Chapter 6
Movement of Indoor Fine Particle

Only when indoor airborne particles move towards the nearby of the precision product and then deposit onto the sensitive area, damage may be caused for the product. So it is important to understand the mechanism of particle movement and deposition for the control of environment.

6.1 Force Acting on Particles

It is the force that changes the state of movement. Forces acting on particles can be roughly divided into five categories.

1. **Mass force.** This refers to the force which is proportional to the particle mass, including the gravity, the inertia force, and the inertial centrifugal force.

2. **Molecular force.** This is the force which pushes particles to move by the motion of gas molecules, including the diffusional force with the Brownian movement, the turbulence force by the fluctuation of gas molecules, and the force by acoustic wave.

3. **Field force.** It is the forces expect the gravity, including the electric field force, the magnetic field force, and the forces formed in the concentration field, the temperature field, and the light. With the effect of these forces, the movement phenomena are formed, such as electrophoresis, magnetophoresis, diffusio- phoresis, temperature-phoresis, and photophoresis.

4. **The attraction force between particles.**

5. **Airflow force.** It is the force caused by supply airflow, return airflow, heat convection airflow, airflow caused by artificial agitation, and other airflows with certain velocity.

For the pollution control of cleanroom, the airflow force is the most important force among the above forces, but it is too complex to be investigated. Secondly, the gravity, the inertia force, and the molecular diffusional force are important, while other kinds of forces are not important for the movement of indoor particles in
cleanroom comparatively. As for the movement of particles in the electric field, it has been introduced in the chapter about air filter, so both the electrostatic force and other kinds of forces with little significance are not discussed in this chapter.

6.2 Gravitational Sedimentation of Particles

For the airborne particle shown in Fig. 6.1, it will be influenced by the gravity $F_1$, the buoyancy $F_2$, and the resistance $F_3$ by the medium.

For spherical particles, the gravity is:

$$F_1 = m_p g = \frac{\pi}{6} d_p^3 \rho_p g$$  \hspace{1cm} (6.1)

The buoyancy is equal to the weight of the medium with the same volume, i.e.,

$$F_2 = m_a g = \frac{\pi}{6} d_p^3 \rho_a g$$  \hspace{1cm} (6.2)

The resistance equals to the multiplication of the relative velocity between the particle and the airflow, the projected area of particles, and the drag coefficient, i.e.,

$$F_3 = \psi \frac{\pi}{4} d_p^2 \frac{v^2}{2} \rho_a = \psi \frac{\pi d_p^2 \rho_a v^2}{8}$$  \hspace{1cm} (6.3)

where

$m_p$ and $m_a$ are mass of particle and air, respectively (kg);
$ho_p$ and $\rho_a$ are density of particle and air, respectively (kg/m$^3$);
$v$ is the relative velocity of particle (m/s);
$d_p$ is the particle diameter (m);
$\psi$ is the drag coefficient.

The unit of various kinds of force is N.

When forces are acting on the particle, it deposits simultaneously. The settling velocity increases during the deposition process. When the resistance, the buoyancy, and the gravity are balanced, i.e., $F_1 - F_2 = F_3$, it becomes the uniform settlement.

Fig. 6.1 Forces acting on the spherical particle during the deposition process
Then, the speed is \( v = v_s \), which is called the settling velocity or Stokes velocity. It can be calculated with the following expression:

\[
v_s = 3.62 \sqrt{\frac{d_p (\rho_p - \rho_a)}{\psi \rho_a}} \text{ (m/s)}
\]

(6.4)

The drag coefficient \( \psi \) depends on the flow state where particle is suspended, i.e., the laminar flow or the turbulent flow. It is also dependent on the shape of particle. The flow state is decided by the Reynolds number \( Re \) of the particle with the relative movement.

\[
Re = \frac{d_p \nu \rho_a}{\mu}
\]

where \( \mu \) is the gas viscous coefficient, Pa \( \cdot \) s. It is also called dynamic viscous coefficient, which is different from the kinematic viscous coefficient \( \nu = \frac{\mu}{\rho_a} \). With the legal unit, for air with temperature 20 °C, \( \mu = 1.83 \times 10^{-5} \) Pa \( \cdot \) s and \( \rho_a = 1.2 \) kg/m\(^3\).

For the movement of particle, \( Re \) is usually less than 1. When \( Re \) is smaller than 1 especially smaller than 0.5, the resistance for spherical particle can be calculated with the following formula:

\[
F_3 = 3\pi \mu d_p \nu
\]

(6.5)

This is the famous Stokes formula, where the resistance has the opposite direction to the movement. 1/3 of this resistance is the component of shape resistance for the particle, and 2/3 is the component of the frictional resistance for the particle. With Eq. (6.3), the drag coefficient can be derived:

\[
\psi = \frac{24}{Re}
\]

(6.6)

Therefore, the resistance is strictly related with the particle velocity. For the flow with larger \( Re \), the value of \( \psi \) is shown in Table 6.1 [1, 2].

For nonspherical particle, the drag coefficient should be multiplied by a correction coefficient \( \beta \). This means the drag coefficient for nonspherical particle is \( \psi' = \beta \psi \). Value of \( \beta \) is shown in Table 6.2.

When Eq. (6.6) is substituted into Eq. (6.4), and let \( \rho_p - \rho_a \approx \rho_v \), then the settling velocity is:

\[
v_s = 3.62 \sqrt{\frac{d_p \rho_v d_a \rho_z}{24 \rho_a}}
\]
When square is performed on both sides, it becomes:

\[ v_s = 0.54 \frac{d_p^2 \rho_p}{\mu} \text{ (m/s)} \]  

(6.7)

Two points should be paid attention to during the application of this equation:

1. In the field of aerosol technology, particle density is generally assumed \( \rho_p = 1,000 \text{ kg/m}^3 \), while for atmospheric dust, particle density is generally assumed \( \rho_p = 2,000 \text{ kg/m}^3 \).

2. The unit of \( \mu \) is very confusing. In some literature, when the wrong unit is used, the calculated result can differ by ten times, where complete opposite conclusion can be obtained (for detailed information, please refer to the later chapter about isokinematic sampling). In this book, the legal system with international unit is adopted. The difference between this kind of unit and the engineering unit in the past is shown as follows:

| Unit | International unit (legal) | cgs unit | Engineering unit | KMS unit |
|------|---------------------------|----------|------------------|----------|
|      | N \cdot m^2/s or Pa \cdot s | P or dyn \cdot cm/cm^2 | kgf \cdot m/s^2 | kg/m \cdot h |
| Difference | 1 | 10 | 0.102 | 3,600 |
|      | 0.1 | 1 | 1.02 \times 10^{-2} | 360 |
|      | 9.807 | 98.07 | 1 | 3.53 \times 10^4 |
|      | 2.778 \times 10^{-4} | 2.778 \times 10^{-3} | 2.833 \times 10^{-5} | 1 |

When the found value of \( \mu \) is based on cgs unit, the corresponding value with legal unit is the found value divided by 10. When the found value is based on the engineering unit, the corresponding value with legal unit is the found value multiplied by 9.81. When the found value of \( \mu \) is based on KMS unit, the corresponding value with legal unit is the found value divided by 3,600.
So, for atmospheric dust, the relationship between the settling velocity (m/s) and particle diameter with normal temperature 20°C can be obtained with Eq. (6.7):

\[
v_s \approx 0.54 \frac{2,000 \times (d_p \times 10^{-6})^2}{1.83 \times 10^{-5}} \text{ (m/s)} = 590 \times 10^{-7} \times 10^2 d_p^2 \text{ (cm/s)}
\]

or

\[
v_s \approx 0.6 \times 10^{-2} d_p^2 \text{ (cm/s)} \quad (6.8)
\]

The calculation result is also shown in Fig. 6.2. It is shown that for particles with diameter 1 μm, \(v_s\) is only 0.006 cm/s. That means it only takes 4 h for the deposition of particles from the working area (0.8 m above the floor) to the floor. But for particles with diameter less than 0.5 μm, the diffusional distance is even larger than the settling distance, and this is why it is not easily deposited.

It should be noted that slip correction should be considered for particles with diameter less than 1 μm. According to the aerosol mechanics, Stokes formula is derived with the continuous flow condition, which assumes that there is no velocity jump on particle surface. That is to say, there is no relative velocity between the flow particles and the infinite thin medium layer attached to the surface, or there is a boundary layer on particle surface without relative velocity. For small particles, when the radius is close to the mean free path of gas molecule or the gas pressure is comparatively small, the movement of particle has the characteristic of molecular. Particles will be so small that they will “slide” between gas molecules, namely, the
existence and movement of particle will neither influence the gas velocity distribution
nor cause any airflow in gas medium. So the abovementioned boundary layer with
zero velocity does not exist. Conversely, there is a speed jump layer on the particle
surface, namely, air slippage phenomena occur on the surface of the moving particle.
Obviously, the resistance caused by medium should be reduced, which is favorable
for the Stokes settling velocity. This is the reason to consider the slip correction for
small particles.

