3\,kg/m^3$.

At $20\,^\circ C$, $\mu = 1.83 \times 10^{-5}\,Pa\cdot s$. From Table 6.4, it is found that $C = 1.33$ ($0.5\,\mu m$) or $1.03$ ($5\,\mu m$). The following results can be obtained with Eq. (3.7) (conversion of unit can be found in Sect. 6.2):

$$St_{(0.5\,\mu m)} = \frac{1.33 \times 1 \times 10^5\,kg/m^3 \times (0.5 \times 10^{-6})^2 \times 0.5\,m/s}{18 \times 1.83 \times 10^{-5}Kg.m/s/(s^2.m^2) \times 6.5 \times 10^{-3}\,m} = 0.00008$$

Fig. 16.9  Relationship among the sampled concentration, $u_0/u$ and $St$
Table 16.1  Relationship between \( u_0/u \) and the sampling error

| Source                                              | \( u_0/u \) | \( St \) | Equivalent diameter (\( \mu \)m) | Error by non-isokinetic sampling (%) |
|-----------------------------------------------------|--------------|----------|-----------------------------------|-------------------------------------|
| Relationship diagram proposed by author based on Eqs. (16.5) and (16.6) | 0.15–3       | ≈0.01    | 7                                 | ≈5                                  |
| Relationship diagram proposed by Dr. Hinds (USA)     | 0.1–10       | ≈0.01    | 7                                 | ≈5                                  |
| Illustration of the measurement error by non-isokinetic sampling in 209E (USA) | 0.143 (=1/7)−3.33 (1/0.3) | ≈0.006 5 | ≈5                                  |

\[ St(0.5 \mu m) = 0.006 \]

So from Eq. (16.6) we can obtain:

\[
\begin{align*}
\alpha(0.5 \mu m) & = 0.00046 \\
\alpha(5 \mu m) & = 0.033 \\
\alpha(0.5 \mu m) & = 0.0017 \\
\alpha(5 \mu m) & = 0.105
\end{align*}
\]

\[ u = 1.42 \text{ m/s} \]

The calculated results about the big error with large flow rate are shown below:

| 0.5 \mu m | Relative error 0.17 % |
|-----------|-----------------------|
| 1 \mu m   | 0.52 %                |
| 2 \mu m   | 2.03 %                |
| 3 \mu m   | 4.15 %                |
| 4 \mu m   | 7.1 %                 |
| 5 \mu m   | 10 %                  |
It should be emphasized that, as pointed out in Chap. 16 and relevant literatures [7], the unit of $\mu$ during calculation of $S_t$ must be paid attention to. If the engineering unit in the past is used, the value of $\mu$ decreases by 9.8 times, which will increase the particle loss rate by 9.8 times and will draw different conclusions.

The above results show that the error with non-isokinetic sampling for $\leq 1 \mu$m particles is less than 1 % even when particle counter with the sampling flow rate 28.3 L/min is used. But it reaches 10 % for $\geq 5 \mu$m particles.

If the requirement of sampling error is not only for particles with a certain size, but also for whole particles with diameter larger than a certain size such as $\geq 0.5 \mu$m, it should be calculated according to the standard distribution of particle size.

From Chaps. 2, 3, and 7, when suppose particles with diameter $\geq 0.5 \mu$m occupy 100 %, particles with diameter 0.5 $\mu$m occupy 33% ~ 38 %, so:

| Diameter Range | Percentage |
|----------------|------------|
| 0.5–1 $\mu$m   | 83–86 %    |
| 1–3 $\mu$m     | 9–12 %     |
| 3–5 $\mu$m     | 2–4 %      |
| 5 $\mu$m~      | 1–3 %      |

It can be calculated that the error is 1–1.9 % for all the particles $\geq 0.5 \mu$m with large sampling flow rate, and the average is 1.5 %. Apparently the error is much smaller with the small sampling flow rate. This result is much smaller than the experiment data in the wind tunnel, but the error of the experiment data is 4.2 % on average [8], which is also less than 5 %.

### 16.2.1.2 Application of Isokinetic Sampling

For sampling of large particles in the flow field with large velocity fluctuation, such as the sampling in the field of dust removal technology, the error will be 5 % by the velocity deviation 10 %. The application of isokinetic sampling is mentioned in all the monographs about this aspect, where the allowable error is also mentioned to be more than 10 % [9–12]. The velocity is required to be controlled strictly in these literatures. One method is the prediction of velocity. When a micromanometer is connected to both inside and outside of the sampling probe, the sampling velocity is adjusted so that the indication value is 0. Of course, when the sampling flow rate changes, it is necessary to use the cumulative flowmeter, and the rotameter is only for the purpose of surveillance and control. In addition, there is another method called isodynamic pressure method. Chinese Academy of Preventive Medicine has developed a specialized isokinetic sampling probe.

In cleanroom, it is obvious that the velocity field is stable. But it is not uncommon that the velocities at many positions are different from the average velocity by one time, or even much larger (e.g., in the blinder area below the shadowless lamp holder in the center of the operating table, where the air cleanliness must be measured). The transient change rate of velocity at each position can
also be more than one time (as shown in Fig. 8.30). Because of the time difference at each sampling position, the variation of velocity may be offset with each other. Literatures have emphasized that the isokinetic sampling procedure must be followed. But the feasibility of isokinetic sampling at various measurement positions in large space is much less than that in the pipeline. In unidirectional flow cleanroom, the sampling velocity can be chosen to be the average velocity. But in turbulent flow cleanroom, it is meaningless to mention the average velocity. So for the measurement of the concentration field in space, the allowable error should be considered. All test results have errors. If the error is within the allowable range, the test results can be accepted. 209E proposed that the error less than 5 % is acceptable which is caused by non-isokinetic sampling. It also points out that when \(\frac{u}{u_0}\) is between 0.3:1 and 7:1, the error is less than 5 %.

The diagram to make correction was also given as appendix C in 209E, which is shown in Fig. 16.10.

![Fig. 16.10 Estimation diagram about the necessity to make correction for the sampling deviation in 209E](image)

The example of the application of Fig. 16.10 is shown as follows:

When the particle counter with small sampling volume 2.83 L/min is used to detect particles with diameter 5 \(\mu\)m (only for this particle size) from airflow with velocity 0.5 m/s, should any correction be made?

**Ans:** We know that \(\frac{u}{u_0} = 1.42/0.5 = 2.84\), and \(St = 0.006\) for 5 \(\mu\)m particles, so point A can be found on Fig. 16.10, which falls in the area where correction is not needed. So there is no need for correction.
The specification of isokinetic sampling is listed below from the main standards, which is shown in Table 16.2.

It is shown that no matter what the particle size and the allowable error are, 209D required isokinetic sampling for unidirectional flow. But for 209E, isokinetic sampling is needed only when the error is >5 % for particles ≥5 μm, where the flow pattern is not specified. In fact it is turbulence flow. Because particle counter with small sampling flow is used, the sampling error is smaller and influence exists only for large size particles. So 209E clearly pointed out: “although isokinetic sampling is good, if it is not feasible, the sampling deviation should be estimated with the method in appendix C,” “It is only meaningful for particles with diameter equal to or larger than 5 μm in clean area by non-isokinetic sampling.” In ISO14644-1, it only kept the specification about the minimum sampling volume and the probe orientation which were given in 209E, while the requirement of isokinetic sampling is not explicitly mentioned. This is identical with the general opinion of 209E. Although the sampling error is big for particles ≥5 μm with non-isokinetic sampling, a lot of practice shows that 10 μm particles do not exist in cleanroom, and 5 μm particles do not exist in high-level cleanroom either, and only a few exist in low-level cleanroom. So the influence on the particle number is small, which can be used for the understanding of ISO specifications.

The next chapter will illustrate that the sampling error including the non-isokinetic sampling by particle counter will generally not exceed the standard estimation range.

