Chapter 4
Characteristics of Air Filters

Air filter is the main equipment in the field of air cleaning technology, and it is an indispensable equipment to create the clean air environment. So it is necessary to know the characteristic of air filters and its design principle so as to use it correctly and effectively.

4.1 Function and Classification of Air Filtration System

In 1992 and 1993, China has issued two national standards “Air Filters” (GB/T 14295-93) and “High-Efficiency Particulate Air Filter” (GB13554-92), respectively. They are revised in 2008.

According to GB/T 14295-2008, air filters could be divided into four types, shown in Table 4.1.

According to GB13554-2008, high-efficiency air filters could be divided into HEPA filter and ULPA filter, which are shown in Tables 4.2 and 4.3.

According to standard, HEPA filter product must pass the leakage test before delivery. The test method and judgment criterion are presented in Table 4.4.

**Coarse Air Filter.** It is mainly used as prefilter to capture large particles and prevent them from entering the system, especially these airborne particles with diameter larger than 5 μm, settling particles larger than 10 μm and various foreign materials.

**Medium-Efficiency Air Filter.** Since roughing air filter has been placed to filter large particles, medium-efficiency air filter can be used as the final filter in general ventilation system and prefilter for HEPA filter. It is mainly used to capture airborne particles with diameter between 1 and 10 μm.

**High-Efficiency Filter.** It is used as final filter for ordinary cleaning ventilation system and as intermediate filter to protect HEPA filter and improve the cleanliness of supply air. It is mainly used to capture airborne particles with diameter between 1 and 5 μm.
Table 4.1  Efficiency and pressure drop of air filters at nominal airflow rate

| Type                  | Label | Face velocity (m/s) | Efficiency with nominal flow rate (E) (%) | Initial resistance with nominal flow rate ($\Delta P_i$) (Pa) | Final resistance with nominal flow rate ($\Delta P_f$) (Pa) |
|-----------------------|-------|---------------------|-----------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Sub-high efficiency   | YG    | 1.0                 | 99.9 > E ≥ 95                           | ≤120                                                        | 240                                                         |
| High and medium       | GZ    | 1.5                 | 95 > E ≥ 70                             | ≤100                                                        | 200                                                         |
| efficiency 1          | Z1    | 2.0                 | 70 > E ≥ 60                             | ≤80                                                         | 160                                                         |
| Medium efficiency 2   | Z2    |                     | 60 > E ≥ 40                             |                                                             |                                                             |
| Medium efficiency 3   | Z3    |                     | 40 > E ≥ 20                             |                                                             |                                                             |
| Coarse 1              | C1    | 2.5                 | E ≥ 50                                  | ≤50                                                         | 100                                                         |
| Coarse 2              | C2    |                     | 50 > E ≥ 20                             |                                                             |                                                             |
| Coarse 3              | C3    |                     | E≥50                                    |                                                             |                                                             |
| Coarse 4              | C4    |                     | 50 > E ≥ 10                             |                                                             |                                                             |

Note: When the measured efficiency value meets the requirement for two types at the same time, the higher type is used for assessment

Table 4.2  Performance of HEPA filter

| Type | Efficiency with sodium flame method under nominal flow rate | Efficiency with sodium flame method under 20% of nominal flow rate | Resistance under nominal flow rate |
|------|------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------|
| A    | 99.99 > E ≥ 99.9                                          | No requirement                                                 | ≤190                              |
| B    | 99.999 > E ≥ 99.99                                         | 99.99                                                          | ≤220                              |
| C    | E ≥ 99.999                                                | 99.999                                                         | ≤250                              |

Table 4.3  Performance of ULPA filter

| Type | Particle counting efficiency under nominal flow rate | Resistance under nominal flow rate | Comment                        |
|------|------------------------------------------------------|-----------------------------------|---------------------------------|
| D    | 99.999                                               | ≤250                              | Scanning leakage detection     |
| E    | 99.9999                                              | ≤250                              | Scanning leakage detection     |
| F    | 99.99999                                             | ≤250                              | Scanning leakage detection     |
Sub-high-Efficiency Particulate Air Filter. It is used as final filter in the cleanroom to obtain a certain class of air cleanness (please refer to Chap. 7), prefilter for HEPA filter to further improve the cleanness of supply air, and final filter of fresh air system to improve the fresh air quality. It is mainly used to capture submicron particles with diameter less than 1 μm, which is similar as that of high-efficiency filter.

HEPA Filter. It is mainly used as final filter in cleanroom. The purpose is to provide various cleanness classes corresponding to 0.5 μm, while its efficiency is usually tested with particle diameter 0.3 μm. If cleanness class corresponding to 0.1 μm is needed, its efficiency should be tested with particle diameter 0.1 μm and it is called ULPA filter. It is usually used as the final filter.

There are several types of roughing air filters and medium-efficiency air filters, such as panel-type air filter, bag air filter, and folded media-type filter. It’s better to choose air filters with larger filtration area.

There are several types of high-efficiency filters, such as bag filter, cartridge air filter, and folded media-type filter.

There are several types of sub-high-efficiency particulate air filters, such as cartridge air filter and folded media-type filter. The former is a type of low-pressure drop, which is a patent product of Institute of HVAC of China Academy of Building Research.

There are several types of HEPA filters, such as folded media-type filter which could be classified as separator HEPA filter and no-separator HEPA filter.

Tables 4.5, 4.6, 4.7, and 4.8 are four examples of foreign standards. Related test methods are illustrated in Chap. 17.
Table 4.5  IEST-RP-CC001.4-2005

| Test with photometer (test aerosol with mass median diameter 0.3 μm and count median diameter <0.2 μm) | Filtration efficiency | Leakage detection | Test with particle counting method (0.1–0.2/0.2–0.3 μm) |
|---|---|---|---|
| Grade A | ≥99.97 % | Leakage detection not needed | Grade H |
| Grade B | | Test efficiency with two flowrates | Grade I |
| Grade E | | Test efficiency with two flowrates for nuclear application | |
| Grade C | ≥99.99 % | Leakage detection needed | Grade J |
| | ≥99.995 % | Leakage detection needed | Grade K |
| Grade D | ≥99.999 % | Leakage detection needed | Grade F |
| | ≥99.9999 % | Leakage detection needed | Grade G (MPPS efficiency) |

Table 4.6  Minimum efficiency reporting value (MERV) parameters in US ASHRAE Standard

| ASHRAE 52.2 MERV | Composite average particle size efficiency (%) | Average arrestance (%), by ASHRAE 52.1–1992 | Minimum final resistance (Pa) |
|---|---|---|---|
| Range 1 | Range 2 | Range 3 |
| 0.3–1.0 m | 1.0–3.0 m | 3.0–10.0 m |
| 1 | – | – | $E_3 < 20$ | $A_{avg} < 65$ | 75 |
| 2 | – | – | $E_3 < 20$ | $65 \leq A_{avg} < 70$ | 75 |
| 3 | – | – | $E_3 < 20$ | $70 \leq A_{avg} < 75$ | 75 |
| 4 | – | – | $E_3 < 20$ | $75 \leq A_{avg}$ | 75 |
| 5 | – | – | $20 \leq E_3 < 35$ | – | 150 |
| 6 | – | – | $35 \leq E_3 < 50$ | – | 150 |
| 7 | – | – | $50 \leq E_3 < 70$ | – | 150 |
| 8 | – | – | $70 \leq E_3$ | – | 150 |
| 9 | – | $E_2 < 50$ | $85 \leq E_3$ | – | 250 |
| 10 | – | $50 \leq E_2 < 65$ | $85 \leq E_3$ | – | 250 |
| 11 | – | $65 \leq E_2 < 80$ | $85 \leq E_3$ | – | 250 |
| 12 | – | $80 \leq E_2$ | $90 \leq E_3$ | – | 250 |
| 13 | $E_1 < 75$ | $90 \leq E_2$ | $90 \leq E_3$ | – | 350 |
| 14 | $75 \leq E_1 < 85$ | $90 \leq E_2$ | $90 \leq E_3$ | – | 350 |
| 15 | $85 \leq E_1 < 95$ | $90 \leq E_2$ | $90 \leq E_3$ | – | 350 |
| 16 | $95 \leq E_1$ | $95 \leq E_2$ | $95 \leq E_3$ | – | 350 |
| 17 | ≥99.97 (0.3 μm) | – | – | – | – |
| 18 | ≥99.99 (0.3 μm) | – | – | – | – |
| 19 | ≥99.999 (0.3 μm) | – | – | – | – |
Different test methods of air filter efficiency exist in various national standards. For the convenience of comparison, Table 4.9 presents the comparison between air filter standards home and abroad. This kind of comparison is only for information and may not match well, so care should be taken before selection of air filters.

The foreign classification methods for general ventilation air filters are quite confusing, which will not be introduced here [1].

Since 1993, IEST classified HEPA filters into two categories. One is HEPA filter, and the other is ULPA filter. Afterwards these terms are used frequently.
| China standard | EUROVENT 4/9 | ASHRAE arrestance (%) | ASHRAE dust spot efficiency (%) | USA DOP efficiency (0.3 μm) | EN779 | EN1822 | DIN 24185 | ASHRAE MERV |
|----------------|----------------|------------------------|-------------------------------|-----------------------------|-------|--------|------------|-------------|
| Coarse filter 4 | EU1            |                         |                               |                             |       |        |            | 1           |
| Coarse filter 3 | EU1            | <65                    |                               |                             | G1    | A      | 2–4        |             |
| Coarse filter 2 | EU2            | 65–80                  |                               |                             | G2    | B1     | 5–6        |             |
| Coarse filter 1 | EU3            | 80–90                  |                               |                             | G3    | B2     | 7–8        |             |
| Medium filter 3 | EU4            | ≥90                    |                               |                             | G4    | B2     | 9–10       |             |
| Medium filter 2 | EU5            | 40–60                  |                               |                             | F5    | C1     | 11–12      |             |
| Medium filter 1 | EU6            | 60–80                  |                               |                             | F6    | C1/C2  | 13         |             |
| High-efficiency | EU7            | 80–90                  |                               |                             | F7    | C2     | 14         |             |
| filter         |                |                        |                               |                             |       |        |            |             |
| High-efficiency | EU8            | 90–95                  |                               |                             | F8    | C3     | 15         |             |
| filter         |                |                        |                               |                             |       |        |            |             |
| High-efficiency | EU9            | ≥95                    |                               |                             | F9    | –      | 15         |             |
| filter         |                |                        |                               |                             |       |        |            |             |
| Sub-HEPA filter | EU10           |                        |                               |                             | H10   | Q      | 16         |             |
| Sub-HEPA filter | EU11           |                        |                               |                             | H11   | R      | 16         |             |
| HEPA filter A   | EU12           |                        |                               |                             | H12   | R/S    | 17         |             |
| HEPA filter A   | EU13           |                        |                               |                             | H13   | S      | 17         |             |
| HEPA filter B   | EU14           |                        |                               |                             | H14   | S/T    | 18–19      |             |
| HEPA filter C   | EU15           |                        |                               |                             | U15   | T      | 19         |             |
| HEPA filter D   | EU16           |                        |                               |                             | U16   | U      | –          |             |
| HEPA filter E–F | EU17           |                        |                               |                             | U17   | V      | –          |             |
4.2 Performance Index of Air Filtration

The most important four indexes to evaluate the performance are face velocity (or filtration velocity), efficiency, pressure drop, and dust holding capacity.

There are also other indexes, such as weight, energy consumption, and regeneration feature, which are mainly related to filter media. It is important to choose which kind of filter media is used to make air filters. Except for the impacting factor of filter media, filter structure is also one of the important impacting determinants for the performance of air filters. For example, both the pressure drop and dust holding capacity are different, when the same filter media is used to make panel filter, bag filter, or wedge filter. So it is another important link to find reasonable optimal structure for air filter. These four performance indexes are introduced in the following section.

4.3 Face Velocity and Filtration Velocity

Both face velocity and filtration velocity can be used to describe the ability of airflow through the air filter.

Face velocity is defined as the airflow velocity passing the cross section of air filter (m/s), i.e.,

\[
 u = \frac{Q}{F \times 3,600} \tag{4.1}
\]

where

- \( Q \) is the flow rate, m\(^3\)/h;
- \( F \) is the cross-sectional area of air filter or frontal area, m\(^2\).

So face velocity represents the passing capacity and installed area of air filter. The larger the face velocity is, the less the occupied area is. Therefore, face velocity is an important parameter to reflect the structural characteristic of air filter.

Filtration velocity is defined as the airflow velocity passing the area of filter media, and it is expressed with the unit L/(cm\(^2\) · min) or cm/s, i.e.,

\[
 v = \frac{Q \times 10^3}{f \times 10^4 \times 60} = 1.67 \frac{Q}{f} \times 10^{-3} \text{L/(cm}^2\text{ · min)} \tag{4.2}
\]

\[
 v = \frac{Q \times 10^6}{f \times 10^4 \times 3,600} = 0.028 \frac{Q}{f} \text{cm/s} \tag{4.3}
\]

where \( f \) is the net area of filter media, i.e., the subtraction of binder area from the total area, m\(^2\).