The decisive parameter for the flow in the slip flow range or others is called
Knudsen number:

$$Kn = \frac{2\lambda}{d_P}$$ \hspace{1cm} (6.9)

The specific division of flow range is shown in Fig. 6.3 (Table 6.3).

Let $C$ the slip correction coefficient, which is also called Cunningham correction
coefficient, the settling velocity after correction becomes:

$$v_s' = Cv_s$$ \hspace{1cm} (6.10)

$$C = 1 + \frac{2\lambda}{d_P} \left( 1.257 + 0.4e^{-1.1\frac{\lambda}{d_P}} \right)$$ \hspace{1cm} (6.11)

Table 6.4 shows the value of $C$ with normal temperature and normal pressure by
Eq. (6.11). It is found that for particles with diameter 1 $\mu$m, the corrected settling
velocity will be faster by that without correction by 16%.
6.3 Movement of Particles Under the Action of Inertia Force

The movement of particles under the action of inertia force means particle moves with inertia with initial velocity after the external force disappears. For example, particles on human body and equipment are affected by the mechanical force because of the activity of people and the movement of equipment. Suppose initial horizontal velocity is obtained after particles leave the human body or equipment, the applied force disappear (now the airflow force and gravity are neglected), then particles decelerate with the inertia.

According to the Newton’s law, the movement of particles with initial horizontal velocity $v_0$ can be described with the following equation:

$$m \frac{dv}{dt} = F - F_3$$  \hspace{1cm} (6.12)

where $F$ is the external force. When only inertia force exists, $F = 0$. $F_3$ is the resistance.

Here the slip correction should be considered. The expression of $F_3$ with Stokes equation becomes

$$F_3 = \frac{3\pi \mu d_p v}{C}$$  \hspace{1cm} (6.13)

Then, Eq. (6.12) becomes:

$$\frac{dv}{dt} = - \frac{v}{\frac{Cm}{3\pi \mu d_p}}$$

Assuming $\frac{Cm}{3\pi \mu d_p} = \tau$, i.e., $\tau = \frac{d_p^2 \rho_p}{18 \mu}$, then

$$\frac{dv}{v} = - \frac{dt}{\tau}$$

---

**Table 6.4** Slip correction coefficient $C$

| $d_p$ (μm) | 0.003 | 0.01 | 0.03 | 0.1 | 0.3 | 1.0 | 3.0 | 10.0 |
|------------|-------|------|------|-----|-----|-----|-----|------|
| $C$        | 90    | 24.5 | 7.9  | 2.9 | 1.57| 1.16| 1.03| 1.0  |
After integration, we get:

\[ v = v_0 e^{-\tau t} \]  

(6.14)

The distance of movement in time \( t \) is:

\[ S_t = \int_0^t v dt = \int_0^t v_0 e^{-\tau t} dt = C\tau v_0 \left(1 - e^{-\tau t}\right) \]  

(6.15)

When \( t \) tends to infinity, the movement of particles becomes stable. The distance of inertia movement, expressed as \( S_R \), can be calculated with the following expression:

\[ S_R = C\tau v_0 \]  

(6.16)

Inserting the expression of \( \tau \) into Eq. (6.16), the calculation results are listed in Table 6.5. It is shown that \( \tau \) has the dimension of time, and it is called the “relaxation time” in aerosol dynamics. It is an important parameter to describe the movement of particles, and it is also termed as the characteristic time. It is the time needed for the transition from initial stable state to another stable state. For example, it is known from Eq. (6.16) that after the force is removed, the velocity of particle with diameter 1 \( \mu \)m will reach 1/3 of the initial velocity within the time \( t = \tau \). So when \( t > \tau \), the movement status of particles will change a little.

From Table 6.5, because of the rapid decline of velocity, the horizontal movement distance of a particle with initial velocity 1,000 cm/s is very short. It is impossible to be suspended with this mechanical force.

### 6.4 Diffusional Movement of Particles

Due to the impact of air molecules with Brownian motion, significant uneven displacement of airborne particles will occur, and the disorderly movement will be shown, which is shown in Fig. 6.3.

After the collision, the movement direction and speed of molecules change suddenly. The trajectory is composed of many segments of straight lines. Because the mass of particle is much larger than that of the air molecule, after the impact
with air molecules, the velocity of particle can be reduced to be small enough to ignore. Only after several times of impact, the direction and velocity of particle will change significantly. So the trajectory of particle is almost smooth curve. This kind of phenomena about disorderly movement for particle is called diffusional movement.

Although the displacement of particle in all direction with diffusional movement is random, pure linear displacement will occur when $t \gg \tau$ and $t = 1$ s is enough. So the absolute value of average displacement during 1 s in the given direction can be obtained with the following expression [3]:

$$S_D = \sqrt{\frac{4Dt}{\pi}}$$

(6.17)

where

$t$ is time (s);

$D$ is the diffusional coefficient of particle (cm$^2$/s).

Figure 6.4 gives the relations between $D$ and particle size. Table 6.6 gives the diffusional movement distance with different sizes. From the table, the movement distance of particle with diffusion is insignificant.
6.5 Deposition of Particles on Surface

6.5.1 Diffusional Deposition of Particles on Vertical Surface of Room Without Air Supply

Inertia deposition of particles onto flat vertical surface can be completely ignored. Usually it is thought that only diffusional deposition exists. This kind of diffusional deposition includes molecular diffusion and convection diffusion. For the room without air supply, indoor air will not keep stagnant because of the existence of convection. With the effect of convective diffusion, particles approach to the surface gradually at first and then deposit onto the surface with the molecular diffusion within a very thin layer near the surface, which is shown in Fig. 6.5.

For the particle with a certain particle size, the molecular diffusion coefficient \( D \) is known, while the convective diffusion coefficient is unknown. Fuchs solved this problem with a simplified method \([4]\).

In any deposition mechanism, the concentration variation of particles because of deposition is linearly proportional to the particle concentration \( N \), i.e.,

\[
\frac{dN}{dt} = -\beta N \tag{6.18}
\]

The negative sign represents the decrease of concentration. After integration, the above expression becomes

\[
\ln\left(\frac{N_0}{N}\right) = \beta t \tag{6.19}
\]

where

- \( N_0 \) is the original concentration (pc/cm\(^3\));
- \( N \) is the concentration at the moment \( t \) after deposition (pc/cm\(^3\)).

Then, the problem is attributed to find out the value of \( \beta \) related to the diffusional deposition mechanism.

There is convection in the room without air supply. It means outside of the molecular diffusion layer, concentration becomes uniform with the effect of convection.

### Table 6.6 Diffusional movement distance of particles during \( t = 1 \) s

| Particle size (\( \mu m \)) | \( S_D \) (cm) |
|-----------------------------|-----------------|
| 10                          | \( 1.23 \times 10^{-4} \) |
| 5                           | \( 1.74 \times 10^{-4} \) |
| 2                           | \( 2.78 \times 10^{-4} \) |
| 1                           | \( 4.02 \times 10^{-4} \) |
| 0.5                         | \( 5.90 \times 10^{-4} \) |
| 0.1                         | \( 1.68 \times 10^{-3} \) |
And the concentration decreases continuously with time (with air supply, \( N \) is a constant). Therefore, the particle number deposited onto the vertical surface with unit area within unit time is

\[
I = v_d N = \frac{DN}{\delta}
\]  

(6.20)

where

- \( v_d \) is the velocity of diffusion deposition (m/s);
- \( N \) is the concentration which decreases continuously;
- \( I \) is the deposition rate [pc/(cm\(^2\)·s)];
- \( \delta \) is the thickness of molecular diffusion layer. Although it is difficult to specify the value, it is about 20 μm on the order of magnitude according to the experimental results [1].

So the variation of particle number in the space because of diffusion deposition within time \( dt \) is

\[
-VdN = sIdt
\]

\[
\frac{dN}{dt} = -\frac{sI}{V}
\]

(6.21)

where

- \( V \) is the space volume (cm\(^3\));
- \( s \) is the area of vertical surface (cm\(^2\)).