Based on the above analysis, we can suggest that (sampling error ≯ 5 % is used as the standard):

1. Under the condition of \( \frac{u_0}{u} = 0.012 \text{--} 25.76 \), as long as \( St ≯ 0.001 \), isokinetic sampling is not required.
2. For sampling in cleanroom according to the current domestic and international standards, isokinetic sampling is not required for particles ≥5 μm.
3. If particle counter with large sampling flow rate is used in cleanroom, isokinetic sampling is required for particles ≥5 μm. (For particles less than 5 μm, calculation should be performed to determine whether isokinetic sampling is needed. Generally isokinetic sampling is needed for 4 μm particles.)
4. When isokinetic sampling is needed but it is impossible, correction of the result should be made with the estimation error on Fig. 16.9.

| Standard       | Flow pattern         | Particle size | Error | Isokinetic sampling |
|----------------|----------------------|---------------|-------|---------------------|
| US 209D (1988) | Unidirectional flow  |               |       | Needed              |
| US 209E (1992) | Unidirectional flow  | ≥5 μm         | >5 %  | Needed              |
| ISO14644 (1999)| Not specified        |               |       | Not specified       |
16.2.2 Sampling in Quiescent Air

Of course, it is absolutely impossible to obtain motionless air, and this is also the case even in some experimental device. Here the so-called quiescent state means that the air velocity is very low, and it is completely in natural state.

There are two kinds of errors when the sampling probe is facing upward in the still air:

1. Error caused by settlement of particles
   When the sampling rate is very low and the sampling mouth is upward, due to the settlement of particles, some particles outside the sampling volume will “fall” into the sampling probe. In the extreme case, the sampling flow rate is zero; sampling error will be infinite because of the natural sedimentation of particles.

2. Error caused by the inertial motion of particles
   This is similar to the sampling in flowing air. With the larger sampling flow rate and the larger particle size, these particles may not be collected.

In order to reduce the first kind of error, sampling with adequate sampling velocity must be performed. In order to reduce the second kind of error, sampling probe with large diameter should be used.

Davies provided a mathematical expression with the above two conditions [13]:

For the first kind of condition

\[
\frac{\mu}{C_2^1} = 25\nu_s^2 \tag{16.8}
\]

where \(\nu_s\) is the settling velocity. Therefore the following expression can be obtained (where the slip boundary correction can be omitted)

\[
D_0 \leq 4.1 \frac{Q^4}{d_p^3} \tag{16.9}
\]

where

- \(D_0\) is the diameter of the sampling probe;
- \(Q\) is the sampling flow rate;
- \(d_p\) is the particle diameter when \(\rho = 1\).

For the second kind of condition (where the slip boundary correction can be omitted):

\[
D_0 \geq 0.062Q^4d_p^2 \tag{16.10}
\]

With the mathematical expressions, Figs. 16.11 and 16.12 can be obtained [14], which facilitates the usage.
The sampling conditions below the dotted line in Fig. 16.12 show that the requirement for both the minimum and maximum allowable sizes of sampling probe cannot be simultaneously satisfied.

**Fig. 16.11** The minimum permissible diameter of sampling probe in quiescent air

**Fig. 16.12** The maximum permissible diameter of sampling probe in quiescent air

The sampling conditions below the dotted line in Fig. 16.12 show that the requirement for both the minimum and maximum allowable sizes of sampling probe cannot be simultaneously satisfied.
16.2.3 Calculation of the Diameter of the Sampling Probe

When isokinetic sampling is required, it does not necessarily change the diameter of the whole sampling tube. It is fine as long as sampling probes with different diameters are placed at the head to the sampling tube, as shown in Fig. 16.13.

If air velocity $u_0$ is expressed with “m/s,” the sampling flow rate $q$ with “L/min,” and the sampling probe diameter $D_0$ with “mm,” we can obtain:

$$D_0 = \sqrt[4]{\frac{q}{0.047u_0}}$$  \hspace{1cm} (16.11)

16.3 Particle Loss in Sampling Line

It is a matter of concern about the measurement error caused by particles loss in the sample tube. It is serious when the sampling loss of microbiology reaches 38.2 % for a 2.8 m long sampling tube [15], which is not impossible. Except for the electrostatic effect during sampling and filtration processes because of the electrostatic charge, there are also other reasons for the particle loss, which mainly include the deposition of particles in the tube caused by diffusion, deposition, collision, and coagulation effect. They will be introduced separately as follows.

16.3.1 Diffusional Deposition Loss in Sampling Tube

Particles loss by diffusional deposition will occur since they will attach onto the tube wall by diffusional movement.

Expressions to calculate the particle loss by diffusional deposition are different according to the different flow states inside the tube. For the common particle counters with large, medium, and small sampling flow rates at home and abroad, Reynolds numbers $Re$ in the sampling tube are shown in Table 16.3.

It is laminar flow when $Re < 2,000$. It is turbulent flow when $Re > 4,000$. So for the particle counter with large sampling flow rate, it should be considered as the
turbulent flow, while the laminar flow should be considered for the particle counter with medium or less sampling flow rate.

16.3.1.1 Laminar Flow in Tube

According to the summary of the conclusions by Fuchs in 1955 [16], the following formula can be obtained. Let

\[ \alpha = \frac{Dx}{R^2u} \] (16.12)

When \( \alpha > 0.03 \)

\[ \frac{N}{N_0} = 0.82e^{-3.66\alpha} + 0.097e^{-22.2\alpha} + 0.0135e^{-53\alpha} \] (16.13)

When \( \alpha < 0.03 \)

\[ \frac{N}{N_0} = 1 - 2.57\alpha^3 \] (16.14)

where

\( N/N_0 \) is the penetration of particles through the sampling tube;
\( N_0 \) is the particle concentration at the entrance of the sampling tube, i.e., the sampling concentration, #/L;
\( N \) is the particle concentration at the distance \( x \) from the entrance of the sampling tube, #/L;
\( D \) is the diffusional coefficient of particles, m\(^2\)/s;
\( R \) is the radius of the sampling tube, m;
\( x \) is the length of the sampling tube, m;
\( u \) is the air velocity inside the sampling tube, m/s.

With the above formula, the dotted line shown in Fig. 16.14 can be obtained [17]. The relationship can be found between particle loss rates, particle size, and flow rate. But it is inconvenient to determine the required length of the tube from the theoretical curve.

| Particle counter | Inner size of sampling tube \( R \) (m) | \( Q \) L/min | \( u \) (m/s) | \( Re \) |
|------------------|----------------------------------------|--------------|-------------|--------|
| Large flow rate  | \( 0.5 \times 10^{-2} \)               | 28.3         | 6           | 3940   |
| Medium flow rate | \( 0.325 \times 10^{-2} \)             | 2.83         | 1.42        | 605    |
| Small flow rate  | \( 0.2 \times 10^{-2} \)               | 0.3          | 0.4         | 105    |
Fuchs gave a slightly different equation in the published monograph in New York in 1964 [18] (in the past this equation was referred by author in relevant publications). When $\alpha > 0.04$,

$$\frac{N}{N_0} = 0.819e^{-3.657\alpha} + 0.097e^{-22.3\alpha} + 0.032e^{-57\alpha}$$  \hspace{1cm} (16.15)$$

When $\alpha < 0.04$,

$$\frac{N}{N_0} = 1 - 2.65\alpha^3 + 1.2\alpha + 0.177\alpha^4$$  \hspace{1cm} (16.16)$$

The $\alpha$ value above may also be 0.02 in some literatures [19].

By comparison, the result from Eq. (16.15) is slightly smaller than that from Eq. (16.13), and the result from Eq. (16.16) is slightly larger than that from Eq. (16.14). But the differences for these two situations are very small.
For particle counters with medium and low sampling flow rates, the value of $\alpha$ of the latter is greater than the former. The smaller the particles are, the larger the diffusion is, which is more disadvantageous. The most disadvantageous situation corresponds with $d_p = 0.1 \mu m$, when $D = 8 \times 10^{-10} \text{ m}^2/\text{s}$. We can obtain

When $x = 5 \text{ m}$ \hspace{1cm} $\alpha = 2.5 \times 10^{-3}$

When $x = 50 \text{ m}$ \hspace{1cm} $\alpha = 2.5 \times 10^{-2}$

So for calculating the diffusional loss of particles for particle counters with medium and small sampling flow rates, $\alpha < 0.04$.