During the sample test on filter media, the unit of \( v \) is L/(cm\(^2\) · min), while it is cm/s for the sample test on air filter. The multiplication of the former value with 16.6 equals with the latter value.
Filtration velocity represents the ability of passing airflow of filter media, especially the filtration performance of filter media. Generally speaking, the smaller the filtration velocity is, the higher the efficiency is. When the allowed filtration velocity of filter is smaller, the pressure drop of filter media is larger.

For given structure of filter, the nominal flow rate can be used to reflect both face velocity and filtration velocity. With the same area of cross section, the larger allowed nominal flow rate is preferred. When the air filter is operated under lower flow rate, the efficiency increases and the pressure drop decreases.

### 4.4 Efficiency

Filtration performance of air filters can be described with efficiency, penetration, and decontamination factor.

#### 4.4.1 Efficiency

When weight concentration is used to describe the particle concentration in the airflow, performance is evaluated with arrestance. When particle counting concentration is used, performance is evaluated with particle counting efficiency. When other physical parameter is used, performance is evaluated with dust spot efficiency or turbidity efficiency.

1. To describe the efficiency with particle concentrations at both the inlet and outlet airflow, i.e.,

   \[
   \eta = \frac{G_1 - G_2}{G_1} = \frac{Q(N_1 - N_2)}{N_1 Q} = 1 - \frac{N_2}{N_1} \tag{4.4}
   \]

   where
   
   \( G_1, G_2 \) refer to particle mass or counting number at inlet and outlet airflow (mg/h or pc/h), respectively;
   
   \( N_1, N_2 \) refer to particle concentration at inlet and outlet airflow (mg/m\(^3\) or pc/L), respectively;
   
   \( Q \) is the airflow rate passing through air filter (m\(^3\)/h or L/h).

   This expression is valid for both arrestance and particle counting efficiency.

2. To describe the efficiency with particle concentrations upstream of air filter and particle mass captured on air filter, i.e.,

   \[
   \eta = \frac{G_3}{QN_1} \tag{4.5}
   \]
where $G_3$ is the particle mass captured on air filter, mg/h.

This expression is only used for arrestance. The value of $\eta$ calculated by this method is termed as dust removal efficiency in some countries.

3. To describe the efficiency with particle concentrations downstream of air filter and particle mass captured on air filter, i.e.,

$$\eta = \frac{G_3}{QN_2}$$

(this expression is also used to describe the arrestance.

4. To describe the efficiency with fractional efficiency corresponding to various particle size channels, i.e.,

$$\eta = \eta_1n_1 + \cdots + \eta_n n_n$$

where

- $\eta_1 - \eta_n$ is the fractional efficiency for various particle size, which is expressed in decimal;
- $n_1 - n_n$ is the percentage of particles for various particle size in the total particle group, which is expressed in decimal.

It should be emphasized that which kind of method is used to obtain the efficiency when the efficiency value is mentioned. For example, when the arrestance with atmospheric dust is 98 %, it will bring misunderstanding or error when the efficiency is only said to be 98 % or the arrestance is 98 %. This will be explained in detail in Chap. 17.

### 4.4.2 Penetration

In most cases, people care not only how many particles are captured on air filters but also how many have penetrated through air filters. The concept of penetration (or penetrating coefficient) can be used to represent the extent of the result, although the basic meanings are the same. In the exhaust cleaning system, penetration is used to replace filtration efficiency.

It is customary to label penetration with $K$, i.e.,

$$K = (1 - \eta) \times 100 \%$$

For cases of $\eta_1 = 0.9999$ and $\eta_2 = 0.9998$, the difference between them is not substantial. When penetration is used, we get $K_1 = 0.01 \%$ and $K_2 = 0.02 \%$, which means $K_2$ is two times of $K_1$. When a filter with penetration $K_2$ is used, the number of particles penetrating through the filter is two times of the filter with penetration $K_1$. This will attract people’s attention.
4.4.3 Decontamination Factor

Decontamination factor $K_c$ is defined as the reciprocal of penetration, i.e.,

$$ K_c = \frac{1}{K} \quad (4.9) $$

It means the extent of the decrease of particle concentration when air passes through filters. When $K = 0.01 \%$,

$$ K_c = \frac{100}{0.01} = 10^4 $$

This means the difference between upstream and downstream of air filter is ten thousands.

4.5 Pressure Drop

4.5.1 Pressure Drop of Filter Media

Pressure drop of air filter is composed of two components: filter media and structure of air filter. Pressure drop of airflow entering and exiting air filters is usually constant, which is about 5 Pa and could be added as a fixed value. The following part will emphasize on the aforementioned two parts of pressure drop. In some literature and monograph, actually only the pressure drop of filter media layer is mentioned during the introduction of pressure drop of air filter, which will cause misconception to readers.

For fibrous filter, pressure drop of filter media is caused by the frontal resistance during the airflows through fibrous layer. Pressure drop depends on whether the airflow through fibrous layer is laminar or turbulent. Generally speaking, extreme small fiber and low filtration velocity will result in extreme small $Re$ number, so airflow is laminar.

For the isolated cylinder with unit length, when its long axis is perpendicular to the airflow, the force acting on its surface is a function of the cross section and dynamic pressure, i.e.,

$$ F = C' d_f \rho_a \frac{v^2}{2} \quad (4.10) $$

where

- $F$ is the drag force, N/m;
- $C'$ is the drag coefficient;
- $\rho_a$ is the gas density, kg/m$^3$;
- $v$ is the filtration velocity, m/s;
- $d_f$ is the fiber diameter, m.
The drag force acting on all fibers inside filter media is \( FL \) where \( L \) is the total length of fibers. The drag force acting on all fibers inside filter media equals with the force that the filter media bears. When it is equally shared to the surface area, the pressure drop is obtained, which is expressed as \( \Delta P \) and shown in Eq. (3.40).

\[
\Delta P = \frac{FL}{S} = \frac{F}{S} \frac{4SL\alpha}{\pi d_f^2} = \frac{4FH\alpha}{\pi d_f^2} \quad (Pa)
\]

(4.11)

where

\( 4\alpha / \pi d_f^2 \) is the fiber length per unit volume;
\( H \) is the thickness of filter layer;
\( S \) is the area of filter media, i.e., filtration area.

Inserting Eq. (4.10) into Eq. (4.11), we could get

\[
\Delta P = \frac{2C_v^2H\alpha^2}{\pi d_f} \quad (Pa)
\]

(4.12)

This is the theoretical expression of pressure drop. The problem is how to determine the drag coefficient \( C' \). Because the value of \( C' \) is related to the arrangement of fibers, solid fraction and \( Re \) number, it is impossible to obtain the relationship between \( \Delta P \) and every parameter directly. Therefore, experiment needs to be carried on. Results from experiment on the five obvious factors show that [2]:

1. When filtration velocity \( v \) varies and other parameters are fixed, the following relationship exist in large range:

\[
\Delta P \propto v
\]

i.e.,

\[
3 \text{ cm/s} < v < 5 \text{ cm/s} \quad \Delta P \propto v^{0.7}
\]

\[
5 \text{ cm/s} < 19 \text{ cm/s} \quad \Delta P \propto v^{1.0}
\]

\[
40 \text{ cm/s} < v < 200 \text{ cm/s} \quad \Delta P \propto v^{1.21.3}
\]

2. During the measurement of pressure drop of filter media for different thickness, we get

\[
\Delta P \propto H
\]

3. When solid fraction \( \alpha \) varies and both \( v \) and \( H \) are fixed, we get

\[
\Delta P \propto \alpha^2
\]
Experiment on fibrous filters shows that

\[ m_2 \approx 1.3d_f^{-0.05} \]

4. For given cross section, the effect of fiber size on \( \Delta P \) is

\[ \Delta P = d_f^{-2} \]

5. The effect of cross section could be obtained from Eq. (4.12):

\[ \pi d_f \Delta P = 2C' \sqrt{\alpha} \rho_a m_2 \]

It is known that \( \Delta P \propto \alpha^{m_2} \), so replace \( \alpha \) in the above equation with \( \alpha^{m_2} \) and \( C' \) becomes \( C'_m \), i.e.,

\[ \pi d_f \Delta P = 2C'_m \sqrt{\alpha} \rho_a m_2 \]

\[ C'_m = \frac{\pi d_f \Delta P}{2\sqrt{\alpha} \rho_a m_2} \quad (4.13) \]

With the experiment on fibers with different cross section and different \( Re \) number, the relationship shown as the straight line in Fig. 4.1 could be obtained, i.e.,

\[ C'_m = \frac{k}{Re \phi^\beta} \quad (4.14) \]

where

\( C'_m \) is the correction factor of pressure drop when influencing factors such as cross-sectional shape are considered while the influence of \( \alpha \) is ignored;

\( k = 60; \)
\( \beta = 0.58; \)

\( \varphi \) is the cross-sectional shape coefficient of fiber

\[
\varphi = \frac{\text{Cross sectional area of fiber}}{\text{Area of circumcircle for the cross section of fiber}}
\]

Values of \( \varphi \) for various fibers are:

| Fiber Type         | Value          |
|--------------------|---------------|
| Cellulose acetate  | 0.3–0.52 (avg. 0.42) |
| Glass fiber        | 1.0           |
| Chloride vinylon   | 0.61          |
| Polyamide          | 1.0           |
| Polypropylene      | 1.0           |
| Polyester          | 1.0           |
| Vinylon            | 0.4           |
| Propylene          | 1.0           |

Inserting Eq. (4.14) into Eq. (4.13), we could get:

\[
\Delta P = \frac{120 \mu v H \alpha_m^2}{\pi d_f^2 \varphi^{0.58}} \text{ (Pa)} \quad (4.15)
\]

In this equation, the relationship between \( \Delta P \) and every parameter is consistent with the experimental results. For example, \( \Delta P \) of filter media is linearly proportional to filtration velocity \( v \), filter layer thickness \( H \), and \( \alpha_m^2 \), while it is inversely proportional to \( d_f^2 \). This means the equation is valid.

According to Eq. (4.15) which is the method of Susumu and other equations by related literatures, pressure drops of three kinds of fibrous layer can be obtained, which is presented in Table 4.10. Substantial difference exists between calculated results by various methods and actual experimental data. Result given by Norio Method has the largest difference. There are many aspects for the difference, of which the accurate determination of every parameter is also important. It is comparatively easy to calculate by Eq. (4.15), while it is complex to use other two methods which will not be introduced in detail here.

### 4.5.2 Total Pressure Drop of Air Filter

For given air filter, the filter media is chosen, so \( H, \alpha, d_f, \) and \( \varphi \) are fixed. Equation (4.15) can be simplified as

\[
\Delta P = A v \quad (4.16)
\]

This means for given particles, pressure drop is linearly proportional to filtration velocity in quite large range of filtration velocity, where \( A \) is a structural coefficient to reflect the structural characteristic of fibrous layer. Figure 4.2 presents the experimental results on several kinds of fibrous filter media about the relationship
Table 4.10 Calculation of pressure drop of fibrous layer

| Fiber          | \( d_f \) (µm) | \( \alpha \) | \( m_2 \) (m) | \( v \) (m/s) | \( \mu \) at 20 °C/Pa·s | Calculated \( \Delta P \) (Pa) | Measured \( \Delta P \) (Pa) |
|----------------|----------------|-------------|---------------|--------------|------------------------|-------------------------------|-----------------------------|
| Glass fiber    | 14–18 (average 16) | 0.037       | 1.393         | 0.02         | 0.28                   | 1.83 × 10^{-5}               | 95                          | 134                         |
| Glass fiber    | 4              | 0.0048      | 1.493         | 0.025        | 0.50                   | 1.83 × 10^{-5}               | 188                         | 239                         | 560                         |
| Glass fiber    | 4              | 0.0048      | 1.493         | 0.013        | 0.50                   | 1.83 × 10^{-5}               | 98                          | 124                         | 291                         |
| Polypropylene fiber | 5 | 0.0032      | 1.493         | 0.025        | 0.50                   | 1.83 × 10^{-5}               | 103                         | 146                         | 372                         |
| Polypropylene fiber | 4 | 0.0032      | 1.493         | 0.013        | 0.50                   | 1.83 × 10^{-5}               | 54                          | 75                          | 194                         |
|                |                |             |               |              |                        |                              | 116                         | 93                          | 100                         |
|                |                |             |               |              |                        |                              | 147                         | Institute of HVAC at China Academy of Building Research |
|                |                |             |               |              |                        |                              | 261                         | Institute of HVAC at Tianjin University [5] |

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between pressure drop and filtration velocity, which was done at Institute of HVAC of China Academy of Building Research.

Figures 4.3, 4.4, and 4.5 give experimental results for nonwoven coarse filter media, medium-efficiency air filter media, and sub-high-efficiency particulate air filter media [6].