Inserting Eq. (6.21) into Eq. (6.18), we obtain:
\[
\frac{sI}{V} = \beta N
\]

So we know:

\[
\beta = \frac{sI}{VN} = \frac{sD}{V\delta}
\]  \hspace{1cm} (6.22)

When it is inserted into Eq. (6.19) and simplification is made, the number of particles deposited on vertical surface with unit area by diffusional deposition is:

\[
N_g = \frac{V}{s} (N_0 - N) = \frac{V}{s} \left(1 - e^{-\frac{DN_0}{s}}\right)N_0 \text{(pc/cm}^2\text{)}
\]  \hspace{1cm} (6.23)

In order to have an idea about the value of \(N\), an example is made as follows:

Assume \(\frac{s}{V} = \frac{1}{4000} \text{cm}^{-1}\), \(t = 3.6 \times 10^3\) s, \(D = 6.2 \times 10^{-7} \text{ cm}^2/\text{s}\) (for particle with diameter 0.5 μm), and the number of these particles is \(N_0 = 1 \text{ pc/cm}^2\), so:

\[
N_g = 4000 \times \left(1 - e^{-0.00028}\right) \times 1 = 4000 \times 0.00028 \times 1 = 1.12 \text{(pc/cm}^2\text{)}
\]

### 6.5.2 Deposition of Particles on Undersurface of Room Without Air Supply

Deposition of particles on undersurface includes the settlement and the diffusion. And diffusion also includes the molecular diffusion and the convective diffusion. In Fuchs’ opinion, the convective diffusion coefficient is close to 0, because the convective velocity approaches zero when it is near the undersurface. It is only the molecular diffusion that plays a role in the very small distance from the undersurface, which will influence the particle concentration distribution near the bottom, but will not influence the total deposition rate. Therefore, the number of particles settled down onto the bottom with area 1 cm\(^2\) within time \(t\) is:

\[
N_g = \int_0^r v_sN \, dt \text{ (pc/cm}^2\text{)}
\]  \hspace{1cm} (6.24)

As mentioned before, although concentration keeps uniform in the space of the room without air supply, it varies with time \(t\). The reduction of particle number in the air column with height \(H\) is consistent with the number of deposited particles, which can be express as:
\[ -H \frac{dN}{dt} = v_s N \frac{dN}{dt} \]

So

\[ N = N_0 e^{-\frac{v_s}{H}} \]

When it is inserted into Eq. (6.24), we know:

\[ N_g = N_0 H \left( 1 - e^{-\frac{v_s}{H}} \right) \text{(pc/cm}^2) \] (6.25)

With the same data of the example in previous section (for particles with diameter 0.5 μm, \( v_s = 0.0015 \text{ cm/s, and assume } H = 200 \text{ cm} \)),

\[
N_g = 1 \times 200 \times \left( 1 - e^{-\frac{0.0015 \times 3.6 \times 10^4}{200}} \right) = 200 \times (1 - e^{-0.027})
\]

\[ = 200 \times (1 - 0.973) = 200 \times 0.027 = 5.4 \text{(pc/cm}^2) \]

### 6.5.3 Deposition of Particles on Interior Surface of Room with Air Supply

Fumiko and Susumi proposed the expression for the deposition of particles on the interior surface in the room with air supply [5, 6]:

\[ N_g = N v_s f t \left( 1 - e^{-\frac{nh_s}{v_s} \times \frac{h}{h_s}} \right) \] (6.26)

where

- \( f \) is the sedimentary area;
- \( t \) is the settling time;
- \( h_s \) is the room height;
- \( h \) is the distance between the settling plane and the ceiling;
- \( n \) is the air change rate.

Since \( \frac{nh_s}{v_s} \) is far greater than 1 for 0.5 min\(^{-1} \), the above expression can be simplified as

\[ N_g = N v_s f t \] (6.27)
It should be noted that Eq. (6.27) is valid for the extreme case with room height $h_s \to \infty$ for the room without air supply. Only when the height is infinite ideally, the indoor particle concentration can be considered without variation because of deposition and considered as a constant. But there is no practical significance for the condition $h_s \to \infty$. In other words, this equation is not valid for the room without air supply.

Although Eq. (6.26) is derived for the room with air supply, author thought it is not comprehensive to consider the particle deposition only, especially for the local plane. In the room with air supply, there are several ways for the deposition of particles onto plane, so the method to estimate the deposition efficiency for these ways is given.

6.5.3.1 Inertial Deposition

Inertial deposition of particles on the plane is shown in Fig. 6.6. The inertial deposition efficiency is:

$$\eta_{St} = \frac{b}{a} = f(St)$$  \hspace{1cm} (6.28)

Figure 6.7 shows the relationship between $\eta_{St}$ and $St$ [8]. $St$ is the inertial parameter, which has been introduced in Chap. 3. Table 6.7 presents the exact value of $\eta_{St}$. In the table, $u$ is the air velocity and $d_p$ is the particle diameter.

6.5.3.2 Interception Deposition

Interception deposition of particles on the plane is shown in Fig. 6.8. For the condition with large Reynolds number (equivalent with the situation of cleanroom) with unknown $Re$ value, only the upper limit of interception deposition efficiency can be calculated, namely,
6.5 Deposition of Particles on Surface

\[ \eta_R < (1 + R) - \frac{1}{(1 + R)} \]  \hspace{1cm} (6.29)

Table 6.8 gives the value of \( \eta_R \). \( R \) is the interception parameter, which has been introduced in Chap. 3.
6.5.3.3 Sedimentation Deposition

Sedimentation deposition of particles on the plane is shown in Fig. 6.9. The sedimentation deposition efficiency is

$$\eta_G = \frac{v_s}{u} \quad (6.30)$$

where

$v_s$ is the sedimentation speed;
$u$ is the air velocity.

Table 6.9 gives the value of $\eta_G$ for the general circumstance.

6.5.3.4 Diffusion Deposition

For horizontal plane, there is a very thin layer close to it, where the height and the temperature gradient are extreme small. Its vertical component of convective velocity is much less than the vertical component to the plane. It tends to zero, which means the convective flux is approaching zero. So the corresponding molecular diffusion flux towards the plane is greatly reduced. When the dispersity of particles is larger, the number of particles deposited on the vertical plane with

| $a$ (cm) | $d_p ($μm$)$ | $\eta_R$ |
|----------|--------------|----------|
| 3 – ≥30  | 1            | $<6 \times 10^{-5}$ to 0 |
|          | 5            | $<3 \times 10^{-4}$ to 0 |

Table 6.8 Value of $\eta_R$

| $a$ (cm) | $d_p ($μm$)$ | $\eta_G$ |
|----------|--------------|----------|
| 0.3      | 0.07         | $10^{-4}$ |
|          | 1            | $2 \times 10^{-4}$ |
|          | 5            | $5 \times 10^{-3}$ |

Table 6.9 Value of $\eta_G$
diffusion deposition is larger, while that on the horizontal plane is less. This means
the diffusion deposition efficiency on horizontal plane is less than that on vertical
plane, or the maximum number of deposited particles can be considered with
vertical plane.

When \( n = 1 \text{ pc/cm}^3 \) and the diffusional coefficient for particles with diameter
1 \( \mu \text{m} \) is \( D = 3 \times 10^{-7} \text{ cm}^2/\text{s} \), we can obtain the value of \( I \) is 0.54 pc/cm\(^2\) within 1 h
according to Eq. (6.20).

So the diffusion deposition efficiency for the velocity 0.3 m/s is

\[
\eta_D = \frac{0.54 (\text{pc/cm}^2) \times 1 \text{ cm}^2}{1 \text{ cm}^2 \times 30 \text{ cm/s} \times 3,600 \text{ s} \times 1 (\text{pc/cm}^3)} \approx 5.4 \times 10^{-6}
\]

For particles with diameter 5 \( \mu \text{m} \), \( \eta_D = 5 \times 10^{-7} \).

Of course, the value of \( \eta_D \) for horizontal plane should be smaller than the above
calculation result, or the maximum value can be determined with vertical plane.

### 6.5.3.5 Electrostatic Deposition

Usually it could be ignored.