Eq. (16.16) can be used to obtain the relationship diagram between $\alpha$ and $1 - N/N_0$, as shown in Fig. 16.15 [20]. In comparison of Fig. 16.14, this figure directly presents the relationship between $\alpha$ and the particle loss rate which is described in Eq. (16.16). It is convenient to calculate the particle loss rate and the pipe length with the known particle loss rate.

It is shown in Fig. 16.15 that as long as $\alpha \leq 0.0033$, the diffusional loss rate will be $\leq 5 \%$. Suppose the allowable maximum loss rate is $5 \%$, we know

$$\alpha = \frac{Dx}{R^2u} \leq 0.0033$$

So the following requirement must be satisfied:

$$x \leq \frac{0.0033R^2u}{D}$$ \hspace{1cm} (16.17)
For particle counter with medium and low sampling flow rates, calculation results are shown in Table 16.4.

Since the diffusional coefficient is independent of the particle density, the allowable tube length in Table 16.4 is also not related to the particle density.

From the calculated results, the diffusional loss for $\frac{\mu m}{C_{21.5}}$ particles is extremely small, which can be completely ignored.

In the literature from B.Y.H. Liu [19], similar equation as Eq. 16.16 was used to obtain the left part of Fig. 16.16 (only specified that $\alpha < 0.02$). Although it was pointed out that the formula was valid for laminar flow, it did not indicate in the figure that it is not suitable for the application in non-laminar flow such as the particle counter with large sampling flow rate. And example was given for this kind of particle counter (e.g., diameter $D_i = 1$ cm, and sampling velocity $u = 6$ m/s).

### Table 16.4 The allowable tube length in laminar flow sampling tube when the diffusional particle loss rate $\leq 5\%$

| $R$ (m) | $u$ (m/s) | $x$ (m) | $D = 8 \times 10^{-10}$ m$^2$/s | $D = 1.2 \times 10^{-10}$ m$^2$/s | $D = 0.7 \times 10^{-10}$ m$^2$/s | $D = 0.3 \times 10^{-10}$ m$^2$/s |
|---------|-----------|---------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| $0.325 \times 10^{-2}$ | 1.42 | 0.1 μm | 62 | 415 | 711 | 1,659 |
| $0.2 \times 10^{-2}$ | 0.4 | 0.3 μm | 44 | 295 | 506 | 1,181 |
| $1 \mu m$ | 0.3 | 0.5 μm | 1,659 | 1,181 |

**Fig. 16.16** The loss rate of aerosol through the sampling tube due to diffusion and deposition.
Taking the 0.1 μm as an example, line with the penetration 95 % is plotted to intersect with the line 0.1 μm at the place $t_{D_2} \approx 100$. According to the instruction of this parameter, we know that

$$\frac{t}{D_i^2} = \frac{100s}{(1 \text{ cm})^2}$$ (16.18)

That means for a sampling tube with $D_i$ 1 cm, when pass-through time of the flow is 100 s and particle loss rate by diffusion is 5 %, the allowable tube length is $100 \text{ s} \times 6 \text{ m/s} = 600 \text{ m}$.

If Eq. (16.17) is used for calculation, when the particle loss rate is 5 %, we can obtain

$$x = \frac{0.0033 \times (0.5 \times 10^{-2})^2 \times 6}{8 \times 10^{-10}} = 618 \text{ m}$$

There is little difference between these two results. So it is acceptable to consider that results are consistent with Fig. 16.16 and Eq. (16.17) for calculation of the turbulent flow.

But as mentioned before, the above formula and figure should not be used for the particle counter with large sampling flow rate where turbulent flow is inside. So it is incorrect to choose either 600 m or 618 m.

It is difficult to obtain the particle loss in the particle counter with medium sampling flow rate from Fig. 16.16. But it is convenient to use Eq. (16.17). The allowable pass-through time $t$ for the flow inside the tube can also be calculated with Eq. (16.12). Because

$$\alpha = \frac{Dx}{R^2u} = \frac{D}{R^2}t \leq 0.0033$$

So

$$t \leq \frac{0.0033R^2}{D}$$ (16.19)

Because the particle loss by diffusion is known to be extremely small, the allowable tube length, i.e., the acceptable value $t$, is very big. The specific number of $t$ will not be calculated. Of course, the value of $t$ can be obtained with the known tube length and flow velocity.

### 16.3.1.2 Turbulent Flow in the Tube

The diffusional deposition onto the surface of tube wall by turbulent flow is much complex than that by laminar flow, and diffusional deposition onto the indoor wall
which is introduced in Sect. 6.5. As pointed out in Sect. 6.5, there is a very thin diffusional boundary layer close to the wall. Particle concentrations beyond the boundary layer will become uniform by turbulent flow. The boundary layer thickness is $\delta$, which is difficult to determine. In Hinds’ monograph [21], it is pointed out that Davis had already discussed the problem, and Fuchs provided the diffusional boundary layer thickness is $\delta$ inside the tube. So the whole penetration $P$ through the tube with length $x$ can be obtained with the following formula after the diffusional loss by the turbulent flow is considered:

$$
P = \frac{N}{N_0} = \exp \left( -\frac{4V_d x}{D_i u} \right)
$$

(16.20)

where $V_d$ is the diffusional velocity (see Sect. 6.5) (m/s);

$$
V_d = \frac{D}{\delta}
$$

$$
\delta = \frac{28.5 D_i D_{i1}^{1/4}}{Re_s \left( \frac{\mu}{\rho} \right)^{1/4}}
$$

(16.21)

where $\rho$ is the air density. Let

$$
\frac{4V_b x}{D_i u} = y
$$

Log-log paper can be used to plot the linear relationship between the loss rate $1-P$ and $y$. So the value of $y$ can be obtained from the figure according to the required loss rate, and then the value of $x$ can be calculated.

Suppose it is required:

$$
1 - P \leq 5\
$$

Substituting it into the Eq. (16.20), we can obtain:

$$
1 - \exp \left( -\frac{4V_b x}{D_i u} \right) \leq 0.05
$$

$$
-\frac{4V_b x}{D_i u} = \ln 0.95 = -0.0513
$$
Substituting $\mu = 1.83 \times 10^{-5} \text{ Pa} \cdot \text{s}$ and $\rho = 1.2 \text{ kg/m}^3$ into the above expressions, we obtain:

$$y = \frac{0.00877D^3Re^2\chi}{D^2u} \leq 0.0513 \quad (16.22)$$

So

$$x \leq 5.85 \frac{D^2u}{D^3Re^2} \quad (16.23)$$

With these above conditions, the loss rate $\leq 5 \%$.

If the value of $y$ is obtained under a certain loss rate, we obtain:

$$x \leq \frac{114yD^2u}{D^3Re^2} \quad (16.24)$$

For the particle counter with large sampling flow rate where turbulent flow exists inside the sampling tube, the allowable lengths are specified in Table 16.5.

As shown in Table 16.5, the allowable tube length calculated according to the turbulent diffusion situation for 0.1 $\mu$m is much less than that with laminar flow diffusion. It is obvious that it’s inappropriate to calculate by the latter situation.

And the allowable pass-through time $t$ of the turbulent flow can also be obtained with Eq. (16.23), which is:

$$t = \frac{x}{u} \leq 5.85 \frac{D^2}{D^3Re^2} \quad (16.25)$$

For the sampling in turbulent flow by particle counter with large sampling flow rate, the allowable pass-through time through the sampling tube is shown in Table 16.6.

Of course, the allowable pass-through time can also be calculated with the division between the allowable tube length and the airflow velocity.