In these figures there are “front and rear.” Fibers near the front side are relatively large. Inside the coarse filter media, fibers are inherently large and spaces between fibers are loose, so difference is small between front and rear. Inside medium-efficiency air filter media, fibers near the rear are relatively dense and they will interfere with the airflow. Sub-high-efficiency particulate air filter media used here is not only polypropylene fiber filter paper, but it is composed of prefilter layer, main filter layer, and enhanced gauze. When the enhanced gauze is placed windward and leeward, the function of preventing filter media from stretching and deformation is different, so the resultant pressure drops are different. For common polypropylene fiber filter paper without enhanced gauze, the difference is not obvious.

From above figures, we could see that for high-efficiency filter media, \( v \) is below 0.2 m/s; for sub-high-efficiency particulate air filter media, \( v \) is below 0.5 m/s; for medium-efficiency air filter media, \( v \) is below 0.8 m/s; and for coarse filter media, \( v \) is below 1.2 m/s.
For these four situations, the following approximated relationship is valid, even the filtration velocity is larger than the limit:

\[ \Delta P \propto v \]

Except for the pressure drop of filter medium, structural pressure drop of air filter must be added to form the total pressure drop of air filter, where pressure drop of inlet and outlet of airflow occupies very small proportion. There is one view that except for
the inherent structure of air filter, pressure drop of structure is also affected by filter media performance. The penetrating performance of filter media may influence the flow state passing through air filter; thus, the pressure drop of structure is affected. This view needs further experimental validation. Experiments show that pressure drop of structure is no longer linearly proportional to the airflow velocity. The main reason to nonlinear relationship is that face velocity $u$ is used to describe the airflows through filter frame, which has the magnitude of m/s and is much larger than the filtration velocity passing through filter media layer. The structural size of filter frame is much larger than that of fiber, so inertial force cannot be ignored at large $Re$ number flow (usually $Re > 1$), and the flow is not laminar. In this situation, pressure drop is not linearly proportional to the velocity but is proportional to $u^n$. Therefore, pressure drop of air filter structure can be expressed as

$$\Delta P_2 = Bu^n$$  \hspace{1cm} (4.17)

where $B$ is the drag coefficient of air filter structure. The total pressure drop of air filter is:

$$\Delta P = \Delta P_1 + \Delta P_2 = Av + Bu_n$$  \hspace{1cm} (4.18)

It is obvious that values of $A$ and $B$ are different for different air filters. Taking a domestic-made GB-01 HEPA filter for an example, experiment shows that $n = 1.37$.

When expressed with unified filtration velocity $v$, the total pressure drop can be written as:

$$\Delta P = Cv^n$$  \hspace{1cm} (4.19)
For domestic-made HEPA filter, $C$ is between 3 and 10 and $m$ is between 1.1 and 1.36. Figure 4.6 shows the experimental curve of pressure drop on domestic-made HEPA filter. Figures 4.7, 4.8, and 4.9 show pressure drop curves of three kinds of HEPA filters [7], from which we can see that for HEPA filter, the value of $m$ is slightly larger than 1 when $v \gg 3$ m/s, i.e., the flow rate is slightly larger than nominal flow rate. So the resultant error will not be big when the relationship between pressure drop and flow rate is considered to be linear. Sub-high-efficiency particulate air filter has similar feature, which will be illustrated in Fig. 4.26.

However, as for coarse filter and medium-efficiency air filter, since their structures differ a lot, the above characteristic is no longer common.
4.6 Dust Holding Capacity

Dust holding capacity is an index directly related to the lifetime of air filter. When the final pressure drop of air filter at operation is about two times of the initial pressure drop (if two times is too low, other ratio can be set), or when the efficiency becomes less than 85% of the initial efficiency, the dust weight deposited on air filter is called the standard dust holding capacity of this air filter, which is called dust holding capacity for short.

When the flow rate is 1,000 m$^3$/h, the dust holding capacity of common folded nonwoven air filter is about 100 g and that of glass fibrous air filter and HEPA filter are 250–300 g and 400–500 g, respectively. Even for the same kind of air filter, dust holding capacities are different for different size.
As the particle deposition process goes on, the pressure drop of air filter increases. But so far no accurate theoretical calculation expression for the relationship between the dust deposited and pressure drop increase exists. Next several examples are introduced.

Figure 4.10 shows the relationship between pressure drop increase and dust deposited for three kinds of HEPA filters which is mentioned before. Initial pressure drops of these three filters are 150 Pa. Dashed lines are added to the figure by us. It is shown that if the relationship is approximated with straight line, error is not large when it is below the standard dust holding capacity or the pressure drop increase is smaller than two times of initial pressure drop. The maximum difference of pressure drop for these three filters is within 10 Pa. The less the upstream concentration is, the stronger the linear relationship is. So when prefilter especially one with high efficiency is usually placed before HEPA filter, this characteristic appears. If the filtration velocity is larger than ordinary value or dust deposited weighs more than standard dust holding capacity, the pressure drop will increase sharply with the increase of the deposited dust.

The increase of pressure drop is usually linearly proportional to the increase of deposited dust for medium-efficiency air filter.

During the deposition of dust, the efficiency of filters with low efficiency will increase at first and then decrease. This is because the dust deposited is comparatively large for air filters with low efficiency and the filter medium is sparse, which will cause particles to penetrate when pressure drop increases and cause deposited particles to rebound and resuspend. During the operation of HEPA filters, efficiency usually increases with the increase of deposited dust.
4.7 Design Efficiency of Air Filter

Classification of air cleanness at home and abroad is mainly evaluated with particle number of those with diameter $\geq 0.5 \mu m$ per unit volume air, while various kinds of air filters are evaluated with the fractional efficiency corresponding to certain particle size. Therefore, during the design process in air cleaning technology field, efficiency of these certain particle size needs to be converted into these particles with diameter $\geq 0.5 \mu m$.

Before delivery or during characterization, HEPA filter is evaluated with mono-disperse particles with diameter 0.3 $\mu m$, which has been introduced in the former chapter. In order to convert into efficiency with particle diameter $\geq 0.5 \mu m$, the efficiency corresponding to 0.5 $\mu m$ needs to be known. According to foreign experimental data, an empirical expression has been derived for the relationship between penetration of HEPA filter and particle size [8], i.e.,

$$ K_2 = \frac{K_1}{e^{(d/d_{0.3})^2}} $$ (4.20)

where

$K_1, K_2$ refer to penetration of particles with diameter 0.3 $\mu m$ and certain diameter which is larger than 0.3 $\mu m$, respectively;

$d_{0.3}, d$ are the particle diameter 0.3 $\mu m$ and certain diameter which is larger than 0.3 $\mu m$, respectively.

The above equation was used to perform calculation on measurement data published abroad [9], which is shown in Table 4.11. In the table, $K_2'$ and $K_1$ are measurement data and $K_2$ is the calculated data with Eq. (4.20). From the comparison between the last two columns, we can see that except for the comparatively large difference for the data on the first row, differences of other data are extreme small. This empirical equation is only valid for HEPA filter with 0.3 $\mu m$, while it is not useful for HEPA filter with 0.1 $\mu m$.

| $d_2$ ($\mu m$) | $d_1$ ($\mu m$) | e$^{-(d_2/d_1)^2}$ | $K_2'$ | $K_1$ | Calculation $K_2$ | $\eta_2'$ (%) | $\eta_2$ (%) |
|----------------|----------------|-------------------|-------|------|-------------------|-------------|-------------|
| 0.5            | 0.3            | 0.0622            | 0.000001 | 0.000005 | 0.00000031 | 0.9999900  | 0.9999969  |
| 0.5            | 0.3            | 0.0622            | 0.000003 | 0.000025 | 0.0000016   | 0.9999970  | 0.9999984  |
| 0.5            | 0.3            | 0.0622            | 0.000001 | 0.00001  | 0.0000007   | 0.9999990  | 0.9999993  |
| 0.5            | 0.3            | 0.0622            | 0.00000013 | 0.000002 | 0.00000013 | 0.9999987  | 0.9999987  |
| 0.5            | 0.3            | 0.0622            | 0.000002 | 0.0003  | 0.000002   | 0.9999980  | 0.9999980  |
| 0.5            | 0.3            | 0.0622            | 0.000007 | 0.0007  | 0.0000046   | 0.9999930  | 0.9999954  |
| 0.5            | 0.3            | 0.0622            | 0.000007 | 0.000045 | 0.000003   | 0.9999930  | 0.9999970  |
| 0.5            | 0.3            | 0.0622            | 0.00000025 | 0.000004 | 0.00000026 | 0.9999975  | 0.9999974  |
Although the test methods for the efficiency of HEPA filter are different at home and abroad, the results are almost consistent with that of particle counting efficiency with particle diameter 0.3 μm, which is shown in Chap. 17. Efficiency for HEPA filter with particle diameter 0.3 μm is usually considered as the reference baseline, so Eq. (4.20) is used to obtain the relationship of HEPA filter between 0.3 μm and 0.5 μm, which is shown in Fig. 4.11 for reference. Meanwhile, Fig. 4.12 shows the curve in Ref. [10], from which we can see that these results match well with each other. Efficiency η in the figure is represented with decimal.

According to the above curve and the particle diameter distribution of atmospheric dust introduced in Chap. 2, the efficiency with particle diameter ≥0.5 μm can be derived, which is shown in Table 4.12.

According to national standard “high-efficiency particulate air filter,” filter with efficiency larger than 99.9 % is called HEPA filter. For filter with efficiency equals with 99.9 %, efficiency with particle diameter larger than 0.5 μm becomes 99.9975 %, which is shown in Table 4.12. Since efficiency of common HEPA filter is actually larger than this limit value, it is reasonable to consider efficiency of particle diameter ≥0.5 μm to be 99.999 %.

With the above conversion method, we compare the experimental data performed on HEPA filter in the cleaning equipment with calculated data and find they are consistent. There is no literature abroad specially dealing with this problem. In Ref. [11], it is said that “for obtaining Class 100 clean environment with all the fresh air when the particle concentration of outdoor air is about 3 × 10^5
pc/L (>0.5 μm), it’s necessary to set filters with minimum efficiency 99.999 %. So HEPA filter with efficiency larger than 99.95 % is recommended to use as the main filter.” Here HEPA filter with efficiency 99.95 % (for 0.3 μm) is thought to have efficiency 99.999 % with particle diameter ≥0.5 μm. For comparison, according to the above conversion method, when particle efficiency is 99.95 % for particle diameter 0.3 μm, its corresponding efficiency for particle diameter 0.5 μm becomes 99.9992 %.

Domestic-made medium-efficiency air filters include glass fibrous medium-efficiency air filter and foam medium-efficiency air filter. At present the most commonly used is nonwoven medium-efficiency air filter, which is actually a kind of fiber felt air filter.

Particle counting efficiency of glass fibrous medium-efficiency air filter (df = 16 μm, H = 20 mm, α = 0.037, v = 0.28 m/s) with atmospheric dust was performed at Institute of HVAC of China Academy of Building Research, which is shown in Table 4.13. In the table, average efficiency corresponds with the arithmetic average diameter of atmospheric dust, and efficiency is obtained with the theoretical curve of Fig. 4.13 with this average diameter. This theoretical curve is obtained by the method of structural nonuniform coefficient. Since the grouping range of particle diameter is comparatively large, difference between average particle diameter and actual value is large. But it is shown from the table that the efficiency calculated with average particle diameter is close to the actual measured data.
which is satisfactory. The calculation method has certain reference value. It is also shown from the figure that difference between calculated efficiency and experimental one is comparatively large when experimental coefficient method and the value of $\eta_0$ with Eq. (3.21) are used.

Figure 4.14 shows the experimental data of glass fibrous air filter and foam air filter at home and abroad. It is shown that the difference of efficiency between 0.5 and 0.3 $\mu$m is quite small, as well as the difference of efficiency between $\geq 0.5$ and $\geq 0.3$ $\mu$m. This is because filtration mechanism for medium-efficiency air filter for small particles has little difference.

From Fig. 4.14, the following approximated relationship exists when $\eta < 0.8$:

$$
\begin{align*}
\eta_{0.5} &= 0.1 + \eta_{0.3} \\
\eta_{\geq 0.5} &= 0.1 + \eta_{\geq 0.3}
\end{align*}
$$

(4.21)

### Table 4.13 Particle counting efficiency with atmospheric dust for glass fibrous medium-efficiency air filter

| Measurement no. | Group ($\mu$m) | Calculated mean size ($\mu$m) | Concentration (pc/L) | Efficiency (%) |
|-----------------|----------------|-------------------------------|----------------------|---------------|
|                 |                |                               | Upstream | Downstream | Measurement | Calculation |
| 1               | 0.3–1.2        | ~0.4                          | 468,000   | 20,296     | 30.6        | 40          |
|                 | 1.2–2.4        | ~1.9                          | 5,310     | 1,350      | 74.6        | 76          |
|                 | 2.4–4.8        | ~4.2                          | 933       | 47         | 95.0        | 94          |
| 2               | 0.3–1.2        | ~0.4                          | 495,000   | 304,300    | 38.4        | 40          |
|                 | 1.2–2.4        | ~1.9                          | 4,550     | 1,780      | 74.4        | 76          |
|                 | 2.4–4.8        | ~4.2                          | 357       | 60         | 98.3        | 94          |
| 3               | 0.3–1.2        | ~0.4                          | 665,000   | 35,700     | 46.4        | 40          |
|                 | 1.2–2.4        | ~1.9                          | 6,170     | 750        | 87.8        | 76          |
|                 | 2.4–4.8        | ~4.2                          | 308       | 0          | 100.0       | 94          |
| Average         | 0.3–1.2        | ~0.4                          |           |            | 40.3        | 40          |
|                 | 1.2–2.4        | ~1.9                          |           |            | 78.9        | 76          |
|                 | 2.4–4.8        | ~4.2                          |           |            | 97.8        | 94          |
4.8 Efficiency of Air Filters in Series

4.8.1 Efficiency of HEPA Filters in Series

In actual air cleaning system, filters are usually placed in series. Here the efficiency of air filters in series is emphasized.