### 6.5.3.6 Total Deposition Efficiency

When the circular monocrystalline silicon wafers with diameter 3 and 30 cm which
is used for the production of integrated circuit are made as an example, the above
deposition efficiency can be listed as follows:

For particles with diameter 1 \( \mu \text{m} \)

| On the plane with diameter 3 cm | On the plane with diameter 30 cm |
|--------------------------------|---------------------------------|
| \( \eta_G = 2 \times 10^{-4} \) | \( \eta_G = 2 \times 10^{-4} \) |
| \( \eta_R \sim 6 \times 10^{-5} \) | \( \eta_R \sim 0 \) |
| \( \eta_D \sim 5.4 \times 10^{-6} \) | \( \eta_D \sim 0 \) |
| \( \eta_{St} \sim 0 \) | \( \eta_{St} \sim 0 \) |

\( \sum \eta \approx 1.3 \times (2 \times 10^{-4}) \)

For particles with diameter 5 \( \mu \text{m} \)

| On the plane with diameter 3 cm | On the plane with diameter 30 cm |
|--------------------------------|---------------------------------|
| \( \eta_G = 5 \times 10^{-3} \) | \( \eta_G = 5 \times 10^{-3} \) |
| \( \eta_R < 5 \times 10^{-4} \) | \( \eta_R \sim 0 \) |
| \( \eta_D = 5 \times 10^{-7} \) | \( \eta_D \sim 5 \times 10^{-7} \) |
| \( \eta_{St} \sim 0 \) | \( \eta_{St} \sim 0 \) |

\( \sum \eta \approx 1 \times (5 \times 10^{-3}) \)
From the above sequence, the probability of sedimentation deposition is the largest in the room with air supply. Others should also be considered appropriately. But the larger the plane area is (such as the example with diameter 30 cm), the lower the efficiency of both the interception deposition and the inertial deposition is (for the plane with diameter 30 cm, \( \eta_R \approx 0 \) for particles with diameter 1 \( \mu \text{m} \), and \( \eta_R < 3 \times 10^{-5} \) for particles with diameter 5 \( \mu \text{m} \)). Therefore, in order to make the estimation simple, the sedimentation deposition can only be considered with a deposition correction factor \( \alpha \). From the above sequence of efficiencies, it is known that for the circular silicon wafer with diameter 3 cm, \( \alpha \) can be 1.3 for particle with diameter 1 \( \mu \text{m} \), and it can be 1.1 for particle with diameter 5 \( \mu \text{m} \), while it can be about 1 for particle with diameter 7.5–10 \( \mu \text{m} \). For the circular silicon wafer with diameter 30 cm, \( \alpha \) can be 1 for particle with diameter larger than 1 \( \mu \text{m} \).

With the above method, the value of \( \alpha \) for particles with diameter \( \leq 1 \mu \text{m} \) when the plane diameter \( \geq 30 \text{ cm} \) is shown in Table 6.10.

For particles with the same diameter, values of \( \alpha \) are different if the air velocity is different. The above data correspond to the air velocity 0.3 m/s. If the air velocity becomes 0.6 and 0.15 m/s, values of \( \alpha \) are 1.6 and 1.15, respectively, for particles with diameter 1 \( \mu \text{m} \) on the plane with diameter 3 cm. That means when the benchmark is based on the air velocity 0.3 m/s, the deposition rate will increase by 1.23 times in the room with the same particle concentration, if the air velocity increases to two times. When the air velocity decreases by half, the deposition rate can also be reduced to 88% of the original value.

So we have the following correction formula:

\[
N_g = \alpha \omega f t N
\] (6.31)

Except for \( \alpha \), the influence factors of settlement amount include air velocity, particle settling resistance, particle density, and equivalent diameter. Further correction can be made for the above express so that it can reflect the real situation well [9]. The formula can be rewritten as:

\[
N_g = \alpha \omega \frac{1}{\sqrt{\beta}} \frac{\rho' \nu}{\rho} v_s f t N
\] (6.32)

Where \( \alpha \) is the deposition correction coefficient;
\( \omega \) is the air velocity correction coefficient, which considers the correction of \( \alpha \) by air velocity. (The previous calculation is based on the air velocity 0.3 m/s in cleanroom. When the air velocity differs, the value of \( \alpha \) will change. So \( \omega = 1 \) for the air velocity 0.3 m/s. When the air velocity increases to two times, the value of \( \alpha \) will increase by 1.23 times, so \( \omega = \alpha \omega \) = 1.23. In the room without air distribution,
there is still flow movement, so the corresponding air velocity can be 0.15 m/s. Meanwhile, the value of \( \alpha \) will decrease to 88% of the original value, so \( \omega = 0.88 \).

\[
\frac{1}{\sqrt{\beta}}
\]

is the settlement resistance correction coefficient, which considers the influence of particle shape on the settling velocity during the natural sedimentation process. It is obtained by Eq. 6.4. (Generally \( v_s \) is calculated with spherical particle. But in reality dust particles are not completely spherical, and their surfaces are irregular. So the correction coefficient \( \beta \) considering the particle shape should be used. \( v_s \) is linear proportional to the root of correction coefficient. For irregular particles, \( \beta \) is 2.75–3.35, and generally it is 2.75. Correction is not needed for the unnatural sedimentation process.)

\[
\frac{\rho_p'}{\rho}
\]

is the density correction coefficient. It can be obtained with Eq. (6.7). (As mentioned before, the density for atmospheric dust is usually \( \rho_p = 2 \). But in the place where people density, activity, and dust are a lot, the particle density \( \rho_p' \) may be 2–2.5. In some experiment such as the liquid droplet, \( \rho_p' = 1 \). So this kind of correction is not needed for the general situation.)

It is easy to determine the value of \( v_s \) in Eq. (6.32) when particles are monodisperse. When airborne particles are polydisperse, it should be calculated with some kind of average diameter. The amount of deposited particles is dependent on the frontal resistance, which is related to the cross-sectional area. So the area weighted diameter should be adopted to describe the average diameter of whole particles, which is used to estimate the deposition amount.

When the particle concentration of cleanroom is \( N = 1,000 \text{ pc/L} = 1 \text{ pc/cm}^3 \), the area weighted diameter for airborne particles with diameter larger than 0.5 \( \mu \text{m} \) is \( D_s = 0.98 \mu \text{m} \) [9]. That means the deposition amount for particles with diameter \( \geq 0.5 \mu \text{m} \) can be considered as the deposition amount with particle diameter 1 \( \mu \text{m} \).

So the total deposition amount of particles on the surface with area 1 \( \text{cm}^2 \) per hour can be obtained in the cleanroom, where the airborne particle concentration is 1,000 pc/L and the air velocity is 0.3 m/s. It is also called the unit deposition rate, which is the deposition concentration mentioned in Chap. 2.

\[
N_g = 1.3 \times 0.006 \text{ cm/s} \times 3,600 \text{ s} \times 1(\text{pc/cm}^3) = 28 \text{ pc/cm}^2
\]

As mentioned before, the calculated result only represents the possibility of the deposition amount of particles. It may be possible for the resuspension after deposition or no deposition because of the disturbance on the ground. The above data can only show the maximum probability of deposition, which is related to the surface exposure time and the actual dispersity of specific particles.

Table 6.11 shows the comparison of measured data and calculated data about the deposition amount of particles on the surface with unit area in the room with air supply. The experimental data are from the report of Tan Dade from Institute of HAVC at Chinese Academy of Building Science. It was obtained with the microscope, when the total number of particle with diameter \( \geq 5 \mu \text{m} \) is counted on the steel disk.
In the table, the calculated deposition rate was obtained with the standard particle size distribution for particle diameter 5–10 μm. The particle size distribution is as follows:

| Diameter (μm) | Value |
|---------------|-------|
| 5             | 0.415 |
| 6             | 0.246 |
| 7             | 0.108 |
| 8             | 0.077 |
| 9             | 0.077 |
| 10            | 0.077 |

From this particle size distribution, it can be obtained that $D_s = 6.59 \, \mu m$ [7].

With the above value of $\alpha$, $\alpha = 1.05$.

With Eq. (6.8), $v_s = 0.26 \, m/s$.

Taking the room No.104 from Table 6.11 as an example, we can perform the calculation with Eq. (6.31) and obtain:

$$N_g = 1.05 \times 0.26 \times 3,600 \times 0.072 = 70.8 \, pc/(cm^2 \cdot h)$$

Other rooms are omitted.

This result is much closer to reality compared with the calculation result with the average diameter as the equivalent diameter performed by author [7].

With the calculation results in previous sections, the ratio of particle deposition amount on the vertical surface to that on the undersurface is very small. So it is unnecessary to use the material such as the advanced stainless steel for the wall in the cleanroom, and the requirement for the hygienic cleaning of the vertical wall is lower than that of the floor.

| Room | Average particle concentration (pc/L) | Measured deposition concentration [pc/(cm²·h)] | Calculated deposition concentration [pc/(cm²·h)] |
|------|-------------------------------------|-----------------------------------------------|-----------------------------------------------|
|      | In total | ≥5 μm | ≥5 μm | ≥5 μm |     |
| 104  | 18,382   | 72   | 39   | 70.8 |
| 106  | 18,180   | 65   | 42   | 63.0 |
| 113  | 11,604   | 44   | 81   | 43.8 |
| 121  | 12,358   | 53   | 77   | 52.0 |
| 122  | 20,799   | 66   | 46   | 63.9 |
| 123  | 17,606   | 29   | 52   | 29.2 |
| 127  | 4,813    | 23   | 11   | 22.8 |
| Average | 50.3 | 50   | 49.4 |     |
6.6 Influence of Airflow on Particle Movement

6.6.1 Influence Factors of Indoor Particle Distribution

From the discussions in previous sections, with the effect of gravity, inertia force (mechanical force), and diffusional force, the velocity and the distance are very small. For particles with diameter 1 μm, the movement distances are 0.006, 0.006, and 0.0004 cm, respectively. The indoor air velocity (including the air velocity with heat convection) is usually more than 0.1 m/s. In the flowing air, small particles will follow the movement of airflow with the same velocity [10]. Semiempirical equation can be used to calculate the flow in circular pipe, and the calculation result is well agreed with the experimental data.