As mentioned before, B.Y.H. Liu just quoted the formula for diffusion loss in laminar flow [19]. He thought that the diffusional loss in the turbulent flow can be calculated according to the laminar flow at first, and then an additional item considering the vortex deposition is added. But the calculation method is very inconvenient for use, so it will not be introduced here.
16.3.2 Settlement Deposition Loss in Sampling Line

For laminar flow, Fuchs quoted the same formula of \( \Gamma \) in two versions of his monographs [16, 18]:\[ 1 - \frac{N}{N_0} = \frac{2}{\pi} \left( 2\beta \sqrt{1 - \beta^2} \right) + \arcsin \beta^\frac{1}{3} \sqrt{1 - \beta^\frac{2}{3}} \] \tag{16.26}

\[ \beta = \frac{3\nu x}{8Ru} \] \tag{16.27}

For turbulence flow, Fuchs gave the following expression in his latter version [13]:\[ \frac{N}{N_0} = e^{-\frac{2\mu x}{3D}} \] \tag{16.28}

It has been pointed out that the difference is small between the calculation results when \( N/N_0 \geq 0.9 \) in two conditions. Here calculation for 5 \( \mu m \) particles is taken as an example:

The allowable tube length is as follows when \( N/N_0 = 0.90 \):

| \( D_t \) (m) | \( u \) (m/s) | \( t \) (s) |
|---------|--------|--------|
| 1 \( \times 10^{-2} \) | 6 | 0.1 \( \mu m \) 0.3 \( \mu m \) 0.5 \( \mu m \) 1 \( \mu m \) |
| \( D = 8 \times 10^{-10} \) m\(^2\)/s | \( D = 1.2 \times 10^{-10} \) m\(^2\)/s | \( D = 0.7 \times 10^{-10} \) m\(^2\)/s | \( D = 0.3 \times 10^{-10} \) m\(^2\)/s |
| 2.8 | 11.5 | 17.3 | 32.6 |

| \( 0.1 \) \( \mu m \) | \( 0.3 \) \( \mu m \) | \( 0.5 \) \( \mu m \) | \( 1 \) \( \mu m \) |
| \( D_t \) (m) | \( u \) (m/s) | \( t \) (s) |
|---------|--------|--------|
| 1 \( \times 10^{-2} \) | 6 | 2.8 | 11.5 | 17.3 | 32.6 |

Deviations for these two kinds of flow regime are both within 10 %, so they can be calculated by laminar flow.

The theoretical curve made by Eq. (16.26) has been shown in Fig. 16.14 [17], which is the solid line. It is also not convenient to determine the tube length by this curve.

The relationship diagram between \( \beta \) and \( 1 - N/N_0 \) is shown in Fig. 16.15, which is very convenient for use to calculate the loss rate.
From Fig. 16.15, if the sampling efficiency is required to be greater than 95\%, namely, the loss rate is less than 5\%, it must follow the condition that $\beta / C_2 \leq 0.032$ [calculate by Eq. (16.26)]. “Arcsin” must be converted into radian. For example, arcsin 0.95 $\approx 78.805 / C_{14} \approx 78.5 / C_{180} \approx 1.253$ rad.

The value of $x/Ru$ can be calculated, which is shown in Table 16.7. The allowable horizontal tube length of different particle counters during sampling are listed in Table 16.8.

The right part of Fig. 16.16 was made with the same formula (just specified that $\alpha < 0.02$) as Eq. (16.26) in B.Y.H. Liu’s literature [19]. For the sampling tube with $D_t = 1$ cm, taking 1 $\mu$m, for example, when the particle penetration is 0.95, we obtain

$$t / D_t \approx 13 \text{ s}$$

The allowable tube length for the particle counter with large sampling flow rate $u = 6$ m/s is

$$x = 13 \times 6 = 78 \text{ m}$$

The deviation is 8\% with the value 85.4 m in Table 16.8. Since interpolation is needed during the application of the figure, it is inconvenient to calculate specifically.

### 16.3.3 Collisional Loss in Sampling Line

In addition to vertical and horizontal tubes, the sampling tube generally has a certain degree of bending. Figure 16.17 shows a real photo. It forms a 90\(^\circ\) bend in the extreme case, as shown in Fig. 16.18 [19]. The minimum bending radius is
only 2 ~ 3 cm. So particles will easily collide at the bending section and attached on the tube wall to cause loss.

B.Y.H. Liu quoted the following formula to calculate the penetration [19]:

\[ P = \frac{N}{N_0} = 1 - St \left[ 1 + \left( \frac{\pi R_0}{2} + \frac{2 R_0^2}{3} \right) \right] \]  

(16.29)

Fig. 16.17  Actual bending condition of sampling tube

Fig. 16.18  Schematic of the extreme case for the sampling tube
This formula is only valid for $St < 0.1$.

$$R_0 = \frac{\text{Bending radius}}{\text{Tube radius}}$$  \hspace{1cm} (16.30)

The calculation results of collision loss are listed in Table 16.9.

It is shown from the table that the larger the particle is, the greater the collisional loss is; the bigger the value $St$ is, the bigger the collisional loss is; the smaller the value $R_0$ is, the greater the collisional loss is.

For particles with diameter equal to and less than 5 μm (this is the maximum controlling particle size in various recent standards), the collisional loss can be ignored. But for 10 μm particles, it should be taken into consideration.

### 16.3.4 Coagulation Loss in Sampling Line

Equation (6.49) has given the method to calculate the coagulation concentration of monodisperse particles. If it is used to estimate the coagulation concentration of polydisperse particles, separate calculation should be performed with different particle size. And further correction can be made according to the geometric standard deviation $\sigma_g$ (see Chap. 1) of the group particles. The correction values from literature [22] are listed in Table 16.10.

Take the unfavorable 0.1 μm particles as an example:

$$\frac{N}{N_0} = \frac{1}{1 + K_0N_0t}$$

When $t = 10s$, and $N_0 = 10^3 \text{ #/cm}^3$, the coagulation coefficient is found from Table 6.13 that $K_0 = 8.6 \times 10^{-10} \text{ cm}^3/s$. So

$$1 - \frac{N}{N_0} = 1 - \frac{1}{1 + 8.6 \times 10^{-10} \times 10^3 \times 10} = 1 - \frac{1}{1 + 0.0000086} = 0.000009$$

Suppose $t = 1 \text{ h}$, we obtain:

$$1 - \frac{N}{N_0} = 0.0031$$

Even when polydispersity is taken into consideration with $\sigma_g = 2$, $K_0$ increases by 1.94 times. The result shows that the coagulation loss is very small, so it can be completely ignored.
### Table 16.9  Collisional loss in the bending sampling tube

| $D_t$ (m) | $u_0$ (m/s) | $\rho$ (kg/m$^3$) | Bending radius/m | $R_0$ | $1 - N/N_0$ |
|-----------|-------------|-------------------|------------------|------|----------------|
|           |             |                   |                  |      | $0.5 \mu m$ | $1 \mu m$ | $2 \mu m$ | $5 \mu m$ | $10 \mu m$ |
| $1 \times 10^{-2}$ | 0.5         | 1,000             | $2 \times 10^{-2}$ | 4    | 0.000875       | 0.00029   | 0.0012   | 0.0073   | 0.029    |
| $1 \times 10^{-2}$ | 0.5         | 1,000             | $20 \times 10^{-2}$ | 40   | 0.00054        | 0.00021   | 0.00085  | 0.0053   | 0.0021   |
| $0.65 \times 10^{-2}$ | 0.5        | 1,000             | $2 \times 10^{-2}$ | 4    | 0.00008        | 0.000046  | 0.0019   | 0.011    | 0.046    |
| $0.65 \times 10^{-2}$ | 0.5        | 1,000             | $20 \times 10^{-2}$ | 40   | 0.00083        | 0.00033   | 0.0014   | 0.0083   | 0.033    |
From the above theoretical calculation, the particle loss by collision, eddy, and coagulation for particles with diameter equal to and smaller than $5 \mu m$ inside the sampling tube is much smaller than that by diffusion and deposition, which generally can be ignored. It should be considered only for particles with diameter more than $5 \mu m$ and in special sampling conditions. For the particle loss by diffusion and deposition, the deposition loss is much important. The diffusional loss of large particles can also be negligible.