In filtration theory, for filtering polydisperse aerosol with the same kind of air filter (e.g., they are all fibrous medium-efficiency air filter or HEPA paper filter), the penetration of second air filter should be larger than that of the first one, i.e., the efficiency of second air filter decreases. This is resulted from the selectivity of particles by filter medium, which has been introduced before. In short, mainly because the filtration mechanism for different particles is different, the dispersity of particles after the first air filter varies, which results in the change of total efficiency for the second air filter.

From Eq. (4.7) to derive the efficiency corresponding to various particle diameters, we can see that in order to calculate the efficiency of second air filter, the particle size distribution after the first filter and efficiency of various filters for different particle size must be known. These two problems have been solved, so detailed calculation can be made. Table 4.14 presents the calculation results for two HEPA filters in series (when the atmospheric dust concentration \(M = 10^6\) pc/L) [12].

![Fig. 4.14](image_url) Comparison of experimental efficiency between 0.3 and 0.5 \(\mu\)m (or \(\geq 0.3\) and \(\geq 0.5\) \(\mu\)m) for glass fiber and foam medium-efficiency air filters
Table 4.14 Efficiency of second HEPA filter

| Particle size (μm) | Proportional upstream the first HEPA filter | Calculated efficiency with ≥0.3 μm (the first filter) | Particle size (μm) | Proportional upstream the second HEPA filter | Calculated efficiency with ≥0.3 μm (the second filter) |
|--------------------|--------------------------------------------|---------------------------------------------------|--------------------|---------------------------------------------|---------------------------------------------------|
| 0.3                | 0.46                                       | 0.9991 × 0.46 = 0.459586                          | 0.3                | 0.935                                       | 0.9991 × 0.935 = 0.9341585                          |
| 0.4                | 0.20                                       | 0.99985 × 0.2 = 0.19997                           | 0.4                | 0.0441                                      | 0.99985 × 0.0441 = 0.0440934                        |
| 0.5                | 0.11                                       | 0.99994 × 0.11 = 0.1099984                         | 0.5                | 0.0154                                      | 0.99994 × 0.0154 = 0.0153991                        |
| 0.6                | 0.11                                       | 0.999984 × 0.11 = 0.1099982                        | 0.6                | 0.004                                       | 0.999984 × 0.004 = 0.0039999                        |
| 0.8                | 0.05                                       | 0.9999992 × 0.05 = 0.04999996 ≥ 0.8               | 0.8                | 0.0015                                      | 1 × 0.0015 = 0.0015                                 |
| ≥ 1.0              | 0.07                                       | 1 × 0.07 = 007                                    |                    | 0.9955                                       | 0.99914                                           |
Under normal conditions, atmospheric dust concentration is $M < 10^6 \text{ pc/L}$. With the decrease of $M$, the absolute quantity of large particles decreases. So the number of large particles passing through the first air filter is close to zero, which makes the proportion of large particles upstream of the second filter smaller. Efficiency of the second filter for particle diameter $\geq d$ is approaching to that for particle diameter equals with $d$. This means the penetration of the second air filter is close to be two times of the first filter. Therefore, when the third HEPA filter is placed, its efficiency for particle diameter $\geq d$ is much closer to that for particle diameter equals with $d$ of the first filter. When $d$ is 0.3 $\mu$m, efficiency decreases from 0.99955 to 0.99991, or the penetration increases two times from 0.045 to 0.09 % and then reaches stable. If monodisperse aerosol is filtered, the change of efficiency for various stages of air filter is small.

Reports on the problem of efficiency for air filters in series are rare [13]. Both theoretical calculation and experimental data in field have proved that the efficiency of the second filter decreases a lot. There are two reasons: one is that particle concentration becomes extremely small after passing through the second air filter and so on, so data is not accurately measured because of the limit of measurement techniques, and even reverse conclusions are obtained, which has been clearly mentioned in the “Nuclear Air Cleaning Handbook” [14]; the other is that during the field test, particle concentration will increase downstream of air filter in case of sealing problem during installation or even the trivial leakage. Field test data from Japan are listed below [13]:

| Filter Type          | Efficiency |
|----------------------|------------|
| The first HEPA filter | 99.99 %    |
| The second HEPA filter| 99.99 %    |
| The third HEPA filter | 99.86 %    |

The increase of penetration between the third HEPA filter and the second one is larger than the calculation result. Tester have pointed out that this is caused by leakage. If there were no leakage made by improper installation, there would be no much difference of efficiency between the third and the second filter. For this aspect, the strict experimental data cited by “Nuclear Air Cleaning Handbook” denied the opinion that the efficiency of air filter in series will decrease.

According to the data from “Nuclear Air Cleaning Handbook,” the decontamination factor of the first HEPA filter is $10^4$, and that of the second HEPA filter remains the same, while that of the third HEPA filter is $5 \times 10^3$.

It is known that $K_c = \frac{1}{K}$, so we can obtain $K_1 = 0.01$ % from $K_{c1} = 10^4$, and $K_3 = 0.02$ % from $K_{c3} = 5 \times 10^3$. So $K_3$ is two times of $K_1$, which is consistent with the calculated result which increases from 0.045 to 0.09 %.

Therefore, it is suitable to choose HEPA filters with these recommended penetrations for exhaust cleaning system:

- The first HEPA filter $K_{1(\geq d)}$
- The second HEPA filter $K_2 = 2K_{1(\geq d)}$
- The third and later HEPA filters $K_{3(d)}$
$K_{3(d)}$ means the penetration of the third and the following HEPA filters for particle diameter $\geq d$ equals with that for particle diameter $d$. In the inlet air cleaning project, efficiency for two HEPA filters in series is quite large, so the influence of the decrease of the efficiency of the second air filter is too small to be neglected. The total efficiency can still be written as:

$$\eta = 1 - (1 - \eta_1) (1 - \eta_2) \cdots (1 - \eta_n)$$

(4.22)

There are two aspects of meaning to prove the small decrease of efficiency for HEPA filters in series:

1. In the application field of exhaust cleaning system. As pointed out in *Nuclear Air Cleaning Handbook*, the emission permission for radioactive elements concentration (such as plutonium or other super uranium substance) is extreme low, so it is not enough to only install one HEPA filter in the exhaust system. Since the efficiency of air filter in series does not decrease, it is preferred to install two or more filters in series, which is easy to increase the efficiency of the first filter.

2. In the application field of cleanroom for cleanliness higher than class 100. When a HEPA filter is installed in series in the fresh air system, the influence of leakage is smaller. Some cleanroom projects in China have adopted this method and the effect is satisfactory.

### 4.8.2 Efficiency of Medium-Efficiency Air Filters in Series

For two medium-efficiency air filters in series, the efficiency of the second filter almost remains the same. If both filters are glass fibrous filters, in theory $\eta_{\geq 0.3} = 0.4$ and $\eta_{\geq 0.5} = 0.54$. We can obtain that the percentage of particles with diameter $\geq 0.5$ μm decreases from 30 to 15 %. The efficiency for particle diameter $\geq 0.3$ μm is 0.39 and that of particle diameter $\geq 0.5$ μm is 0.54 which remains the same. So the total efficiency of coarse and medium-efficiency air filters in series can be written as:

$$\eta = 1 - (1 - \eta_1) (1 - \eta_2) \cdots (1 - \eta_n)$$

### 4.9 Service Life

#### 4.9.1 Lifetime of Air Filter

The weight of dust deposited on air filter can be expressed with the following equation:

$$P = TN_1 \times 10^{-3} Q t \eta$$

(4.23)
where

\( P \) is the weight of deposited particles on air filter, g;
\( T \) is the lifetime of air filter, d;
\( N_1 \) is the particle concentration upstream of air filter, mg/m\(^3\);
\( Q \) is the flow rate, m\(^3\)/h;
\( t \) is the operational time per day of air filter, h;
\( \eta \) is the arrestance of air filter.

When air filter is operated under the rated flow \( Q_0 \) and the pressure drop increases to several times of initial pressure drop (usually it is two times), the air filter can no longer be used, and the weight of deposited particles is called standard dust holding capacity \( P_0 \). The used time of air filter is called lifetime \( T_0 \), i.e.,

\[
T_0 = \frac{P_0}{N_1 \times 10^{-3} \times Q_0 \eta}
\]

(4.24)

where \( N_1 \) can be calculated with the method in Chap. 10, i.e.,

\[
N_1 = M(1 - s)(1 - \eta_n) + N_r s(1 - \eta_r)
\]

where

\( M \) is the atmospheric particle concentration, mg/m\(^3\);
\( s \) is the recirculation air ratio;
\( N_r \) is the return air concentration. For cleanroom with Class 10 000, the concentration is between 0.001 and 0.01 mg/m\(^3\);
\( \eta_n \) is the arrestance of air filter in the fresh air ventilation system;
\( \eta_r \) is the arrestance of air filter in the return air ventilation system.

For different systems with different \( \eta_n \) and \( \eta_r \), the detailed calculation method will be introduced in Chap. 10. For example, \( P_0 = 450 \) g for flow rate 1,000 m\(^3\)/h, \( M = 0.3 \) m\(^3\)/h, \( N_r = 0.005 \) m\(^3\)/h, \( s = 0.7, \eta_n = 0.7, \eta_r = 0.65, t = 24 \) h, \( \eta \approx 1 \) (for HEPA filter), \( Q = 1,000 \) m\(^3\)/h, the service life of HEPA filter can be calculated to be 660 day. If the operational time per day is 12 h, \( T \) can be prolonged to be 1,320 day, which is 3.5 years. Since particles will also be deposited onto other surfaces, the lifetime of HEPA filters is longer than that of calculation.

Figure 4.15 shows the relationship between operational time and the increase of pressure drop of HEPA filter [15]. In the figure, the dust spot efficiency of prefilter in Curve b is 40–50 %, which is equivalent with the arrestance with atmospheric dust shown in Chap. 17. The service time of air filter is close to the data in the above example. It should be mentioned that there is one opinion that the increase of pressure drop of HEPA filter is faster than that of dust holding capacity, so it is unsafe to calculate the service time with dust holding capacity [16]. Actually it is not clearly pointed out here. Since the concept of dust holding capacity has included the increase of pressure drop, the service time or lifetime calculated with dust holding capacity equals with the operational time needed when the pressure drop becomes two times of the initial pressure drop (or other certain times).
4.9.2 Relationship Between Lifetime and Flow Rate

The following relationship is obtained from Eq. (4.24):

\[
\frac{T_1}{T_0} = \frac{Q_0}{Q_1}
\]  

(4.25)

It should be noted that \(T_1\) is not the lifetime of air filter under that flow rate \(Q_1\) but is the time needed for the weight of deposited particles on air filter to be \(P_0\) under the flow rate \(Q_1\). For example, if

\[Q_1 < Q_0\]

then

\[T_1 < T_{1,0}\]

\[T_{1,0} > T_0\]

and vice versa. Here \(T_{1,0}\) is the lifetime under the flow rate \(Q_1\).

Operational pressure drops are different when \(Q_1 \neq Q_0\). Experimental data were given which is given in Fig. 4.16 [17]. It is shown that when \(Q_1 = \frac{1}{2}Q_0\), the lifetime is larger than 2 \(T_0\). When we denote \(\frac{Q_0}{Q_2} = K\) and the pressure drop \(H\), Tu Guangbei obtained the following equations based on these curves [18]:

\[K = 1.25\ H = 30.45 + 2.0143T + 0.251T^2\]  

(4.26)

\[K = 1.0\ H = 28.86 + 1.481T + 0.1555T^2\]  

(4.27)

\[K = 0.75\ H = 17.35 + 0.687T + 0.0805T^2\]  

(4.28)

\[K = 0.5\ H = 11.08 + 0.2474T + 0.0318T^2\]  

(4.29)
The following comprehensive equation was obtained when log-log plot paper was used with $K$ as the abscissa (Fig. 4.16):

\[
H = 23.86K^{1.106} + 1.481K^{2.519}T + 0.1555K^{2.290}T^2
\]  
(4.30)

It is obvious that the constants in Eqs. (4.26), (4.27), (4.28), and (4.29) are initial pressure drops.