For the single spherical particle with diameter $d_p$ and density $\rho_p$ in the flowing air with density $\rho_a$, when it follows the airflow completely, the force acting on the particle equals with that on the fluid whose volume is occupied by the particle, i.e.,

$$\frac{d}{dt} \left( \frac{\pi}{6} d_p^3 \rho_p u_a \right)$$

where

$u_a$ is the velocity of the fluid in the space which is occupied by the particle;

$t$ is the time.

In fact, particles will not completely follow the airflow. The force exerted on the particle equals with the force component $F_r$ by the relative movement between particles and the fluid subtracted from the above force. So the governing equation for the movement of the particle is

$$\frac{d}{dt} \left( \frac{\pi}{6} d_p^3 \rho_p v_p \right) = \frac{d}{dt} \left( \frac{\pi}{6} d_p^3 \rho_a u_a \right) - F_r$$

(6.33)

where

$v_p$ is the particle velocity;

$F_r$ is equivalent to the resistance on the particle with velocity $v_p - u_a$ in the still viscous flow.

The solution process of this equation is so complex that it will not be cited here. The study result is given:

$$\frac{v_p}{u_a} = \frac{\left( a + C \sqrt{\left( \frac{\pi \omega}{2} \right)} \right)^2 + \left( b \omega + C \sqrt{\left( \frac{\pi \omega}{2} \right)} \right)^2}{\left( a + C \sqrt{\left( \frac{\pi \omega}{2} \right)} \right)^2 + \left( \omega + C \sqrt{\left( \frac{\pi \omega}{2} \right)} \right)^2}$$

(6.34)
where

$$
\begin{align*}
\begin{cases}
a = \frac{36\mu}{(2\rho_p + \rho_a)d_p^2} \\
b = \frac{5\rho_a}{2\rho_p + \rho_a} \\
c = \frac{18}{(2\rho_p + \rho_a)d_p} \sqrt{\frac{\rho_a\mu}{\pi}}.
\end{cases}
\end{align*}
$$

(6.35)

$\omega$ is the fluctuation frequency of turbulent flow (kHz). Except the semiempirical equation for the flow in circular pipe where both the calculation and the experimental results agree well with each other, so far there is no good result in this aspect for the cleanroom. But compared with the calculation result in circular pipe, the order of $\omega$ is only thousands Hz in the cleanroom. So particles with diameter $d_p = 5 \mu m$ and $\rho_p = 1 g/cm^3$, $\frac{u_a}{u_i} \approx 0.9$; for $d_p = 1 \mu m$, $\frac{u_a}{u_i} \approx 0.999$; for $d_p < 1 \mu m$, $\frac{u_a}{u_i} = 1$. This means the relative difference between the velocity of particle following the airflow when the diameter $d_p = 1 \mu m$ and the air velocity is less than $10^{-3}$. This can be further verified by the research about the particle trajectory and the streamline trajectory at the control site (such as the bench) which was performed by Shuji et al. [11]. The obstacle at the control site will cause influence on the particle and generate the energy by the turbulent flow. This influence is larger than that at other places. These influences include the inertial force, the diffusional force, the buoyant force, and the electrostatic force. Only when the gravity was considered, the $x$- and $y$-components of the velocity were calculated with the movement equation of the particle by Fujii [11]. The change rate was obtained with the integration in the small time $\Delta T (1 \times 10^{-5} s)$, and the movement coordinates of the particle is then calculated.

Figure 6.10 shows the calculation result about the particle trajectory. The initial condition of calculation is that the particle velocity is the same as the air velocity. The calculation terminates at the height with ordinate $-0.05$ above the control site. The particle sizes used were 0.621 and 1.004 $\mu m$. It is shown from the figure that $\Delta M_X$ and $\Delta M_Y$ are the difference between the particle trajectory and the streamline trajectory in $X$- and $Y$-directions. The values are shown in Table 6.12. It is shown in the table that for particle with diameter 1.004 $\mu m$, when $u_a$ is less than 0.3 m/s, the relative deviation between the particle trajectory and the streamline trajectory is not possible to be larger than $10^{-3}$, which agrees with the above velocity. So the conclusion of this research was that the particle trajectory at the control site is approximately the streamline trajectory. So in other places of the cleanroom, it is reasonable to consider that particle moves with the airflow together.

From the above result, it can be thought that even for the case $\frac{u_a}{u_i} < 0.9$, the air velocity is much larger than that caused by settlement, diffusion, and inertia of particles. So the following velocity of particle is still the main factor that influences the distribution of particles, but there is a lag of time for the airflow. It will not cause any problem for the investigation, and it should be considered only for the study of laser Doppler velocimetry.
Therefore, it is the air distribution that mainly influences the airborne particle distribution. Indoor particles will be affected by the airflow from air supply (including the primary air and the secondary air), the flow caused by occupant’s walk, and the flow by heat convection. Except for the primary air from the supplied air, the influence of other kinds of flow will be introduced in this section.

### 6.6.2 Migration of Particles

It is a concern for the people that under what kind of situation, resuspension of particles by the airflow will occur, after they deposit onto the surface. Because resuspended particles may be taken away by vortex and then cause damage. This is the migration effect of airflow.

When particles are assumed spherical, the force to suspend particles with the effect of horizontal airflow is a function of the weather area of the particle, i.e.,

\[
F = \varphi \frac{\pi}{4} d^3 \rho_a \frac{\rho_a}{2} u_c^2
\]

(6.36)
where

\( u_c \) is the surface velocity, namely, the air velocity flowing along the surface of the particle (m/s);

\( \phi \) is the suspension coefficient.

When the suspension force is larger than the particle weight, it can be expressed as:

\[
\phi \frac{\pi}{4} d_p^2 \rho_p \frac{u_c^2}{2} > \frac{\pi}{6} d_p^3 g (\rho_p - \rho_a)
\]

So

\[
u_c > \sqrt[4]{\frac{4d_p g (\rho_p - \rho_a)}{3\phi \rho_a}} \quad (6.37)
\]

The suspension coefficient is an experimental value, which is difficult to determine. But for spherical particles, the suspension coefficient is approximately same as the resistance coefficient. So when \( Re < 1 \), \( \phi = \frac{24}{Re} \) can be inserted into Eq. (6.36). When \( \rho_a \) is ignored, we can obtain

\[
u_c > \frac{d_p^2 \rho_p g}{18\mu} \quad (6.38)
\]

There is a boundary layer when air flows along the surface. The air velocity above the boundary layer is much larger than that within the boundary layer, and usually it reaches more than three times. So the air velocity to suspend particles should be

\[
u > 3u_c = \frac{d_p^2 \rho_p g}{6\mu} \quad (m/s) \quad (6.39)
\]

When the air velocity reaches \( u \), the migration of particles is formed in the following way. As shown in Fig. 6.11, with the effect of gravity, particles in the airflow will deposit on the bottom gradually and rotate forward and slide with the frontal airflow. When air passes through the rotating particles, vortex will be formed at the bottom and the side of the particle, which increases the pressure relatively. The pressure at the top of the particle reduces by the airflow. With the difference of the pressure between the top and the bottom, particles are suspended. When particles suspend to the height where the air velocity at the top is the same as that at the bottom, particles begin to deposit again with the gravity. Particles near the surface undergone the migration process of deposition-rotation-suspension with the enough intensity of the horizontal airflow, and it repeats continuously.
The migration velocity calculated with Eq. (6.36) is very small. But experiment has shown that it is not easy for the very small particle on the plate to be blown away by the airflow, and the reason is that the molecular force of the interaction between the particle and the wall surface, as well as between particles, is not considered. It is shown in Eq. (6.36) that the velocity $u_c$ needed for the suspension of the particle will be large when this kind of molecular force is added. But detailed experimental data in this aspect are very rare, and it is very difficult to determine the magnitude of this molecular force. However, the influence of the molecular force can be estimated from the experimental curve in Fig. 6.12 [12]. In the figure, the abscissa represents the particle radius. The curve shows that the air velocity needed to suspend particles with radius less than 50 μm will increase. The solid line in the figure is the experimental data, and the dashed line for extrapolation is added by author. After suspended by the airflow, particles with diameter larger than 10 μm will deposit soon. While for particles with diameter less than 10 μm, the air velocity needed to suspend them is bigger, namely, these particles are difficult to be suspended. Therefore, when air velocity should be controlled that particles will not be suspended, the control diameter can be 10 μm. In the experiment, the grit was used. For the grit with diameter 10 μm, $u$ is about 32 cm/s. If particles with the density which is 2/3 of the grit, $u$ can be 20 cm/s. This means the air velocity along the surface (mainly the floor) in the cleanroom should not be larger than 20 cm/s (it is not limited...
for the horizontally unidirectional flow air cleanroom). For example, the backflow velocity for the side air supply mode should be determined with this consideration.