Comparison is performed between three experimental data and theoretical calculation results:

1. For the horizontal sampling tube with diameter $0.4 \text{ cm}$ and length $15 \text{ cm}$ (A) and $500 \text{ cm}$ (B), respectively, particle counter with small sampling flow rate was used to measure the concentration of standard particles after steady state reached. The sampling velocities were both $27 \text{ cm/s}$. The test result is shown in Table 16.11 [23].

   | No. | Times | Size ($\mu m$) | Avg. concentration (#) |
   |-----|-------|---------------|------------------------|
   | A   | 1     | 0.3–0.4       | 1,377                  |
   |     | 2     | 0.4–0.5       | 1,071                  |
   |     | 3     | 0.5–0.6       | 598                    |
   |     | 4     | 0.6–0.8       | 180                    |
   |     | 5     | 0.8–1.0       | 74                     |

   | B   | 1     | 0.3–0.4       | 1,376                  |
   |     | 2     | 0.4–0.5       | 1,074                  |
   |     | 3     | 0.5–0.6       | 578                    |
   |     | 4     | 0.6–0.8       | 186                    |
   |     | 5     | 0.8–1.0       | 67                     |

2. For a horizontal sampling tube with diameter $D$, $1.09 \text{ cm}$ and length $500 \text{ cm}$, measurement was performed to test the concentration of the standard particles when the sampling velocity was $0.44 \text{ m/s}$. The result is shown in Fig. 16.19 [24].

   By comparison of the particle loss rate in the figure with the theoretical particle loss rate, results are shown in Table 16.12.
In the two experiments, small spherical PSL particles were used as the standard particles, whose density is 1.06 g/cm$^3$. From comparison, the actual particle loss rate is close to the theoretical value for particles with diameter less than 2 μm. But the actual loss rate is 70% of the calculated value for particles with diameter larger than 2 μm. This is because the resuspension phenomenon is not considered in the formula after particles deposit. However, it cannot be ignored for big particles. Because the smaller the particles are, the larger the molecular force is. The corresponding suspension velocity is bigger, which needs bigger force to blow them up, and it is hard to resuspend again. As shown in Fig. 16.13, the suspension velocity suddenly decreases from about 2–25 μm. It showed that it is hard for particles with diameter more than 2 μm to resuspend, while it is quite easy for particles with diameter more than

### Table 16.12 Results of comparison

| Particle size range (μm) | Calculation particle size (μm) | Test loss rate (%) | Calculated loss rate (%) |
|-------------------------|--------------------------------|--------------------|--------------------------|
| 0.5–0.6                 | 0.5                            | 2                  | 0.5                      |
| 0.8–1.0                 | 0.9                            | 9.5                | 0.3                      |

**Calculation:**

\[
\frac{[1 - (1 - 0.025) \times (1 - 0.005)]}{C_0} = 3
\]

\[
\frac{[1 - (1 - 0.11) \times (1 - 0.003)]}{C_0} = 11.3
\]

**Fig. 16.19** Experimental result of the particle loss by deposition in sampling tube
2 μm to resuspend again. It shows that the deposition loss rate is smaller than that of small particles.

3. For the horizontal sampling tube with diameter 0.5 cm and length 400 cm, when the sampling velocity is 0.28 m–1.41 m/s, the actual loss rate for polydisperse DOP particles in the tube is shown in Fig. 16.20 [17].

Taking \( u = 0.42 \) m/s, for example, comparison with theoretical results is shown in Table 16.13 (the particle density is 0.981 g/cm\(^3\)).

In the experimental results with six grades of velocity channels, most of the actual tested results are closed to the theoretical value, and both have the same trend. For example, the loss rate becomes bigger when the sampling velocity is small, and the loss rate increases quickly with the increase of the particle size. With the same sampling velocity, for most particle sizes, the particle loss rate in pipes with small diameter is bigger than that in big pipes.
Table 16.13  Comparison of results

| Particle size range (μm) | 0.5  | 1.1  | 2.02 | 3.7–7 |
|-------------------------|------|------|------|-------|
| Calculation particle size (μm) | 0.5  | 1.0  | 2.0  | 5     |
| Test loss rate (%) | 3    | 4.2  | 11   | 54    |
| Calculated loss rate |     |      |      |       |
| Diffusion (%) | 0.23 | ~0   | ~0   | ~0    |
| Deposition (%) | 1.3  | 3.6  | 13   | 82    |
| Total (%) | [1 − (1−0.013) × (1−0.0023)] = 1.5 | 3.6  | 13   | 82    |

Table 16.14  Comparison of results

| Particle size (μm) | 0.1  | 0.5  |
|-------------------|------|------|
| Test loss rate (%) | 5.5  | 3    |
| Calculated loss rate |      |      |
| Diffusion (%) | 2.5  | 0.2  |
| Deposition (%) | ~0   | 6.5  |
| Total (%) | [1 − (1−0.017) × (1−0.005)] = 2.2 | [1 − (1−0.065) × (1−0.002)] = 6.7 | [1 − (1−0.25) × (1−0.001)] = 25.1 |

Through the comparison of three examples, it is reasonable to consider that the theoretical calculation is closer to the reality. Correct on the actual test data will be performed according to the theoretical calculation if necessary.

What should be emphasized is that, the theoretical calculation results are all obtained from the formula and the given parameters in this section, instead of directly in the Fig. 16.14. The values from this figure are a little smaller. Since the values of some parameters are unknown during the plot of the figure, the reason why it is smaller cannot be confirmed (Table 16.14).

16.3.6  Comprehensive Conclusion

Through the above analysis of particle loss inside the sampling tube, the following conclusions can be obtained:

1. For particles with diameter less than 5 μm, the length of sampling tube should be considered just according to the particle loss by diffusion and deposition.
2. For 0.5–5 μm particles, the deposition loss rate is gradually bigger than that by diffusion, so the length of the sampling tube should be considered according to the deposition loss.
3. For particles with diameter less than 0.5 μm, the length of the sampling tube should be considered according to the diffusional loss when only particle counter with large flow rate is used. When particle counters with medium and small sampling flows, the length should be considered according to the deposition loss.
4. The allowable pass-through time in the sampling tube is not a definite number.
5. According to the above conclusion, it is reasonable to believe that the recommendation in 209E about the length of the sampling tube is inappropriate.

In the appendix B 40.2 of FS209E, the sampling tube in the “air sampling system” for particle counters is required that “the size of the sampling tube should be determined in such a way that the flow time in the tube should not be more than 10s.” And in the B40.2.1, further suggestion was given in the section about “the consideration for particle delivery.” “For 0.1–1 μm particles, the maximum sampling tube could be 30 m. For 2–10 μm particles, the length of the sampling tube should not be more than 3 m. In this condition, the particle loss rate can be less than 5 % for small particles by diffusion and large particles by deposition and inertia (see appendix C).”

In the above references, the Reynolds number of sampling flow is required to be 500–2,500, and the diameter of the sampling tube is not specified. So in this $Re$ conditions, when calculation is performed with the turbulent formula, if the diameter is bigger than that the diameter 1 cm for the particle counter with large sampling flow rate by 50 %, the allowable length could be 30 m for 0.1–1 μm particles. If the diameter is 1 cm, the maximum length could not be more than 17 m according to Table 16.5. The second channel should not be 2–10 μm, but instead it should be 2–5 μm as the interval, because 5 μm is the prescribed maximum control particle size in 209E. Therefore from Table 16.8, it is suitable that the length of the horizontal sampling tube is not more than 3 m (209E only mentioned it as the sampling tube, which is not accurate). If the diameter of control particles is 2–10 μm, it cannot be more than 1 m. For the special needs with the 5–10 μm particles as the control object, it should not be more than 1 m for the horizontal sampling tube. So for 209E, it is reconcilable that 2–10 μm is changed to 2–5 μm.