When $H$ is considered constant, $T$ is easily obtained by simplifying Eq. (4.30) [19]:

\[
T = \frac{-1.481K^{2.519} \pm \sqrt{(1.481K^{2.519})^2 - 4 \times 0.1555 \times (23.86K^{1.106} - H)}}{2 \times 0.1555}
\]  
(4.31)

When $H = H_0$, $T$ becomes the lifetime $T_0$. The value of $T$ is only positive.

However, the above expression was obtained from one test case, and it is inconvenient to use it for calculation, which is not obvious to obtain the characteristic at a glance. So it is still unsure whether the relationship between $T$ and $K$ is also universally valid.

From another point of view, author proposed an approximation method for the theoretical analysis of relationship between $T$ and $K$ [19]. When both the operational and rated flow rates are known, the change trend of the lifetime can be calculated.

For example, the increase of pressure drop is $\Delta H$ under the rated flow $Q_0$ when the initial pressure drop is $H_0$ and standard dust holding capacity is $P_0$, so the final
pressure drop is $H_0 + \Delta H$ and the operational time or lifetime is $T_0$. The curve ($K = 1$) is shown in Fig. 4.17.

When the flow rate becomes $Q_1 (< Q_0)$, $\frac{Q_1}{Q_0} = K$ ($K < 1$), what is the time $T_{1,0}$ when the pressure drop reaches $H_0 + \Delta H$?

Simplification was made with the assumed condition $\Delta H \approx H_0$. From the aforementioned introduction, we know the increase of pressure drops of HEPA filter and sub-HEPA filter are linearly proportional to the weight of dust deposited under this condition.

1. From Eq. (4.25), it is known that the operational time is reversely proportional to the flow rate, i.e.,

$$T_1 = \frac{Q_0}{Q_1} T_0 = \frac{T_0}{K}$$

2. After operation time $\frac{T_0}{K}$ under flow rate $Q_1$, the weight of deposited particles becomes the standard dust holding capacity $P_0$, but the final pressure drop at this time is still far from $H_0 + \Delta H$. From Figs. 4.6, 4.7, 4.8, and 4.9, it is shown that $H$ is approximately linearly proportional to $Q$ (when $Q$ is less than $Q_0$ or slightly larger than $Q_0$). Since the final pressure drop is $(1 - K)$ times less, continuous dust loading process is needed to increase the pressure drop. It is known the pressure drop increase is approximately linearly proportional to the weight of deposited particles, and the weight of deposited particles is also linearly proportional to the time, so the time needed for continuous particle loading process or the increased time is:

$$\Delta T_1 = (1 - K)T_0$$
3. According to the relationship between \( H \) and \( Q \), the initial pressure drop decreases to \( KH_0 \) under the flow rate \( Q_1 \), this is \((1 - K)\) times less. If the operational flow rate is \( Q_0 \) and \((1 - K)\) times of original pressure drop is added, the prolonged time needed is \((1 - K)T_0\). Now the operational flow rate is \( Q_1 \), so the time should be reversely proportional to \( Q_0 \), i.e., the actual prolonged time is

\[
\Delta T_2 = \frac{1 - K}{K} T_0
\]  

(4.34)

4. Therefore, for the case \( K < 1 \), the time needed for the pressure drop to become the final pressure drop with \( K = 1 \) should be

\[
T_{1,0} = T_1 + \Delta T_1 + \Delta T_2 = \frac{T_0}{K} + (1 - K)T_0 + \frac{1 - K}{K} T_0
\]  

(4.35)

If \( Q_1 > Q_0 \), \( Q_0 < 1 \) when \( Q_1 \) is assumed 1, and \( \frac{Q_0}{Q_1} = K \) \((K < 1)\). So the reciprocal of prolonged time \( Q_0/Q_1 \) is obtained, which is the shortened time.

With the above equations and principles, the relationship between \( K \) and \( T_{1,0} \) for reaching the final pressure drop with rated airflow, which is shown in Table 4.15. In the table, \( K = 1.25 \), which is equivalent with \( K = \frac{1}{Q_0/Q_1} = \frac{1}{0.8} \). It is equivalent to the reciprocal of its multiple of \( T_0 \), which is obtained with the value 0.8.

Table 4.15 Relationship between \( K \) and \( T \)

| \( K \)  | 0.5 | 0.7 | 0.75 | 0.8 | 1.0 | 1.25 |
|--------|-----|-----|------|-----|-----|------|
| \( T_{1,0} \) | 3.5 \( T_0 \) | 2.15 \( T_0 \) | 1.91 \( T_0 \) | 1.7 \( T_0 \) | \( T_0 \) | \( \frac{T_0}{0.59} \) |

One important conclusion from the above analysis is obtained. The operational flow rate of air filter is suggested to be about 70 % of the rated flow, and the lifetime of air filter will be doubled, which is beneficial for both economic operation and energy saving.

In practice, it is impossible to directly estimate how much particles have been deposited onto filters. It is usually to determine whether to change air filters according to the measured pressure drop or the outlet velocity of air filter.

For air filters used in the radioactive exhaust system, except for the index of dust holding capacity or pressure drop, the index of surface contamination is also used to determine the service time. Air filters must be replaced when each index reaches the specified value. The extent of surface contamination of air filter is determined according to the specific situation of usage.
Table 4.16  Comparison of different $T_0$ obtained with different methods

| $H_0$ (Pa) | $H_0 + \Delta H$ (Pa) | $T_0$ (kh) | $K = 0.5$ | $K = 0.75$ | $K = 1$ | $K = 1.25$ |
|------------|-----------------------|------------|------------|------------|------------|------------|
| 240        | 480                   | Eq. (4.31) | Eq. (4.35) | Measurement | Eq. (4.31) | Eq. (4.35) |
|            | 30.2                   | 30.1       | 30.0       | 15.6       | 15.9       | 8.6        |
|            | 4.6                   | 5.1        | 5.0        |            |            |            |
4.10 Estimate of Arrestance

Arrestance of air filter is used to calculate the service time of air filter in previous section. Experimental data of arrestance can be used if it is available. But in the current national standard the fractional efficiency with atmospheric dust is used to assess the efficiency of air filters in general ventilation. Therefore, the particle counting efficiency should be converted into arrestance.

Here an estimation method is introduced [20].

Taking the data in Table 2.28 as an example, particle size distribution between 0.5 and 1 μm can be divided into the following parts according to the relationship shown in Table 2.30:

| Diameter (μm) | Percentage |
|--------------|------------|
| 0.5          | 31.64 %    |
| 0.6          | 29.72 %    |
| 0.8          | 14.28 %    |
| 1.0          | 5.75 %     |

In total 81.49 %

From Table 2.28, when the particle counting efficiency for particles with diameter ≥0.5 μm is 100 %, at least 99 % of particles by weight are filtered. Weight of particles with diameter less than 0.5 μm occupies 1 % of the total weight. Since part of particles with diameter less than 0.5 μm will be captured, the penetration will be less than 1 %. This can be omitted since it is a small value. That is to say, when the particle counting efficiency for particles with diameter ≥0.5 μm is 100 %, the arrestance cannot reach 100 % in theory, but it can be still considered as 100 % because the error is less than 1 %.

From the above analysis, we know when the particle counting efficiency for particles with diameter ≥1 μm is 100 %, at least 97 % of particles by weight and 18.51 % of particles with diameter larger than 0.5 μm will be captured. Since part of particles with diameter between 0.5 and 1 μm will also be captured, the total arrestance will be slightly larger than 97 %. For the convenience of estimation, this excess value can be omitted. Therefore, when the particle counting efficiency for particles with diameter ≥1 μm is 100 %, the corresponding arrestance can be estimated as 97 % or 100 %. When the particle counting efficiency for particles with diameter ≥1 μm is 80 %, 18.51 % × 0.8 = 14.81 % of the total number with particle diameter ≥0.5 μm will be captured, so less particles with diameter between 0.5 μm and 1 μm will be filtered (because efficiency for particles with diameter ≥1 μm is less, the corresponding efficiency for smaller particles is much less, which can be omitted). Therefore, the arrestance corresponding with the particle counting efficiency 14.81 % with particle diameter ≥0.5 μm can be used to express the particle counting efficiency 80 %, i.e., 96.5 %.

But when only the particle counting efficiency with particle diameter ≥5 μm is known without any information about the efficiency with particles diameter between 1 and 5 μm, the above method to estimate the arrestance is not valid since the weight percentage of these particles cannot be omitted.

According to the above analysis, the data in Table 2.28 are used to plot Fig. 4.18. The arrestance found in the figure is an estimation value or the minimum limit value.
Fig. 4.18: Conversion from particle counting efficiency to arrestance: 
1. 100% efficiency curve for particle diameter ≥0.5 μm, 
2. 100% efficiency curve for particle diameter ≥1 μm, 
3. 100% efficiency curve for particle diameter ≥3 μm, 
4. 100% efficiency curve for particle diameter ≥5 μm
4.11 Filter-Paper Filter

4.11.1 Folded Filter-Paper Filter

Now the filter-paper HEPA filter is one typical example of folded filter-paper filter, which was developed in the nuclear industry in the Second World War to remove radioactive particles. The main characteristic is its extreme low resistance because the filter paper is thin and filtration area is dozen times of frontal area by the folded structure, which makes the practical use of filter-paper filter possible.

In 1942 the folded filter-paper HEPA filter was first manufactured in the USA and put into the market for sale in 1954. In 1956 HEPA filter was imported into Japan from the USA. Later in 1958 Japanese began to develop their own product, which appeared in the market in 1965 [21]. In 1960s, Chinese began to develop HEPA filter, which passed the identification and began the mass production.

The first filter-paper material used in the air filter of nuclear industry was plant fiber together with blue asbestos fiber. Blue asbestos fiber is very fine with diameter between 0.1 and 1 μm. The yield is very low. It is thought that asbestos fiber will cause cancer, so it is gradually replaced by popular ultrafine glass fiber and glass fiber filter paper, which promotes the application of high-efficiency filter-paper filter and the development of air cleaning technology.

Filter-paper HEPA filters can be classified according to the type of filter media material, and they can also be divided based on whether separator is used; whether the diameter of filtered particle is 0.3 μm (it is called common HEPA filter or 0.3 μm filter) or 0.1 μm (it is called ultrafine air filter or 0.1 μm filter); whether the frame material is board, laminate, plastic plate, aluminum alloy plate, steel plate, or stainless steel plate; whether the structural shape is flat or V type; and whether it is able to endure high pressure, endure high humidity, and endure acid and alkali, high resistance, low resistance, or sterilization.

At present there are three types of structure in filter-paper filter, i.e., with separator, with inclined separator, and without separator. The product of air filters with inclined separator is rare, while the other two types are popular. Structures of these three types are shown in Figs. 4.19, 4.20, and 4.21.

Inside HEPA filters, separator is placed between two sides of folded filter paper to provide the airflow channel, which is the standard practice. So it is called as separator HEPA filter. Separator is also called as corrugated separator. After hot rolling stamp, high-quality kraft paper can be used to make the separator with different crests and pitches. In order to prevent the particle emission from the stretch of separator caused by the cold, hot, dry, or wet conditions, as well as to fix the separator shape, both sides of separator should be immersed into some kind of coating material, which has the disadvantage of abnormal odor. Now chrome papers gluing at two sides are used to make separator. But some practical experience has shown that there is some hidden danger: particles will be released as the pollution source because of its stretch deformation with the variation of temperature and humidity. So aluminum and plastic can also be used to make separator.
For the separator air filters, corrugation angle is one important parameter, which has great influence on the pressure drop. Practice has shown that 90º corrugation angle is suitable. The influence of cross-sectional area on the pressure drop is not large. With the large cross section and same filtration velocity and thickness along the flow direction, the corrugation height has comparatively large influence on the pressure drop, which will be analyzed in detail later.

Fig. 4.19 Structure of separator HEPA filter: 1 frame, 2 heat glue, 3 separator, 4 filter paper, 5 gasket, 6 Sealant. (a) Wooden frame. (b) Iron frame. (c) Details of glue separator

Fig. 4.20 Structure of inclined HEPA filter: 1 frame, 2 separator, 3 filter paper. (a) Cross section of inclined separator. (b) Peak height of inclined separator
The traditional practice to make the separator air filter is to glue at both edges of the corrugation at first, then the endsealing glue is added to the inner side at both two edges of wooden frame painting so as to make the glue sides in order and to prevent leakage. But practice has shown that the endsealing glue has little effect on the leakage prevention, and once there is leakage, it is more difficult to detect the leakage and make repair. Taking the current GB-01 type air filter as an example, the cross-sectional area of filter cartridge is about \(0.454 \, \text{m}^2\) and the width of endsealing glue is 1.5 cm. When it was considered as 1 cm, the corresponding cross-sectional area of filter cartridge is about \(0.454 \, \text{m}^2 \times 0.434 \, \text{m}^2 = 0.197 \, \text{m}^2\), which means the cross-sectional area without endsealing glue is 5% larger than that of with endsealing glue. When the net area of filter paper increases, the pressure drop will decrease to some extent. Therefore, the practice to use the endsealing glue on air filter is canceled, which is replaced with potting glue method or inserting glue method.