From the analysis above about the particle deposition and suspension, for the deposited particles on the horizontal plane such as the floor in the cleanroom, big particles are more likely to suspend and migrate, which generate the secondary float. This is opposite with the common opinion that the smaller particles are likely to be blown away from the floor. For cleanroom, one large particle is more hazardous than one small particle. On the other hand, large particles are likely to deposit, and the number of deposited particles on the floor is large. So the cleaning work on the horizontal surface in the cleanroom cannot be neglected. Surface cleaning treatment must be performed for the object entering the room, since the air velocity along the surface is much larger and particles on the surface are more likely to suspend than that on the floor.

### 6.6.3 Influence of Heat Convection Airflow

Since particles follow the airflow almost with the same velocity of the air, except for the supply air, other local airflows will also have influence on the movement and distribution of particles. Heat convection airflow is one kind of important factors. For example, the buoyant flow near the shadowless lamp can be 0.6 m/s [13], but its influence on the particle distribution in the cleanroom has not been noticed and investigated.

There are three kinds of situations for the buoyant flow generated by heat convection airflow. The following part will introduce the method to determine the velocity for this kind of the airflow.

#### 6.6.3.1 Vertical Heat Wall

The surface temperature of the heat wall is higher than that of the ambient air. Convection will be generated near the wall surface because of the temperature difference. After the rise of the air, it will stretch out, which will promote the dispersion of particle pollution [14].

Author has ever observed the fluorescent lamp with 40 W vertically installed on the wall (the bottom of the lamp was 0.62 m above the floor) as shown in Fig. 6.13 [15]; the buoyant flow in a certain range of two ends was measured with thermometer velocimetry when no air supply was provided. At the top, the air velocity at the place 2 cm from the lamp surface reached 0.22 m/s, and the thickness of the layer with obvious air velocity reached 20 cm. When smoke was released to observe along the whole length of the lamp surface with 15 cm away, the buoyant flow appeared. Outside the layer of this buoyant flow and until about 1 m away, backflow appeared with both the method of the silk thread and the smoke release. So it is advisable to consider the airflow within 15 cm away from the surface turbulent, and
that in the range between 15 cm and 1 m is eddy with uncertain direction. In Ref. [16], it is also pointed out that there is usually three layers of airflow in the direction perpendicular to the vertical heat wall. Except for the above two layers, the most inner layer is laminar flow with very thin thickness, which is difficult to distinguish. The combined thickness of laminar and turbulent flow is much thinner than the third layer.

Figure 6.14 shows the situation of parallel flow with air supply velocity 0.25 m/s. The two flow patterns observed in the above experiment near the fluorescent lamp
still exist, and only the range along the horizontal and vertical directions reduces. Below the backflow, the air turns to downwards with the influence of return air.

The above observed phenomena show that:

1. The buoyant flow near the vertical heat wall such as vertically installed fluorescent lamp is very strong, and the influence range is very large.
2. Under the situation of air supply with a certain velocity, the influence will be limited. When the particle source is 0.5 m outside of the lamp surface, the particle distribution will not be affected by this buoyant flow. Experiment with the particle source located in the room center where is 1.5 m away from the lamp.

Fig. 6.14  Airflow near the lamp in the room with air supply (unit: mm)
surface shows that even though the air supply velocity is as small as 0.105 m/s, particles released from the source will appear in the range 1 m below the lamp. Ref. [10] also pointed out that if the pollution source is in the stagnant region of the lee side of the object, its influence is much larger than that in the backflow region. If there is also no pollution source in the backflow region, no influence will be generated. This is consistent with the above observed case when pollution source is far from the backflow region.

Since it is difficult to install the lamp at the ceiling of the unidirectional flow cleanroom and it also occupies the air supply area, someone has ever proposed to install the lamp on the vertical wall. From the above analysis, when there is air supply with a certain speed in the room where the indoor area is very small, the buoyant flow generated will cause very large influence, when the fluorescent lamp was installed at a relative high position of the vertical wall (such as above 1.5 m).

Fuchs gave the equation to calculate the buoyant flow velocity along the heat wall [17], (Table 6.13):

\[ u = 0.55\sqrt{gl/\beta(T_s - T_a)} \quad (6.40) \]

where

- \( l \) is the height from the bottom of the heat wall (m);
- \( T_s \) and \( T_a \) are the surface temperature of the wall and air temperature, respectively (K);
- \( \beta \) is the air expansion coefficient, which equals with \( 1/T_a \);
- \( g \) is the gravitational acceleration (m/s\(^2\)).

But according to the experimental data provided by Батурин [18], Eq. (6.40) should be modified to:

\[ u = 0.36\sqrt{gl/\beta(T_s - T_a)} \quad (6.41) \]

In the environment with normal temperature 23 °C, the surface temperature of the fluorescent lamp with 40W was measured to be about 40 °C, namely, the temperature difference is 17 °C. Table 6.14 shows the calculated velocity of the buoyant flow with Eq. (6.39) and the measured velocity. They are close to each other. So it is appropriate to use Eq. (6.41) to calculate the buoyant flow velocity near the heat wall. The velocity of the buoyant flow on the heat surface reaches the maximum at 1–2 cm above the surface [16].

In author’s opinion, human body can be treated as the vertical heat wall approximately [15]. The relationship between surface temperature of the human body and the room temperature is shown in Fig. 6.15 [19]. When the temperature difference is 5 and 7 °C, the calculated value of \( u \) with Eq. (6.40) is 0.18 and 0.22 m/s, respectively. According to the measurement abroad [13], the velocity of the buoyant flow near the surface of human body reaches 0.2 m/s, which is consistent with the calculated result. It is clearly shown in Fig. 6.16 that even with the down supply of
Table 6.13  Velocity of the buoyant flow along the vertical heat wall (m/s) (wall height 2.74 m, \( t_s = 59 \, ^\circ C \), \( t_a = 20 \, ^\circ C \))

| Horizontal distance from the hot wall (cm) | 11  | 22  | 33  | 44  | 55  | 66  | 77  | 88  | 99  | 110 | 121 | 132 | 143 | 154 | 165 | 176 | 187 | 198 | 209 | 220 | 274 |
|------------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1                                        | 0.15| 0.26| 0.38| 0.44| 0.45| 0.46| 0.48| 0.50| 0.47| 0.49| 0.52| 0.49| 0.47| 0.49| 0.55| 0.53| 0.60| 0.53| 0.55| 0.57| 0.55|
| 2                                        | 0.12| 0.19| 0.23| 0.31| 0.38| 0.42| 0.44| 0.46| 0.47| 0.50| 0.50| 0.51| 0.55| 0.57| 0.58| 0.60| 0.60| 0.65| 0.60|     |     |     |     |
Table 6.14  Velocity of the buoyant flow near the fluorescent lamp (m/s)

| Ascending velocity | 0.1 m apart from the bottom of the lamp tube | 1 m apart from the bottom of the lamp tube |
|--------------------|---------------------------------------------|------------------------------------------|
| Calculated value   | 0.083                                       | 0.25                                     |
| Measured value     | 0.08–0.1                                    | 0.22                                     |

Fig. 6.15  Relationship between surface temperature of human body and the room temperature

Fig. 6.16  Influence of the buoyant flow near human body on the air distribution. Human body located at two both sides with the white color. The white part in the middle represents the airflow. The white part below means the operating table
parallel flow, backflow will appear near the surface of human body [20] (of course the surface of human body is uneven). This explains the influence of the buoyant flow on the air distribution.

As for the buoyant flow along the wall in the room with air-conditioning system in summer, the temperature difference between room and inner wall is about 2 °C, so the buoyant flow along the wall is weaker than that along the human body.

6.6.3.2 Heat Object with a Certain Volume

Лыков gave the equation to calculate the velocity of the buoyant flow along the heat object with a certain volume [14]:

\[
u = 0.71 \sqrt{\frac{gl\beta(T_s - T_a)}{T_a}}\]

(6.42)

where \(l\) is the characteristic length, i.e., the length of the airflow around a body (m).

For example, \(l = l'\) (\(l'\) is the thickness of the plate) for the plate, \(l = (\pi d/2)\) for sphere, and \(l = h\) for the cube where its height is \(h\).

It is obvious that compared with the pure vertical heat wall, the velocity of the buoyant flow along the heat object with the same height is much larger, which can be explained by the fact that the coefficient in Eq. (6.24) is much larger than that in Eq. (6.41).