For the particle counter with so-called medium sampling flow rate 2.83 L/min in China, the control particle size generally begins from 0.5 μm. So the lower limit 0.1–0.5 μm can be classified as one channel (corresponding to 0.1–1 μm in 209E). Based on the results from Table 15.2 and the calculated results from Ref. [19] cited in 209E, the length of the allowable sampling tube can be long in terms of the diffusional loss. Therefore only the deposition loss should be considered. From Table 16.8, when the atmospheric particle concentration is large (2000), it is safe to set the length of the sampling tube within 30 m in theory. For cleanroom where the maximum control size is 5 μm commonly, it is more likely that only the deposition loss is considered. From Table 16.8, it is known that the horizontal sampling tube should be less than 0.5 m, which means that in order to ensure the loss rate less than 5 % for 5 μm particles, it is better that the length of the horizontal sampling tube is less than 0.5 m. As shown in Fig. 16.17, it is allowable that the length of the horizontal sampling tube is not more than the instrument length, and it is not suitable if the tube is longer. Ref. [20] gives the suggested length value of the sampling tube for domestic situation, as listed in Table 16.15.
The Minimum Sampling Volume

16.4 Background of the Problem

For the environment with different air cleanliness levels, the sampling flow rates should be different. During the measurement with the balance meter, it is relevant to the sensitivity of the balance. During the dust sampling with membrane filter, the sampling flow rate is related to the background value of the membrane filter. An appropriate proportion must be kept between the captured particle number and the background value of the membrane filter. For both cases, appropriate sampling flow rates are needed. The minimum sampling volume put forward here is for the particle counter [25]. In the 1970s, particle counters with medium and big sampling flow rates had appeared. Due to the difference of the measurement results between large sampling flow rate and small sampling flow rate, this problem is naturally proposed. For measurement in cleanroom with air cleanliness level higher than Class 100, what is the requirement for the sampling flow rate of the particle counter? If requested, how to determine the minimum sampling volume? This is the new problem that is put forward by the development of air cleaning technology.

In US standards before 209C in 1987, including that from federal government, NASA, and air pollution control association, and in related standards from Britain and Germany, the problem of the minimum sampling volume, the minimum sampling times, and the necessary number of measuring points were not provided. Only in 1973, 209B generally put forward that for turbulent flow cleanroom, it is suitable to set the sampling flow rates 0.01, 0.1, and 0.25 ft³/min, and for laminar (now unidirectional flow) cleanroom, it is suitable to set the sampling flow rates 0.25, 1.0, and 5.0 ft³/min. In 1983, German Standard VDI-2083-III only put forward that it is better to use particle counter with sampling flow rate 1 ft³/min for cleanroom with air cleanliness level above Class 100. In 1984 the standard IES-RP-CC-006 made by Institute of Environmental Sciences and Technology in USA pointed out the number of measuring points for the first time, and the method to determine the number of measuring points by the area of the cleanroom was proposed. For turbulence and laminar flow cleanroom, the area (ft²) corresponding to each measuring point is \( \leq \sqrt{\text{Air cleanliness level}} \), but the minimum sampling volume was also not mentioned.

| Sampling flow rate of particle counter | Sampling particle size range and allowable length of sampling tube |
|--------------------------------------|---------------------------------------------------------------|
| 0.028 m³/min                         | 0.1–1 μm 2–5 μm 10 μm                                        |
|                                      | 30 m 3 m 1 m                                                |
| 0.0028 m³/min                        | 0.1–0.5 μm 1 μm 2 μm 5 μm                                  |
|                                      | 30 m 10 m 3 m 0.5 m                                        |

Table 16.15: Suggested length values of horizontal sampling tube
In October of 1977, Sato [26] proposed to perform short-period sampling on several positions with small sampling volume particle counter for the first time. For Class 100 cleanroom, it is reasonable to doubt the accuracy of the measured results. But how to determine the sampling volume was not discussed.

It was the first time in China that the concept of the minimum sampling volume was officially put forward also in October of 1977. The nonzero principle to determine this minimum sampling volume was given, and the calculation method was also provided [25]. In 1980, the concept of necessary number of measuring points and the corresponding calculation method were put forward [27]. The minimum sampling volumes obtained by this method and by data (data from Japan JIS standard in 1987 adopted from US standard) from 209C later (in 1987) belong to the same class, which will be described in detail later.

16.4.2 Nonzero Sampling Principle

Particle counter can only display numbers which are positive integers such as 0, 1, 2, and 3. If the particle concentration of the measured space is extremely low, and the sampled air volume for each reading number every time, namely, the sampling volume is very small, the average concentration in the sampling volume may be a number that is less than 1. In this case, each reading may appear many times with the value of “0,” or the majority is “0.” For the occasion that the particle concentration is extremely low, when the average reading at each sampling point is “1” and there are few sampling points such as only three points, the average concentration should be “1.” If there are errors, for example, there are two times of “1” and one time of “0,” the average concentration becomes “0.7,” so the difference between two concentrations reaches 1.5 times. In this case, the real particle concentration cannot be really reflected. If the sampling volume is big, each reading from every sampling volume may be more than 1, such as 2 and 3, then the frequency with number “0” in each sampling volume is few. Even if there are some particles, the average concentration is only affected in the magnitude of 0.01–0.1, so the difference from true concentration will be smaller. The above situation mainly appears in the place with high air cleanliness requirement (such as higher than Class 1000).

Therefore, the minimum sampling volume of the particle counter should have such characteristics. The possibility that particles fall into the minimum sampling volume is large, which means there is no possibility for the appearance of zero particle inside the sampling volume. This method can be called “nonzero inspection principle.”

As pointed out in Chap. 1, if the average concentration in the sampling volume is set as $\lambda$, the particle distribution in the space can be described by the Poisson
distribution when $\lambda \leq 10$. Eq. (1.16) has given the probability $P$ for the appearance of $K$ particles at most in the sampling volume. It is rewritten here:

$$P(\zeta = K) = \frac{\lambda^K}{K!} e^{-\lambda}$$

So the probability for “0” particle is:

$$P(\zeta = 0) = e^{-\lambda} \quad (16.31)$$

The curve in Fig. 16.21 can be made with the two above formulas. The “0 particle” curve corresponds to the probability for the appearance of “0 particle.” The “$\leq 1$ particle” corresponds with the sum of appearance of “0” and “1” particle. The probability of appearance “1” particle is the difference between “$\leq 1$” and “0,” which is analogous for other cases.

From Fig. 16.21, if the probability of nonzero reading is required to reach 95 %, namely, the probability of the appearance of “0” particle is only 5 %, $\lambda$ must reach 3. The sampling volume obtained is the minimum sampling volume.

The calculation example of the minimum sampling volume will be given below.
Now the lower limit of the particle concentration for each air cleanliness level is used to represent the concentration for this level (which is safer than that with the upper limit of the concentration). We can obtain:

\[
\text{The minimum sampling volume} = \frac{3 \text{ particles}}{\text{the lower limit of concentration at this level}} \tag{16.32}
\]

The calculated results are shown in Table 16.16.

From Table 16.16, we can obtain:

1. In China, the legal unit system is used, while in air cleaning technology, “L” is used as the basic unit. So it is appropriate to take 0.1 L.

2. For the environment with the particle concentration less than 35#/L, when ordinary particle counter with small sampling flow rate is used, the sampling time should be extended to ensure adequate sampling volume and larger possibility of the appearance of nonzero particle. If the sampling time is not prolonged and the sampling volume is not increased, most of the measured results will be zero, which will reduce the reliability of the measurement results.

3. For the measurement in the space with high air cleanliness requirement with ordinary small sampling flow rate particle counter, if the extension of the required time is not long, the extension of time is feasible. If the extension of the time is too long, it is not only uneconomic, but also likely to cause other errors. So it is necessary to use the particle counter with large sampling flow rate in this case. But the effect of large sampling volume on the concentration field must be considered, which may be also likely to produce false phenomena. So in the above circumstances, it may not be necessary to use large sampling flow rate particle counter.