For traditional separator air filter, the cross-sectional areas of air channel formed by the corrugations on the separator are the same. When the concept of area variable cross sections is applied on air filter, inclined air filter is created, whose projection shape is a right-angled trapezoid when the separator is erected. The cross-sectional area is large when air enters into the channel. As air goes through the filter paper, the air volume near the channel terminal is the minimum, so is the cross-sectional area. In this way, both the length of filter paper around each separator and the number of corrugations increase. According to the product specification abroad, the filtration area will increase by 50% for inclined separator air filter compared with vertical separator air filter, so the pressure drop under the same flow rate will be much less.

Another method of improvement on traditional HEPA filter is to cancel the separator. It is beneficial for the mechanized production of mini-pleat filter. One case is to cancel the separator, and the filter paper is folded with corrugation matching corrugation and point matching point after corrugation and salient point are pressed on filter paper. The other case is to replace the separator plate with other
separator, such as the streak formed by thermosol on filter paper, the dipping flame retardant silk thread, glass fiber thread, or filter strip pasted on filter paper. During the process of folding filter paper, filter strips are inserted from the two sides of corrugation and they are held with the friction force.

It should also be mentioned that the cross-sectional size of domestic-made HEPA filter includes 484 mm $\times$ 484 mm, 630 mm $\times$ 630 mm, etc., which are quite irregular. National standard issued in 2008 canceled the specification of maximum overall dimension. It also requires that (1), (2) separator plate is 5–8 mm lower than the frame edge, and (3) the filter element is 3–5 mm lower than the separator edge. The national standard also provides the following specification: (1) The frame width is 15 mm (when the side length is less than or equal to 600 mm) or 20 mm (when the side length is equal to or larger than 600 mm). This is a way to guarantee the quality of air filter, but some manufacturer does not pay attention to it. During the calculation related to air filter, these data should also be considered.

In order to enlarge the filtration area, double folding structure is also adopted. The first folding structure is for filter paper itself, which means a piece of folded filter material is used. The second folding structure is the W type structure inside the frame. The structure is shown in Fig. 4.22.

### 4.11.2 Cylindrical Filter-Paper Filter

In early times, the former USSR made transversely placed large cylindrical filter with $\phi$II-15-1.5 filter fabric which is hard to be folded but can be pasted, which is shown in Fig. 4.23. Strictly speaking, that is a kind of equipment, not a single air filter.
YCG-type low-resistance sub-HEPA filter is one typical example of filter-paper filter, which was one type of air filters with lower structural resistance innovated firstly in China [23]. Hundreds of filter cylinders are hot welded with polypropylene fiber filter paper. Filter cylinders are plugged onto the panel with the plastic cap stopper with wings. Wings are meant to support the filter cylinders and separator the air channel into two parts.

Figure 4.24 is the perspective of this kind of filter. Figure 4.25 shows the panel plugged with cap stopper, its hole size and details of cap stopper. Figure 4.26 presents the experimental results between this filter and Japanese CP-9A high-efficiency air filter, which was performed on the test rig at Institute of HVAC of China Academy of Building Research. It is shown that efficiency increases by an order of magnitude when the pressure drop is slightly less.

Main features of this kind of air filter include:

1. Low resistance. With the same size of GB-01 HEPA filter (484 mm × 484 mm × 220 mm), the pressure drop is only about 40 Pa under the rated flow 1,000 m³/h and sodium flame efficiency ≥95 %.
Fig. 4.25 Details of cylindrical filter panel

Fig. 4.26 Performance comparison between UGG air filter and Japanese CP-9A filter
2. Non-abandon. Old filter cylinders are replaced only with new ones. Others can be used several times for cost saving.

3. Any shape. Diameter of filter cylinder is only 19 mm, so they can be plugged onto the panel with various shapes. Panel is needed while the frame is not, so it is convenient to match with various equipments.

4. No peculiar smell. Unlike the HEPA filter which needs to use glue, it is adhesive-free product, so secondary pollution caused by peculiar smell does not exist, which is suitable for the application with stringent environmental requirement.

5. Light. The weight is only half of the HEPA filter with the same size.

Structural calculation of this kind of air filter will be introduced in Chap. 5.

### 4.11.3 Filter Paper Used in Filter-Paper Filter

#### 4.11.3.1 Cellulose Filter Paper

It usually means the filter paper made by plant cellulose. Several domestic-made air filters with performance similar as sub-HEPA filter are made of short cotton lint filter paper. The characteristic of this kind of filter paper is that its efficiency is between medium efficiency and sub-high efficiency. The efficiency is small for low filtration velocity. Efficiency increases with the increase of filtration velocity. The performance differs for different kinds of particles.

Table 4.17 shows the filtration efficiency of one cellulose fiber filter paper with PSL [24]. It is shown that for particles with diameter smaller than 0.557 μm, the efficiency is the minimum for filtration velocity 9.5–17 cm/s. Moreover, the minimum efficiency corresponds with smaller particle size with the increase of filtration velocity. The surface dust holding capacity of this kind of filter paper is slightly larger than that of glass fiber filter paper by 60–70 %, but it is smaller than that of membrane filter.
4.11.3.2 Cellulose-Asbestos Fiber Filter Paper

This kind of filter paper has high efficiency and high resistance. Since the surface dust holding capacity is also very high, even higher than that of glass fiber filter paper, it is usually applied in the exhaust treatment system for nuclear facility.

4.11.3.3 Glass Fiber Filter Paper

This kind of filter paper also has high efficiency. Efficiency changes little with the change of particle type and filtration velocity. The relationship between efficiency and composite proportion of glass fiber inside the filter paper is shown in Table 4.18 [25]. The pressure drop is smaller than that of cellulose-asbestos fiber filter paper.

Fiber diameters inside glass fibrous filter paper become smaller. In 1970s diameter of foreign made filter paper reduces to 0.3 μm, and the value of domestic made reduces to 0.5 μm. Figure 4.27 presents statistical analysis of the fiber diameter distribution inside domestic-made filter paper using SEM graph, where all the average diameters are slightly smaller than 0.5 μm. In 1980s the diameter of domestic-made glass fiber was smaller than that of foreign made, which reduced to 0.04 μm. Efficiency increases apparently and that of some filter paper was higher than that made in the USA. However, the most obvious shortcomings of domestic-made filter paper are fiber shedding and the amount of particles deposited by filter media itself is great, which is related to the inaccurate control of manufactory environment and production process. Furthermore, pressure drop of common HEPA filter paper is very high under the usual filtration velocity, and that of most ULPA filters is even much higher [9].

4.11.3.4 Synthetic Fiber (Chemical Fiber) Filter Paper

Since the synthetic fiber has high resistivity and can bring large amount of electrostatic charge, it is an ideal material for making electrostatic material. Perchloroethylene φII filter fabric produced in the former USSR in 1950s is one of the kinds of fibrous filter paper. Penetration is 20% when filtration velocity is 0.1 m/s, while it is 3.2% when filtration velocity decreases to 0.01 m/s and the corresponding $d_{\text{max}}$ is 0.1 μm [22].

| Efficiency with 0.3 μm DOP particles (%) | Proportion of glass fibers in filter paper (%) |
|----------------------------------------|-----------------------------------------------|
| >99.995                                | >90                                           |
| >99.97                                 | >60                                           |
| 99                                     | ~45                                           |

Table 4.18 Relationship between efficiency and composite proportion of glass fiber inside HEPA filter
Polypropylene fibrous filter paper developed in the late 1970s is another example. Its performance is much better than ϕΙΙ filter fabric. Polypropylene slice is used to make ultrafine fiber through the meltblown process. Further filtration material is manufactured, which is a soft nonwoven felt. Diameter of single fiber is 2–18 μm (usually it is 4 μm). The sodium flame efficiency with standard specific velocity is 99–99.999 %. It is quite difficult to make the fiber diameter smaller. Fibers are not uniformly distributed inside the filter media. Electrostatic charge on the filter media fades away gradually, so at present it cannot be used to replace glass fibrous HEPA filter. But it is indeed a promising filter media.

Except for the features mentioned in the above chapter and sections in this chapter, polypropylene fibrous filter media has the following characteristics:

1. Pressure Drop. Under the same efficiency range, the pressure drop is only 1/6 that of glass fiber. Table 4.19 presents the pressure drop of several domestic-made polypropylene filter paper when the filtration velocity is 1 cm/s.

The reason for small pressure drop is that the fiber diameter is comparatively large and particles can penetrate deeper (several hundred micrometers). But particles can only penetrate tens of micrometers from the surface of glass fibrous filter paper.

Table 4.19 Pressure drop of polypropylene fibrous filter paper

| Efficiency with sodium flame method (%) | 90  | 99  | 99.9 | 99.99 | 99.999 |
|----------------------------------------|-----|-----|------|-------|--------|
| Resistance (Pa)                        | 1   | 3   | 6    | 9     | 12     |

Fig. 4.27  Statistical analysis of fiber diameter distribution inside domestic-made filter paper
2. Stability of Electrostatic Charge. After passing through the corona discharge, filter media become the electrets which carry large amount of electrostatic charge, and the surface electrostatic potential can reach 1,000 V. With the electrostatic effect, the penetration decreases by 1–2 order of magnitude. After the filter media is immersed into the alcohol and then dried in the vacuum, the electrostatic charge is neutralized and the efficiency decreases a lot, which is shown in Figs. 4.28 [26] and 4.29 [27]. At the same time, it is also found that the electrostatic potential increases by the friction effect when air flows through the filter media, which is shown in Table 4.20. The potential at smooth side is high, so the efficiency using this side as the frontal face is high, while the pressure drops using both sides facing upstream is almost the same (Table 4.19).

3. Dust Loading Performance. Experimental results with NaCl aerosol show that the relative penetration (the ratio of penetration after dust loading \( K \) to the initial penetration \( K_0 \)) of polypropylene fibrous filter media increases firstly then decreases with the time. There is an extreme short transient period where the relative pressure drop (the ratio of pressure drop after dust loading \( \Delta P \) to the initial pressure drop \( \Delta P_0 \)) increases with the time, which is shown in Figs. 4.30 and 4.31 (Although the unit was not given in the original literature, the qualitative analysis is not influenced).

But experiment was performed on the electrets air filters with polyolefin fiber which concluded that efficiency decreased from 99.9999 to 99.99 % after 2 years’ operation without any prefilters. The reason is that the electrostatic effect is shielded by the deposited particles [29].
1. Hydrophobicity. Polypropylene fibrous filter media are hydrophobic. The hygroscopicity is only 0.01–0.1 %. Under the wet condition, the strength is almost unchanged. When it is placed in the environment with relative humidity 80 %, no obvious influence is made on both the efficiency and pressure drop [28].

2. Temperature Characteristic. The operating temperature is −40 to +110 °C. When it is baked under the temperature 50 °C for 4 h, no obvious change appears in both efficiency and pressure drop [26]. But efficiency decreases when the operating temperature is above 120 °C. The melting point is 164–174 °C.

3. Density. It is 0.91 g/cm². The solid fraction is 0.12 with measurement [26].

4. Characteristic of Acid and Alkaline Resistance. Except chlorosulfuric acid, concentrated nitric acid, and some oxidants, it has good performance of resisting acid, alkaline, and organic solvent.

**Table 4.20** Influence of airflow on the electrostatic charge (unit: V)

| Condition | Front and back of filter media | Blow with hair drier for 2 min (normal temperature) | Dry with vacuum oven after immersed in alcohol for 5 min | Dry with vacuum oven after immersed in alcohol for 5 min, and then blow with hair drier |
|-----------|-------------------------------|---------------------------------------------------|-------------------------------------------------------|----------------------------------------------------------------------------------|
| Glaze surface | Without any treatment | −1434 | −1601 | +12 | −204 |
| Rough surface | Blow with hair drier for 2 min (normal temperature) | +916 | +1280 | +4 | −80 |

**Fig. 4.29** Relationship between efficiency and filtration velocity for polypropylene fibrous filter media with the electrostatic effect
5. Strength. The transverse tensile strength is larger than 500 g/100 × 15 cm, and the longitudinal tensile strength is larger than 1,000 g/100 × 15 cm. The strength is more than two times of glass fibrous filter paper. It is fold resistant.

6. Environmental Property. Nontoxic, odorless, no borer, and it can be disposed by combustion.

7. Ability to Absorb Oil. It can absorb oil with weight equals with 14–15 times of self weight.

8. Bonding Characteristic. It is difficult to bond with the glue, but it’s easy to bond with iron.

4.11.3.5 Membrane Filter Paper

The gel type microporous filter membrane is the main form, which is made of the nitrocellulose. The gel is the mixture of the ether alcohol with the fibers of nitrate
ester, and it is also called celloidin. When the celloidin is diluted with the acetone and the pentanol, the gel used for make the membrane is formed. This kind of filtration membrane has very high efficiency and surface particle deposition rate, so it is usually used to act as a standard filter paper to measure the efficiency of other filter papers. It is also used to capture radioactive particles, but it is not convenient to use since the pressure drop is high and the tensile strength is low.