Figure 6.17 shows the electric furnace with two pipes. The velocities of the buoyant flow at the intervals of 20 cm above the shell were measured, and the measuring positions are shown in the figure. The velocity of the buoyant flow increases and reaches the maximum (0.75 m/s) at about 1.2 m above the shell and then reduces gradually. It is not easy to choose the value of the parameter in Eq. (6.42) when it is used for calculation. Since the value of \(l\) is only several centimeters (when the porcelain tube is concerned) and the temperature difference is several hundreds, the order of magnitude for the calculated result is equivalent with that of measurement.

6.6.3.3 Plane Heat Source and Heat Surface with Small Thickness

It is obvious that Eq. (6.42) is not suitable to describe this problem. Эльтерман has performed experimental study [18], and Куница derived the theoretical expression which agrees well with experiment [21]:

\[
u_{Z} = 0.06\Delta t^{4/9}Z^{1/3}\left\{1 - \exp\left[-9.4\left(\frac{R_{y}}{Z}\right)^{2}\right]\right\}\]

(6.43)
where

$Z$ is the vertical height from the heat source surface (m);
$u_Z$ is the air velocity at $Z$ (m/s);
$\Delta t$ is the temperature difference between surface and ambient medium ($^\circ$C);
$R_y$ is the equivalent radius of planar heat source (m).

For rectangular heat source

$$R_y = b \sqrt{\frac{k}{\pi}} (\text{m})$$

where

$k = \frac{a}{b}$

where

$a$ is the length of long side on the rectangle (m);
$b$ is the length of short side on the rectangle (m).

For circular heat source

$$R_y = R (\text{m})$$
When $Z \approx 1.8R_y$, the above equation can be simplified as

$$u_Z = 0.06 \Delta t^{4/9} Z^{1/3}$$

(6.44)

The above equation shows that the velocity of the buoyant flow above the heat source increases from zero to the maximum which is at about $Z \approx 0.43$ m and then reduces gradually when it is further above the heat source.

Figure 6.18 shows the curve by experiment abroad [22]. It represents the boundary of the pollution (namely, the boundary of the particle distribution). The larger the air supply velocity is, the lower the height of the pollution boundary is. Data on the right are the data added by author with the above equation. When the temperature of hot surface reaches 200 °C in the room without air supply, the maximum velocity of the buoyant flow is 0.47 m/s, which appears at $Z = 0.43$ m. At the height of 1.2 m, the measured velocity is 0.375 m/s, while the calculated value is 0.4 m/s. So the calculated result is close to the measure value.

### 6.6.4 Influence of Secondary Airflow by Movement of Occupant

In the common references, people in cleanroom should not walk too fast. Usually it is about 3.6 km/h (1 m/s), because the secondary flow caused by people’s walk will drive particles to move together. But there is no study about how much is the
velocity of secondary flow caused by people’s walk. Experiment was performed with the walk route shown in Fig. 6.19, and the following conclusions were obtained:

1. The maximum velocity of secondary flow. This value was not obtained with the velocity sampling at some place when people pass by (the intersection place “o” in the figure) but was the measured velocity at the place where people stop (a certain distance from the sampling place). Meanwhile, the closer the distance from the human body is, the larger the velocity of secondary flow is.

2. The relationship between the maximum velocity of secondary flow and the speed of people’s walk. Figure 6.20 shows the measured velocities along $x$- and $y$-directions. Although the relationship between the maximum velocity $v_{\text{max}}$ of secondary flow and the speed $v$ of people’s walk is not apparent, the boundary for the maximum value can be estimated with the following equation:

$$v_{\text{max}} = 0.21 + 0.13v$$  \hspace{1cm} (6.45)$$

where $v$ is the speed of people’s walk.

The maximum velocity of the secondary flow can be calculated with the above equation about the speed of people’s walk. For example, if $v = 1 \text{ m/s}$, $v_{\text{max}} = 0.34 \text{ m/s}$; if $v = 2 \text{ m/s}$, $v_{\text{max}} = 0.48 \text{ m/s}$. This means the velocity of
secondary flow caused by people’s walk is less than the speed of people’s walk. Usually \( \frac{v_{\text{max}}}{v} \) is in the range of 0.2–0.4.

3. Direction of the secondary flow. Experiment has shown that secondary flow has two obvious components along \( x \)- and \( y \)-directions, and they are equal with each other.

The above measurement and analysis of the secondary flow caused by people’s walk can be the basis to determine the lower limit of air velocity in horizontally unidirectional flow cleanroom. This will be discussed in Chap. 8.

### 6.7 Coagulation of Particles in Airflow

Airborne particles will become big particle because of the mutual collision and adhesion during the relative movement process (that caused by Brownian motion, gravity, or aerodynamic force). This phenomenon is called coagulation of particles. With particle coagulation, particle size will become large, which is good for observation, measurement, and removal. The coagulation process can be classified as thermal coagulation and movement coagulation (the movement resulted from airflow movement and acoustic vibration).

Next the phenomenon of thermal coagulation will be briefly introduced.

According to Fuchs’ derivation [23], the average time interval between two collisions is \( \frac{1}{4\pi D_{\text{eff}}N} \). The relative dispersion coefficient of two contacting particles equals with the summation of dispersion coefficients of two particles. When two particles have the same size, it becomes \( 2D \). So the number of particles which contact with one particle per unit volume in the time period \( t = 1 \text{ s} \) is
\[
\frac{1}{4\pi^2 D\rho N} = 8\pi D\rho N
\]

Because there are \(N\) particles in total per unit volume, the time of collisions will be \(\frac{1}{2}N8\pi D\rho N\). The coefficient \(\frac{1}{2}\) was introduced because two particles will coagulate and become one particle when they collide with each other. The collision rate \((dN/dt)\) will be negative with the following expression:

\[
\frac{dN}{dt} = -4\pi D\rho N^2
\] (6.46)

Since \(d\rho D\) can be approximately constant, the change rate of particle concentration will become

\[
\frac{dN}{dt} = -K_0 N^2
\] (6.47)

where \(K_0\) is called coagulation coefficient. It can be calculated with the following expression:

\[
K_0 = 4\pi D\rho
\] (6.48)

When integration is performed on Eq. (6.47), we obtain:

\[
\int_{N_0}^{N_t} \frac{dN}{N} = \int_0^t -K_0 dt
\]

So we get:

\[
\frac{1}{N_t} - \frac{1}{N_0} = K_0 t
\] (6.49)

where \(N_0\) is the initial concentration;

\(N_t\) is the concentration at the moment \(t\), which can be obtained with the following expression:

\[
N_t = \frac{N_0}{1 + N_0 K_0 t}
\] (6.50)

Table 6.15 shows the value of \(K_0\) under standard condition. Table 6.16 shows the variation of concentration during the thermal coagulation process for monodisperse particles when \(K_0 = 5 \times 10^{-16}\) cm\(^3\)/s [24].

From the above data, when initial concentration is less than \(10^6\) pc/cm\(^3\), the influence of coagulation can be neglected during measurement with time period
Table 6.15 Value of $K_0$ under standard condition

| $d_p$ (μm) | $K_0 \times 10^{-10}$ (cm$^3$/s) |
|------------|----------------------------------|
| 0.01       | 67                               |
| 0.1        | 8.6                              |
| 1.0        | 3.5                              |
| 10         | 3.0                              |

Table 6.16 Time needed to double particle size with coagulation and to reduce half of concentration

| Initial concentration $N_0$ (1/cm$^3$) | Time needed when concentration becomes 0.5 $N_0$ | Time needed when particle size doubles ($N = 0.125 N_0$) |
|----------------------------------------|-----------------------------------------------|-----------------------------------------------------|
| $10^{14}$                              | 20 μs                                         | 140 μs                                              |
| $10^{12}$                              | 2 ms                                          | 14 ms                                               |
| $10^{10}$                              | 0.2 s                                         | 1.4 s                                               |
| $10^8$                                 | 20 s                                          | 140 s                                               |
| $10^6$                                 | 33 min                                        | 4 h                                                 |
| $10^4$                                 | 55 h                                          | 16 day                                              |
| $10^2$                                 | 231 day                                       | $4 \times 365$ day                                  |

10 min. If the measurement time is 2 days, the concentration should be less than $10^3$ pc/cm$^3$ so that the coagulation effect can be ignored. This aspect should be noticed during the experimental study, leakage detection of air filter, and self-purification time with smoke release.