As already mentioned before, the Poisson distribution may not be suitable to describe the particle concentration distribution in the cleanroom. Although this aspect has been explained in Chap. 1, which believed that the Poisson distribution can still be used as the basic means to predict the particle distribution in space with high air cleanliness, if local serious leakage occurs in unidirectional flow

| Air cleanliness level | The lower limit of concentration at this level (≥0.5 μm) (#/L) | Minimum sampling volume | Calculated value (L (ft³)) | Suggested value (L) |
|----------------------|---------------------------------------------------------------|-------------------------|---------------------------|---------------------|
| 100,000              | 351                                                           | 0.0085 (0.0003)         | 0.1                       |
| 10,000               | 35.1                                                          | 0.085 (0.003)           | 0.1                       |
| 1,000                | 3.51                                                          | 0.85 (0.03)             | 1                         |
| 10                   | 0.351                                                         | 8.5 (0.3)               | 8.5                       |
| 10                   | 0.0351                                                        | 85 (3)                  | 85                        |
| 1                    | 0.00351                                                       | 850 (30)                | 850                       |

Table 16.16 The minimum sampling volume with “nonzero inspection principle”
cleanroom, it will have effects. But this kind of influence also exists in the turbulent flow cleanroom, especially when the sampling points are close to the leakage airstream. So *Code for Construction and Acceptance of Cleanroom* (GB50591-2010) has required that air filters installed in the cleanroom must undergo the leakage detection one by one. After installation, leakage scanning must be performed along the frame of the air supply surface. When all the situations are confirmed, the statistical result is effective. Otherwise, if the frequency of a particle size is more than their due value, it is apparent that there are abnormal reasons, which means the data is not believable or the possible reason must be found. It does not mean that the Poisson distribution cannot be used to predict the particle distribution.

For example, during the measurement with 20 times (the sampling volume is 1 L), there are 19 times with “0” particle and one time with “1” particle. Please judge if this is a normal situation.

With Eq. (16.30), we can calculate \( \lambda = \frac{1}{20} = 0.05 \), which means the probability of the appearance of “0” particle should be 95 %, namely, it should be 19 times, which is consistent with the actual condition. So although the sampling volume is not enough according to the value of \( \lambda \), the result can be considered as normal.

When the first measured value is “3” in the above example, please judge if this is a normal situation.

After calculation, we obtain \( \lambda = 0.15 \), so the frequency of the appearance of “0” particle should be 17 times. There are obvious differences.

From Eq. (16.30) we know:

\[
P(\zeta = 0) = \frac{x}{k} e^{-\lambda}
\]

So

\[
\lambda = - \ln \frac{x}{k} \tag{16.33}
\]

where

- \( k \) is the total times of measurement;
- \( x \) is the times of the appearance with “0” particle.

If there are 19 times of the appearance of “0” particle in total 20 times, \( \lambda = 0.051 \), which means the average particle concentration in theory should be 0.051#/L, instead of \( 3/20 = 0.15#/L \). Since the average concentration in the sampling volume 1 L is 0.051, the probability for the appearance of three particles is determined by Eq. (1.13) in this sampling volume, which is:

\[
P(\zeta = 3) = \frac{0.051^3}{3!} = e^{-0.051} = 0.000022 \times 0.95 = 0.000021
\]

So the probability of the appearance of three particles is extremely small, which is impossible. If it appears, it is an illusion, and it cannot be used to calculate the average concentration.
It is very likely that the occurrence of three particles is caused by leakage. But as illustrated in 209E, the statistics method is not aimed to changing multipoint leakage positions during sampling (the possibility of leakage at one place is very small), which means the application of statistical methods or the minimum sampling volume cannot modify the random abnormal error caused by the leakage. In other words, the abnormal situation of measurement results should not deny the particle distribution characteristic and the application of statistical methods.

Instrument performance may also become one of the abnormal reasons. Table 16.17 listed foreign measurement data (the data at each point is the average value of many sampling times), where air cleanliness Class 1 was realized in the cleanroom when Instrument 1 was used, while the conclusion was opposite when Instrument 2 was used [28]. The performances of these two instruments were compared, and it was found that the function to reset zero cannot be performed in Instrument 2. So it is inappropriate to conclude that the above particle distribution characteristic is not correct and the minimum sampling volume is not applicable when two instruments with different performances were used for measurement and the measured results do not follow the above distribution characteristics.

In Table 1.8, an example was presented where two instruments with identical performance after calibration were used to determine the particle distribution in three rooms, and the results are completely consistent. When statistical analysis is made on these data, it is more likely to conform to the distribution characteristic law.

The monograph *Air Cleaning Technical Measures* was published before the concept of “nonzero inspection principle.” So the data of Table 16.15 were not adopted, but the empirical data were used. At that time the concept of the minimum
sampling volume was not established, and instead the concept of the sampling volume at every time was used. That is:

When particle concentration < 30#/L (equivalent to Class 1000), sampling volume \( \geq 0.9 \text{ L} \);
When particle concentration 30–300#/L (equivalent to Class 10000), sampling volume \( \geq 0.3 \text{ L} \);
When particle concentration \( \geq 300\# / \text{L} \) (equivalent to Class 100000), sampling volume \( \geq 0.1 \text{ L} \).

The *Code for Design of Clean Room* approved in 1984 and implemented in 1985 also adopted the similar data as the monograph “Air cleaning technical measures,” which was later than the “nonzero inspection principle.” The data are:

| Class          | Sampling volume each time |
|----------------|---------------------------|
| 100            | \( \geq 1 \text{ L} \)    |
| 1000–10000     | \( \geq 0.3 \text{ L} \)    |
| 100000         | \( \geq 0.1 \text{ L} \)    |

The concept of the minimum sampling volume was also not given. It did not mention that particle distribution in cleanroom belongs to Poisson distribution, so the method with “nonzero inspection principle” was not cited to obtain the minimum sampling volume.

As for the sampling volume specified in *Code for Construction and Acceptance of Cleanroom* (JGJ 71-90) published in 1991 and *Code for Design of Clean Room* (GB50073-2001) published in 2002, it is consistent with related international standards (209D, ISO14644-1). The exact data will be presented later.

The above discussion is aimed to measure accurately, so the concept of the minimum sampling volume must be used. But it is still not enough only to use the minimum sampling volume; there must be enough sampling points, which have already pointed out in the past [27]. But the specification in this aspect in related foreign standards is not enough. The problem will be discussed in the next chapter.

### 16.4.3 The Principle of Minimum Total Particle Number [29–31]

Because sampling process is the collection of the counting data at every sampling point, it can be treated as the Poisson process. According to the Poisson distribution, the interval estimation of the average value for the test data can be made.

From Eq. (1.15), if the total number \( N \) obtained from the actual measurement is used to replace \( K \), the distribution function of the estimation value \( \lambda_0 \) for \( \lambda \) is

\[
F(0 < \lambda_0 < \lambda_0') = \int_0^{\lambda_0'} \frac{N^N}{N!} e^{-\lambda_0} d\lambda_0
\]

where \( \lambda_0' \) is the upper confidence limit of \( \lambda_0 \), as shown in Fig. 16.22.
When $\zeta$ is the probability (i.e., the confidence level) for the given value of $F(0 < \lambda_0 < \lambda'_0)$ and integration can be performed for the right expression of the above equation, the upper limit of $\lambda'_0$ of the estimation parameter $\lambda_0$ can be obtained with the value of $N$ for different $\zeta$. Results are shown in Table 16.18.