Pores on the surface of microporous membrane are irregular, which is similar as that of foam. Their SEM figures are shown in Figs. 4.32 and 4.33 [30], where the spheres are methylene blue particles.

Nuclear microporous membrane is also one kind of membrane filter paper. It is called nuclear track microporous membrane, which is developed in the late 1960s. Thermal neutron during the nuclear reaction is used to bombard the heavy element such as $^{235}$U. Then the fission fragment from $^{235}$U is used to bombard the plastic film such as polycarbonate film or polyester film, or the heavy element such as K, and $X_e$ accelerated by the accelerator is used to bombard these films, so track injury
is left. Afterwards, they are etched with chemical reagent, and pores appear on the surface. Its strength is good. It is fold resistant and can bear high temperature 140–170 °C. Pore density can be controlled when both the bombardment intensity and time are monitored. Pore size can be controlled when the reagent concentration, temperature, and etching time are controlled. The thickness of nuclear microporous membrane is usually between several micrometer and dozens of micrometer. The thickness of domestic-made nuclear microporous membrane is 11 μm. Diameter of pore size is between 30 Å and tens of micrometer, and it is usually about 1 μm. The porosity is about 20 %. The monodisperse of pore size is better than chemical microporous membrane. Since the surface is quite smooth, it is suitable for qualitative analysis of aerosol sampling and study of bacteria filtration. The pressure drop of nuclear microporous membrane is large, so it is not suitable for common air filter, but it is very useful for special filtration (for the application field where particles with diameter larger than certain value are not allowed to penetrate). It is shown from Fig. 4.34 that almost no particles appear on the rear face when the frontal surface is already clogged. It is widely used in the medical applications. As for the filtration mechanisms of nuclear microporous membrane, domestic scholars have already made detailed investigation [31], which will not be introduced here.

Except for the above five kinds of filter paper, there is also plastic fibrous filter paper, which is not illustrated here.
4.11.4 General Features of Filter Paper

Special attention should be paid on the representative features during the selection of filter paper, which is presented in Table 4.21. It is hoped that the larger tensile strength and smaller fiber are preferred. While larger thickness and larger solid fraction will result in high efficiency, but the pressure drop will increase dramatically at the same time.

The content of metal component is one important feature for filter paper. When the content of metal component in the captured particles is investigated, the background value in the filter paper itself is needed. There is little study in this aspect home and abroad. For reference purpose, Table 4.22 presents the contents of several metal components inside the common glass fibrous filter paper according to the literatures home and abroad.

It is shown in Table 4.21 that the largest shortcoming of this kind of glass fibrous filter paper is the weak tensile strength. The ability to bear the shock press is extreme low. During the manufacturing process, it is too fragile to be damaged if it is not careful enough. Experiment of the compressive strength of HEPA filter was performed using the shock tube. Protection device was developed to increase the ability to bear high shock force. Common HEPA filter with tensile strength of filter paper no less than 230 g and other air filters were used in the test. Different conditions were compared when no baffle was placed and different baffles were set 5 cm upstream of the air filter. The test results for common HEPA filters are shown in Table 4.23. Both Figs. 4.35 and 4.36 show the damaged filters, where the white part means the damaged part of filter paper which turned outwards [32]. Moreover, the stiffness and rigidity of filter paper have decisive influence on the height of corrugation and pressure drop.

From the test results shown above, the pressure for damaging domestic-made glass fibrous filter paper (or 6901 filter paper) used in common HEPA filters is less than 0.16 kg/cm². According to American Air Force Design Manual (AD295408, TDR-62-138 Report), the pressure to cause damage on AEC filter from US Atomic Energy Commission is only 0.14 kg/cm². Therefore, when glass fibrous filter is installed on the pipeline with shock press, the protection device must be installed, and the most common measurement is to place the baffle plate.

The tensile strength of glass fibrous filter paper is very small, and it decreases a lot under the high wet environment, so it is easy to be blown through. If special treatment is made on filter paper, its tensile strength can be improved. Domestic researchers have proved that when the filter paper is treated by spraying with “soft No. 1” leather treatment agent, the tensile strength can be increased by ten times, while the pressure drop does not increase too much and the efficiency remains the same [33]. Experimental results are summarized in Table 4.24.

Table 4.24 is the experimental result of pressure drop with high filtration velocity 0.16 m/s. Pressure drop data for low filtration velocity are not available. With low filtration velocity, the rise velocity of pressure drop is slower than that of high filtration velocity.
### Table 4.21 Characteristic of filter paper

| Item | Thickness (mm) | Average mass per unit area (g/m²) | Solid fraction of fiber | Fiber size (μm) | Pore size (μm) | Tensile strength (g) | Combustion content (%) | Metal content (μg/g) |
|------|----------------|----------------------------------|------------------------|-----------------|---------------|---------------------|------------------------|--------------------|
| Common range | 0.15–0.4 | Depend on material | HEPA: 0.1–0.25 | HEPA: <0.1 | <1 (filter membrane) | 250–450 | Depend on material |
| Example | Glass fibrous filter paper with 99.99999% | 0.4 ± 0.03 | 130–140 | 0.118 | 0.5 | ≥645 |
| | Glass fibrous filter paper with 99.9999% | 0.36 ± 0.02 | 110 | 0.113 | 0.5 | >400 |
| | Glass fibrous filter paper used in clean bench | 0.20 ± 0.03 | 60–70 | 0.12 | 0.4 | 200 |
| | Glass fibrous filter paper used as general HEPA filter (such as 6901 paper) | 0.23 ± 0.02 | 70–80 | 0.12 | 0.4 | >230 |
| | Japan GB-100 glass fibrous filter paper | 0.41 | 148 | 0.138 | 0.3 |
| | Japan No. 228 glass fibrous filter paper | 0.275 | 76 | 0.102 | 0.92 |
| | No. 3 asbestos filter paper | 0.5 | 170 | 0.09 | ~300 |

*aAccording to domestic requirement, the tensile strength is the reading value at fracture when one side of filter paper with width 15 mm and length 180 mm is fixed and the other side is stretched with the spring balance.*
The filter paper is still undamaged when it is treated with “soft No. 1” leather treatment agent and then with steam. This means it can bear high temperature environment of steam for sterilization, so it is useful for pharmaceutical and biological clean rooms.

It is dependent on the application and performance to choose what kind of components including filter paper, frame, and separator (corrugation) for making air filter, especially HEPA filters. For information, Table 4.25 shows the general performance of air filter made by components with different materials.

Because the filter paper is too fragile to be damaged during the manufacturing process, the efficiency of filter-paper air filter is usually smaller than that of small filter-paper sample by “half 9,” and the poorest performance difference could be less than “one 9.” Therefore, for making HEPA filter with efficiency for particle diameter 0.3 μm to be above “three 9” (i.e., 99.9 %), filter paper with efficiency “four 9” must be used.

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**Table 4.22** Common range of content of metal component in glass fibrous filter paper (atomic extinction analysis)

| Metal | Content (μg/g) | Metal | Content (μg/g) | Metal | Content (μg/g) |
|-------|----------------|-------|----------------|-------|----------------|
| Cd    | <1             | Pb    | 5–90           | K     | 400–1,800      |
| Cu    | 1.5–3          | Sb    | 20–60          | Ca    | 300–6,000      |
| Ni    | 1–15           | Zn    | 10–50,000      | Na    | 4,000–40,000   |
| Mn    | 2–30           | Fe    | 60–500         |       |                |
| Cr    | 2.5–10         | Mg    | 300–1,600      |       |                |

**Table 4.23** Ability of common HEPA filter to bear shock press

| Inlet pressure (kg/cm²) | Bypass flow baffle | Damage situation |
|-------------------------|--------------------|------------------|
|                         | No type V or type V | Damage occurs in the center of the air outlet face |
|                         | 200 circular plates. No perforation within 60. | |
|                         | Perforations with 4 and distance 8 mm are made in the left area of the plates | |
| 0.16–0.18               | air filter         | No damage occurs in the center. |
|                         |                    | Damage occurs at both sides |
|                         |                    | 200 circular plates. No perforation within 60. |
|                         |                    | Perforations with 4 and distance 8 mm are made in the left area of the plates |
| 0.23                    | air filter         | No damage occurs in the center. |
|                         |                    | Damage occurs at both sides |

The filter paper is still undamaged when it is treated with “soft No. 1” leather treatment agent and then with steam. This means it can bear high temperature environment of steam for sterilization, so it is useful for pharmaceutical and biological clean rooms.
4.11.5 Development of Filter-Paper Air Filter

With the development of science, technology and manufacturing process, both the standard and test methods for HEPA filters in many countries are developing, which will not be introduced here [34]. More stringent requirement for filter-paper air filter will be put forward. There are following requirements [35]:

1. Efficiency for particle diameter 0.1 μm should get close to 99.99999 %, or for particle diameter 0.01 μm should get close to “eight 9,” which is called ULPA filter and shown in Fig. 4.37.
2. It is more stringent to make requirement on the chemical pollution of filter paper.

At present, most of HEPA filter is composed of filter media with ultrafine glass fiber which is made from silicon boric acid. 58 % of its component is SiO₂.

In 1980s the requirement of silicon pollution was proposed. Silicon particles volatilize and emit from the hydrophobia material, which cause harmful effect on the production of hard disk drive.

In 1990s the problem of phosphorus pollution was put forward. Phosphorus pollution comes from the seal glue of air filter, which may cause pollution to the wafer.
In the late twentieth century, the problem of boron pollution was put forward, since about 11% of the component in the filter media is B$_2$O$_3$. Except for the boron pollution of atmospheric air as the main source, air filter is also one important source. Under high-humid environment, hydrofluoric acid will make corrosion on glass fiber and produce gaseous boric acid if hydrofluoric acid exists, which will pollute the wafer.

1. The pressure drop with rated flow is smaller than 50 Pa.
2. The deposited particles are unlikely to reenter into the flow.
3. No crack exits inside the structure of air filter, so no seal material is needed and no leakage appears on it. Leakage test before delivery is not needed.
4. The lifetime is more than 5 years.
5. It is easy to handle after usage.

In the late of twentieth century, PTFE filter with filter media made by microporous PTFE membrane appeared in the market. The average diameter of the pores

| No. | Handling method | Tensile strength$^a$ (g) | Tenacity$^b$ | Resistance (filtration velocity 0.15 m/s) (Pa) | Efficiency (%) |
|-----|-----------------|--------------------------|--------------|-----------------------------------------------|----------------|
| 1   | No treatment    | 163                      | Break after 0.57 s | 1,360                                         | 99.99–99.999   |
| 2   | Spray or coat with 5 % 2124 phenolic resin | 275                      | Break immediately at start | 1,460                                         |
| 3   | Spray or coat with mixture of 5 % organic silicon and 2.5 % phenolic resin | 300                      | Break immediately at start | 1,570                                         |
| 4   | Uniform spray with 5 % emulsion by dilution of “No. 1 soft” leather agent by either times of water. The spray for filter paper with thickness 0.25 mm is 0.06 mL/cm$^2$. Then dry it naturally. | 1,625                      | Break after 2.8 s | 1,660                                         | 99.9978        |
| 5   | Treat with “No. 1 soft” leather agent, then bake for 24 h with the environment 120 °C | | | 1,580                                         |
| 6   | Treat with “No. 1 soft” leather agent, then immerse it into the water, then bake for 16 h with the environment 100–120 °C | | | 1,510                                         |

$^a$Test filter paper: width 7.5 mm, length 70 mm
$^b$The time of filter paper with width 7.5 mm and length 25 mm having fractures during the repeated process of stretching and folding, when its one side is fixed and the other side is connected with an eccentric wheel which has an eccentricity 7 mm and speed 1,390 r/min
| Frame material          | Filter material  | DOP efficiency (%) | Separator | Glue             | Maximum temperature (°C) | Heat resistance | Moisture resistance (relative humidity) (%) | Acid-base resistance property | Organic solvent resistance |
|------------------------|------------------|--------------------|-----------|------------------|--------------------------|----------------|---------------------------------------------|--------------------------------|---------------------------|
| Laminated board or board | Glass fiber      | 99.97              | Kraft paper Chrome paper | Fire resistant neoprene | 104                      | Combustible     | 85                                          | Poor                           | Poor                      |
|                        | Asbestos fiber   | 99.5               | Aluminum Polyvinyl chloride | Kraft paper Chrome paper | 85                      | Rare            | Good                                        |                                |                           |
| Fire resistant laminated board | Glass fiber | 99.97              | Aluminum Asbestos | Fire resistant | 100                      | Poor            |                                   |                                |                           |
| Galvanized iron         | Stainless steel  |                   | Aluminum Glass ceramic | Asbestos          | 287                      | Good            |                                   |                                |                           |
| Galvanized iron         | Galvanized iron  |                   | Aluminum Neoprene Silicon resin Neoprene | 121                      | 260                      | Poor            |                                   |                                |                           |

Table 4.25 Performance of air filters
| Material                        | Coating/Composition          | Properties | Quality |
|--------------------------------|------------------------------|------------|---------|
| Epoxy resin coated copper plate| Polyvinyl chloride           |            |         |
| Galvanized iron                | Aluminum                     | 287        | Noninflammable | Poor   | Good   |
|                                | Glass                        | 427        | Fire resistant |
|                                | Neoprene                     | 121        | Noninflammable | Poor   | Good   |
|                                | Silicon resin                | 260        |                |
|                                | Glass                        | 287        |                |
|                                | ceramic                      |            |                |
| Stainless steel Waterproof     | Neoprene                     | 104        | Combustible    | Good   | Poor   |
| ceramic asbestos               | Polyvinyl chloride           |            | Noninflammable |        |
| Galvanized iron                | Ceramic                       | 870        | Resist other acid and base except strong and middle alkali | Good |
within the filter media is about 0.3 μm. Fiber diameter is between 0.05 and 0.2 μm, which is only a fraction of that of glass fiber and shown in Fig. 4.38 [36].