6.8 Enclosure Line of Point Pollution in Parallel Flow

The above sections have discussed various movement situations of single particle and the influence generated by local airflow. Now the further study is presented about the particle distribution with particles released by the source in the flow field. The simplest case is the particle distribution with the point source in the parallel flow field. The specific aim is to determine the boundary of particle distribution, namely, the range of pollution. Here it is called the enclosure line of pollution. In practice, there is the particle source which can be treated as point source, such as the spray of the leakage hole in one direction or several directions or the release of the leakage from the unsealed equipment. These particle sources exist in clean environment, and their size is very small; otherwise, they are not allowed to be inside the room. The meaning to study this problem is to find the basis for the air velocity which can be used to control pollution from various directions. This will also be discussed in Chap. 8 about the lower limit of air velocity in unidirectional flow cleanroom.
6.8.1 **Enclosure Line of Point Pollution**

Figure 6.21 shows the case with point pollution source in parallel supply air. The flow field in the room is the combination of the parallel supply air and the flow field by point pollution source. Now the spherical coordinate is adopted. $R$ is the radial distance from point pollution source. $\theta$ is the intersection angle between $R$ and $z$ axis, and the anticlockwise direction is positive.

The stream function of parallel flow field is:

$$\varphi_1 = \frac{1}{2} v_\infty R^2 \sin^2 \theta$$  \hspace{1cm} (6.51)

The stream function of point source flow field is:

$$\varphi_2 = -\frac{Q}{4\pi} \cos \theta$$  \hspace{1cm} (6.52)

The stream function of the stack flow field is:

$$\varphi = \varphi_1 + \varphi_2 = \frac{1}{2} v_\infty R^2 \sin^2 \theta - \frac{Q}{4\pi} \cos \theta$$  \hspace{1cm} (6.53)

where $v_\infty$ is the air velocity of parallel supply air (m/s);
$Q$ is the source strength, which is equal to the flow rate of polluted flow (m$^3$/h).

When the air velocity equals with the velocity of polluted air, the polluted air along $z$ axis direction is restrained at the position $a$ (shown in Fig. 6.22), which can be called the stagnation point. Polluted air in other directions will be restrained at positions $b$ and $c$. When the supplied air arrives at position $a$, it begins to turn round and moves forward when passing positions $b$ and $c$ (it is the same for other directions). This means when the polluted air flows through the lines $a$, $b$, and $c$, the component of velocity along $z$ direction disappears. When the influence of molecular dispersion is not considered and that of flow fluctuation is very small, the polluted air cannot pass through this line and is strained under this line. Therefore, this line can be called the enclosure line of pollution [15].

So the enclosure line of pollution is the line passing through points $a$, $b$, and $c$. For position $a$, $\theta = 180^\circ$, so the stream function is:

$$\varphi_{180} = \frac{Q}{4\pi}$$ (6.54)

When the above two equations are combined, we obtain:

$$\frac{Q}{4\pi} = \frac{1}{2}v_\infty R^2 \sin^2 \theta - \frac{Q}{4\pi} \cos \theta$$ (6.55)
In fact, pollution source is not a geometrical point; instead, it should have a certain volume. Suppose the radius is \( r \) and the velocity on the spherical surface with radius \( r \) is \( v(Q = 4\pi r^2v) \), the above expression can be simplified as

\[
R = 1.414 \frac{r}{\sqrt{v_{\infty}(1 - \cos \theta)}} \tag{6.56}
\]

This is the trajectory equation for the enclosure line of pollution which passes through points \( a, b, \) and \( c \).

### 6.8.2 Actual Particle Distribution of Pollution Source

Now take the actual distribution of particles released by point pollution source simulated in parallel flow as an example, the test rig is shown in Fig. 6.23 [15]. The pollution source was the table tennis with radius \( r = 2 \text{ cm} \) and many perforation on it. Compressed air was used to spray the smoke from five cigarettes. The average pollution concentration supplied into the room is shown in Table 6.17. Particle counter was used to measure the cross-sectional concentration in the center of the room at the working area height 0.8 m above the floor, when different conditions

**Table 6.17 Average pollution concentration releasing into the room (pc/min)**

| Item                                      | Polluted air velocity (m/s)\(^a\) |
|-------------------------------------------|-----------------------------------|
| One Balan cigarette was lighted indoors   | 7.8 \times 10^8 6.18 \times 10^8 7.36 \times 10^8 9.53 \times 10^8 |
| Five cigarettes were lighted inside the cigarette box and smoke was released as point source indoors | 7.8 \times 10^8 6.18 \times 10^8 7.36 \times 10^8 9.53 \times 10^8 |

\(^a\)The data in the bracket is the flow rate (L/min)
with parallel air velocity and particle generation rate were provided. Figures 6.24, 6.25, 6.26, 6.27, and 6.28 are several cases. In the figure, the abscissa represents the sampling position. The measured concentrations by particle counter were labeled. The sampling position without data means the measured value is zero. This means the average concentration in these positions is extremely low, so these places are not polluted.

It is observed in the experiment that for pollution flow with velocity \( v = 1.27 \) m/s from the pollution source, it disappears once leaving the hole. From the figure of concentration field, pollution can barely be measured at the same height of the pollution source. For pollution source with velocity 2.5 m/s, the elevated height of the polluted buoyant flow was observed only several centimeters. From the figure of concentration field, pollution can only be detected at the height of the pollution source. For pollution source with velocity 2.7 m/s, the increase of pollution concentration becomes larger. The elevated height of the buoyant flow was observed 10 cm. It is shown from the figure of concentration field that pollution was detected at the height 10 cm above the pollution source. In short, when the ratio of the polluted air velocity to the supply air velocity is less than 20, the elevated height of the polluted flow is within 20 cm (in the figure of concentration field, there is not sampling point at 10 cm below).

Experiment has also shown the situation of the buoyant thermal flow from the fluorescent lamp on the wall. The left of the concentration field is the situation when the lamp is turned on. Since the downwards supply air velocity above the lamp is between 0.16 and 0.3 m/s and the dust source is 1.5 m away, polluted particles are not detected near the region above the lamp. The right of the figure shows that the downwards supply air velocity above the lamp is less than 0.1 m/s. Three rows of measured data at 0.5 m away from the lamp show the obvious increase of pollution when the lamp is turned on. The pollution height reaches 1.5 m (shown in Fig. 6.25). This is consistent with the previous case about the buoyant flow near the wall.

### 6.8.3 Calculation of Enclosure Line of Pollution

Difference is large between the calculated enclosure line with Eq. (6.54) and the boundary of particle distribution by experiment. The range of the former case is relative narrow, while that of the latter case is much spacious. It can be found with the analysis of experimental concentration field that:

1. Although the decrease rate of pollution flow is very fast, it is still slower than the calculated result with spherical coordinate.
2. The crosswise stretching range of polluted air is much larger than the range in the enclosure line.

As for the first conclusion, the main reason is that the actual pollution source is not a uniform spherical dispersion source, and it has the characteristic of jet flow.
Fig. 6.24 Actual measured pollution range with point pollution source (1)
Fig. 6.25 Actual measured pollution range with point pollution source (2)
Fig. 6.26  Actual measured pollution range with point pollution source (3)
Fig. 6.27  Actual measured pollution range with point pollution source (4)
Fig. 6.28  Actual measured pollution range with point pollution source (5)
from small pore. The decline of velocity is very slow. After a certain distance, it declines like the spherical surface. As for this problem, there is no special investigation, and the data of perforated spherical air supplier performed by Baturin can be referred [17], which is shown in Fig. 6.29 and Table 6.18.

As for the second conclusion, it has also been shown in the experiment performed by Baturin, which was specially pointed out in Fig. 6.29. This kind of velocity field in different directions with $\theta$ is not uniform, and the crosswise stretch is much faster. The feature of the velocity field with the perforated spherical air supplier should be investigated further. A correction coefficient related to $\theta$ should be added for Eq. (6.56). According to the in-site tested concentration field, the value of this correction coefficient can be $(1 - \cos \theta)^{-1.5}$. So Eq. (6.56) becomes the following semiempirical equation:

$$R = 5.7(1 - \cos \theta)^{-1.5} r \sqrt{\frac{v}{v_\infty (1 - \cos \theta)}}$$  \hspace{1cm} (6.57)

where $R$ is called pollution radius.
Curves in Figs. 6.24, 6.25, 6.26, 6.27, and 6.28 are the enclosure line calculated with this equation.

As mentioned before, with the influence of thermal convection caused by the fluorescent lamp and the influence of the eddy caused by the frame between air filter and side wall (refer to Chap. 8 about the unidirectional flow cleanroom), the buoyant flow along the wall will drive the polluted flow towards two sides, so the two end of the pollution region from experiment is wider than the width of the calculated envelope line. It is also the case under the height of the return air grille. But compared with the calculated envelope line, it is still consistent for the pollution region above the return air grille. Particles released from the pollution source are within the range of the envelope line. Only when \( \frac{v}{v_1} \) is larger than 20, some particles will go outside of the envelop line. It can be estimated that the theoretical result will match well with practice for the standard parallel line by full return air on the floor.

The further discussion about Eq. (6.57) will be performed in Chap. 8 about the lower limit of air velocity.

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