The random absolute error of this sampling is:

$$R' = \lambda'_0 - N$$  \hspace{1cm} (16.35)$$

The random relative error is:

$$R = \frac{R'}{N} = \frac{\lambda'_0 - N}{N}$$  \hspace{1cm} (16.36)$$

### Table 16.18 Relationship among $N, \lambda'_0, \lambda_0$

| $N$ | $\lambda'_0$ | $R$ | $\lambda_0$ | $R$ |
|-----|---------------|-----|-------------|-----|
| 5   | 11.67         | 1.334 | 10.51       | 1.03 |
| 10  | 18.89         | 0.839 | 16.96       | 0.696 |
| 15  | 24.74         | 0.649 | 23.10       | 0.540 |
| 20  | 30.89         | 0.544 | 29.06       | 0.453 |
| 25  | 36.91         | 0.476 | 34.91       | 0.397 |
| 30  | 42.83         | 0.428 | 40.69       | 0.356 |
| 35  | 48.68         | 0.391 | 46.40       | 0.326 |
| 40  | 54.47         | 0.362 | 52.07       | 0.302 |
| 50  | 65.92         | 0.318 | 63.29       | 0.266 |
| 60  | 77.23         | 0.287 | 74.39       | 0.240 |
| 70  | 88.44         | 0.263 | 86.40       | 0.220 |
| 80  | 99.57         | 0.246 | 96.35       | 0.204 |
| 90  | 110.62        | 0.229 | 107.24      | 0.192 |
| 100 | 121.62        | 0.216 | 118.08      | 0.181 |
As shown in Fig. 16.22, for the given confidence level $\zeta$, the more the sampled total particle number is, the bigger the upper confidence limit $\lambda_0$ is. From Eq. (16.36), the relative error $R$ decreases.

As for the minimum sampling volume in US 209C standard, it is based on the principle that the total sampled particle number is 20 for the corresponding air cleanliness level according to the explanation of 209B revision attendant. With this principle, when the confidence level is 95 %, the maximum concentration is 31 particles and the minimum is 12 particles. That means there is 95 % probability that the total particle number sampled is between 12 and 31. For example, when the upper concentration limit is calculated, it could be $30.89 \approx 31$ when Table 15.15 is used with the confidence level 97.5 %, which is consistent with the above explanation by 209B revision proposals. From the table, the sampling error is $R = 54.5 \%$.

If the confidence level reduces to 95 %, $\lambda_0 = 29$ particles. Although the increased total sampled particle number can reduce error, the sampling time will be prolonged. It is completely artificial to set 20 particles. So we obtain:

Minimum sampling volume = \frac{20}{\text{Upper concentration limit with the air cleanliness}}  
(16.37)

For Class 100, the upper concentration limit is 100#/ft$^3$, $20/100 = 0.2$ ft$^3$.

For Class 1000, the upper concentration limit is 1,000#/ft$^3$, $20/1,000 = 0.02$ ft$^3$.

According to the same principle, ISO14644-1 uses “L” to represent the sampling volume, so:

Minimum sampling volume = \frac{20}{\text{Upper concentration limit with the air cleanliness/m}^3} 
\times 1,000 \text{ L}  
(16.38)

In *Code for Design of Clean Room* (GB50073-2001), the value 1,000 in the above equation was mistaken as 100.

The above results are shown in Table 16.19. The mantissa of L in 209E and ISO are different slightly. At the same time, ISO specified that the minimum value should not be less than 2 L.

From the comparison of Tables 16.16 and 16.19, we can know:

1. The above two principles to determine the minimum sampling volume are based on the collection of the point data. So all of them applied the Poisson distribution, but with different methods.

   The method with $\lambda = 3$ is aimed to guarantee that the probability of nonzero data is not less than 95 %. The method with total particle number = 20 is slightly optional. So although Eq. (16.32) and Eq. (16.37) have similar shapes, the nature is different. Only American literature [29] has not pointed out that the test statistics is based on the counting points’ data when it comes to Poisson distribution. So when the statistical analysis about the average concentration
(it will be introduced in detail in next chapter) was mentioned in this literature, it concluded that “both experience and theory have proved that Poisson distribution is seldom applicable for the actual concentration in the cleanroom,” and $t$ distribution was recommended, which will cause misunderstanding. It seems that $t$ distribution may fit the particle concentration in the cleanroom. In fact, different principles were used to treat the statistical problems with two different features between the counting points’ data and the average value.

From statistics theory, it is known that this is the problem with two different natures, and it is not a problem that which distribution is more suitable to describe the particle distribution in cleanroom. One is the density distribution, where the Poisson distribution is applicable. The other is the particle number distribution according to the particle size, which is aimed to calculate the error of the average value, namely, the so-called treatment of “actual measured concentration data from the cleanroom,” so $t$ distribution method reflects the average distribution characteristics from small subsamples. The method will be discussed in the next chapter.

2. The US Federal Standard 209C adopted the English unit, which chooses ft$^3$ as the basic unit. It is understandable that 0.1 of this unit, namely, 0.1 ft$^3$, is taken.

3. The minimum sampling volume specified in 209C is calculated according to the upper concentration limit. Although the concentration increased by 10 times, $\lambda$ only improves 6.7 times. So in contrast, the minimum sampling volume of each air cleanliness level should be less than that in Table 16.15. Because the difference of the specific value represented by 0.1 unit for air cleanliness level lower than Class 100, the minimum sampling volume (L) is bigger than that in Table 16.16. But in all, the two values of the minimum sampling volume are very close.

### 16.4.4 The Minimum Sampling Volume of Airborne Bacteria

Like the measurement of particles, there is also the problem of the minimum sampling volume for airborne bacteria sampling. Now the minimum sampling volumes are calculated with “nonzero inspection principle” and the airborne bacterial concentration, which is shown in Table 16.20 [32].
16.5 The Minimum Deposition Area

As pointed out in Chap. 1, deposition of particles on surface follows the Poisson distribution. Therefore like the minimum sampling volume mentioned in the above section, there is also the minimum sampling volume problem during the measurement of particle settlement. If the deposition area is too small, it will reduce the reliability of the whole measurement because the probability of the appearance of “0” particle is extremely large. This problem is especially important during measuring the colony in biological cleanroom with the deposition method. As the minimum sampling volume analyzed in the previous section, in order to ensure 95 % of readings are nonzero, the particle deposition density must also reach or exceed 3. From Table 9.11, the allowable colony in the specified period in each Petri dish is known, which is the deposition density (take one Petri dish as the base). So the minimum deposition area needed for measuring the bacterial concentration with the deposition method in the environment with different air cleanliness levels can be obtained, which corresponds with the minimum number of Petri dishes. For example, when it is 3.5#/L from Table 9.11, the probable maximum settlement in each Petri dish is 0.239 CFU. Then in order to obtain three CFU, it needs 12.55 dishes, approximately 13 dishes. Results are listed in Table 16.21. If it is 3#/L, the number of Petri dishes is 14 and 4. That is the upper concentration limit corresponding with the air cleanliness level in Fig. 16.23 or the value used by author in the past.

The minimum number of Petri dishes should be adapt to the necessary number of sampling points or the number of sampling points specified in the regulation, which will be introduced later. If the minimum number of Petri dishes is bigger than the number of sampling points, the former value is adopted, and both the requirement of the number of sampling points and the minimum deposition area should be satisfied. If the minimum number of Petri dishes is less than the number of sampling points, the number of Petri dishes should choose the number of measurement points. If the sampling space is small and Petri dishes cannot be placed, the deposition period could be appropriately prolonged (not more than 1 h), and the number of the Petri dishes can decrease proportionally.

### Table 16.20 The minimum sampling volume of the airborne bacteria

| Upper concentration limit of airborne bacteria (#/L) | Calculated minimum sampling volume (L) |
|-----------------------------------------------------|----------------------------------------|
| 10                                                  | 0.3                                    |
| 5                                                   | 0.6                                    |
| 1                                                   | 3                                      |
| 0.5                                                 | 6                                      |
| 0.1                                                 | 30                                     |
| 0.05                                                | 60                                     |
| 0.01                                                | 300                                    |
| 0.005                                               | 600                                    |
| 0.001                                               | 3,000                                  |

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Table 16.21  The least number of Petri dishes to measure bacteria with the deposition method

| Maximum particle concentration (#/L) | Number of Petri dishes needed (settling for 0.5 h) |
|--------------------------------------|-----------------------------------------------|
| 0.35                                 | 40                                            |
| 3.5                                  | 13                                            |
| 35                                   | 4                                             |
| 350                                  | 2                                             |
| 3,500–35,000                         | 1                                             |

Fig. 16.23  Relationship between the number of Petri dishes and the particle concentration for the deposition period 0.5 h

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