The main characteristics of PTFE filter is:

It has strong ability to anticorrosion including acid and alkali.

The volatile amount of chemical substance is extremely low. For example, the volatile amount of boron and sodium is only 1/400 to 1/200 of that from glass fiber filter.

The pressure drop is very small, which is less than common HEPA filter by 2040%.

At present the price of PTFE filter is comparatively high and the dust holding capacity is a little small.

As for the structure of nonleakage air filter with the requirement as item (5) mentioned above, it has been replaced by author’s invention patent of zero leakage air supply outlet. When common air filter is installed in this air outlet, no leakage into the room can be realized.

4.12 Fibrous Layer Filter

Fibrous layer filter is mainly composed of a fibrous filling layer. The fiber used can be divided into three categories: one is natural fiber such as wool and cotton fiber, another is chemical fiber which is made with chemical method to modify the characteristic of raw material, and the third is artificial fiber which is separated
from the raw material with fibrous shape by physical method or formed to be fibers from raw material. For the second type, the chemical feature of fiber is totally different from that of raw material. For the third type, the chemical feature before and after fiber formation remains the same, such as spinning after the melt of glass.

The surface feature of fiber has great influence on the filtration effect. Taking natural fiber including wool and cotton as an example, the particle capture efficiency is higher than that of smooth plastic fiber because of the scale shape and fibrous shape. The efficiency of glass fiber improves after treatment with hydrofluoric acid [37].

In order to prevent the fiber abscission during operation, binder is sprayed onto fibers. Fibers with different diameter can be chosen to make packed bed with different solid fraction. Particles with large diameter are captured by crude fiber layer. Posterior fine fiber layer is used to filter small particles. In this way, the needed filtration efficiency and dust holding capacity are guaranteed, and the resultant pressure drop is not too high.

Fibrous layer made by nonwoven manufacturing process can also be used to make air filter. Figure 4.39 shows the nonwoven bag filter. The common techniques include needle injection sticking method and hot melt method.

Fibers with different diameters are used as raw material. It forms the web shape after loose carding and folding. Movement of thousands of needles on the needle board of the needle machine makes fibers move along the perpendicular direction. After going forward and backwards, certain numbers of fibers entangle together on the fiber web because of this movement. The glue is sprayed on the surface and then dried. This is called the needle injection sticking method.
If fibers with low melting point such as polypropylene are added into fibers such as polyester, the fiber web formed by folding is placed into the hot melt equipment and heated to certain temperature, then fibers with low melting point are melted and binding other fibers to form the filter media. This is called the hot melt method. Nonwoven fabric made by this kind of method is in the range of coarse efficiency, which is suitable for making rolling filter material. In terms of nonwoven fabric shape, it is one kind of felt fibrous layer. The thickness of this fibrous layer is between less than 1 mm and dozens of micrometer. The efficiency range is so large to cover the coarse efficiency and sub-high-efficiency ranges. Taking one kind of domestic-made polypropylene nonwoven fabric PP-K2 for an example, its thickness is 1 mm and the pressure drop is about 8 Pa with the filtration velocity 0.06 L/(cm$^2 \cdot$ min). The particle counting efficiency with atmospheric dust is 94 % when particle counter is used. It is comparatively cheap and is only several Yuan for each meter squared.

Table 4.26 presents the characteristic of several fibers, which could be used for reference during selection of filter material [38].

Fibrous layer air filter has small solid fraction, so its pressure drop is very low. It is especially suitable for the application of HVAC air cleaning system as medium-efficiency air filter.

There are two principles during the design and selection of fibrous layer air filter. One is based on a single index. It is the priority to consider the requirement of efficiency during the design of air filter. So with the same filtration efficiency, the optimum of certain index is expected. For example, the minimum pressure drop is expected, when requirements of other indexes should follow this requirement of pressure drop. This is a simple case. The other is based on the comprehensive index. With the same filtration velocity, the optimum comprehensive index is expected. When this comprehensive index is labeled with $E$, Chen proposed to use the ratio of efficiency and pressure drop [3], i.e.,

$$E = \frac{-\ln(1 - \eta)}{\Delta P}$$  \hspace{1cm} (4.36)

It is obvious that this index is only related to the technical performance of air filter, while its economic performance is not included. If the cost of filter material
was considered, the comprehensive index reflecting the usage of filter material should be used [5]. When this index is denoted with $J$, we get,

$$J = \frac{W_f}{E}$$ (4.37)

where $W_f$ is the usage amount of filter in the filter layer per each meter squared.

It is shown from the above two expressions that $E$ is larger when the efficiency is larger or the pressure drop is smaller. $J$ is smaller when $E$ is larger or the usage amount of filter material $W_f$ is more. Therefore, the smaller value of $J$ is preferred when the efficiency of air filter is given.

Moreover, comprehensive analysis with the fuzzy method was performed [6]. It is comprehensive, but it is not easy for visual understanding because of so many influencing factors. The weight of each factor is determined subjectively by the interest of referee. The comparability of this index is weakened.

Whatever evaluation method is adopted, the filtration efficiency requirement is of the priority, and then other comprehensive indexes are considered. The following items should be noted during the design of air filter:

First of all, filter material with suitable fiber diameter should be selected. It is known from filtration theory that efficiency decreases with the increase of fiber diameter, but the decrease velocity is slower than the decrease velocity of pressure drop caused by the increase of fiber diameter. Meanwhile, for the given filtration velocity and solid fraction of fibrous layer, thicker fibrous layer is needed for large fiber diameter in order to obtain the same efficiency. Although the usage amount of filter material is obviously much for thicker fibrous layer, the pressure drop still decreases compared with that of small fiber diameter. Therefore, suitable fiber diameter should be determined according to the design requirement.

Secondly, the fibrous layer thickness should be determined. This index depends on the structure and operation condition of air filter.

Thirdly, it should be remembered to keep the structure from being too close or too loose. It seems that the corrugation number could be increased, but this will cause two unreasonable consequences. One is that air does not flow thoroughly near the corrugation edge and stagnant airflow space is formed, so the effective filtration area reduces. At the same time, the corresponding support for filter material increases, so part of filtration area reduces by 7–20 % since the filter material is sheltered by the support. The other is that distance of filter material in each corrugation is very close when the corrugation number increases. Under the airflow pressure, the soft filter material between two corrugations squeezed together, which increases the pressure drop. In order to obtain the maximum effective filtration area, comprehensive consideration of various factors including filter thickness, ridge distance, ridge angle, and filter material thickness. Take bag-type air filter with frame of fixed volume, for example. When bag number increases from two to four, the filter material area increases and the pressure drop of filter material decreases. But the pressure drop of structure will increase because the flow channel is narrowed to increase the pressure drop of structure. When the number of bags is not large, the pressure drop decreases with the increase of the number of bags. On the contrary, when the number
### Table 4.26 Properties of several fibers

| Chemical name                | Natural fiber | Chemical fiber |
|-----------------------------|---------------|----------------|
|                             | Wool          | Cotton         | Polyvinyl chloride | Poval | Polyamine | Polyamine (aromatic) |
| Density (g/cm³)              | 1.32          | 1.47–1.5       | 1.39–1.44           | 1.3   | 1.13–1.15 | 1.38–1.41            |
| Tensile strength             | 9–15.3        | 22.5–36        | 24.3–35             |       |           |                   |
| (expressed with breaking     |               |                |                     |       |           |                   |
| length⁶ (mm)                 |               |                |                     |       |           |                   |
| Ratio between wet            | 85            | 110            | 100                 | 90    |           |                   |
| strength and dry strength    |               |                |                     |       |           |                   |
| (%)                         |               |                |                     |       |           |                   |
| Extension ratio at           | 25–35         | 7–10           | 12–25               | 25–45 |           |                   |
| breakage (%)                 |               |                |                     |       |           |                   |
| Hygroscopic capacity at 20⁰C| 10–15         | 8–9            | 0                   | 3.4   | 4.0–45    | 4.5–5               |
| and 65 % (%)                 |               |                |                     |       |           |                   |
| Expansion ratio (%)          | 50–70         | 50–80          | Max. 1              | 10–14 |           |                   |
| Acid resistance property     | Good under low temperature and concentration | Poor | Good under various concentrations | Satisfying | Good under low concentration, poor at high temperature | Insufficient |
| Alkaline resistance property | Poor          | Good           | Good for almost all the alkali | Extreme good | Stable | Good |
| Insect and bacterial         | Resist without treatment | Resist without treatment | Absolute to resist | |
| resistant property           |               |                |                     |       |           |                   |
| Thermal resistant: normal    | 80–90         | 75–85          | 40–50               | 115   | 75–85     | 220                 |
| temperature (ºC)             |               |                |                     |       |           |                   |
| Thermal resistant: maximum   | 100           | 95             | 65                  | 180   | 95        | 260                 |
| temperature (ºC)             |               |                |                     |       |           |                   |
| Price factor (the value in 1971 is used as the standard) | 3.5           | 1              | 2.7                |       |           | 13                  |

⁶The weight of the fiber with this length is equivalent with the breakage load.
| Artificial fiber | Polyacrylonitrile | Polyacrylonitrile | Polyester | Polyester compound | Polypropylene | Polyethylene | PTFE | Glass |
|------------------|------------------|------------------|-----------|-------------------|---------------|--------------|------|-------|
| Acrylic fiber    | Acrylic fiber    | Terylene         |           |                   | Polypropylene fiber |              |      |       |
|                  |                  |                  |           |                   |                |              |      |       |
| 1.17             | 1.14–1.16        | 1.14–1.16        | 1.14      | 1.38              | 1.23          | 0.9–0.91     | 0.95–0.96 | 2.3   |
| 25–30            | 27–31.5          | 23–30            | 36–45     | 40–49             |               |              | 45–80 | 2.54  |
|                  |                  |                  |           |                   | Polyethylene  |              |      |       |
|                  |                  |                  |           |                   |                |              |      |       |
| 90–95            | 90–95            | 90               | 90        | 93–97             | 100           |              |      |       |
|                  |                  |                  |           |                   | Polyethylene  |              |      |       |
|                  |                  |                  |           |                   |                |              |      |       |
| 30–40            | 15–30            | 24–30            | 18–22     | 40–55             | 10–25         |              | 3–4  |       |
| 1.3              | 2                | 1                | 1         | 0.4               | 0.4           | 0.01–0.1     | 0     | 0     |
|                  |                  |                  |           |                   | Good          |              |      |       |
| −7               | Good             | Good             | 3–4       | Good for almost all the acid | Good          | Extreme good | Extreme good | Very good |
|                  | Good             | Good             | Good      |                    | Extreme good  |              |      |       |
|                  | Good             | Good             | Good      |                    | Very good     |              |      |       |
|                  | Good             | Good             | Good      |                    | Poor for some acid |              |      |       |
| Have enough resistance to weak base | Good | Good | Good | Good | Extreme good | Extreme good | Very good | Poor under high concentration |
|                  |                  |                  |           |                   | Extreme good  |              |      |       |
|                  |                  |                  |           |                   |              | non corrosion | non corrosion |      |
| Extreme good     | Extreme good     | Extreme good     | Extreme good | non corrosion | non corrosion |      |       |
| 125—135          | 125–135          | 110–130          | 110–130   | 140–160            | 180           | 95           | 60   | 220–250 |
|                  |                  |                  |           |                   |              |              |      | 250–300 |
| 150              | 150              |                  |          | Resistance to dry heat | 200           | 120          | 100  | 350   |
| 2.7              | 2.7              | 2.7              | 2.7       | 2.7                | 2.7           | 1.7          | 2    | 25    |
|                  |                  |                  |           |                    | 25            | 3            |      |       |

4.12 Fibrous Layer Filter
of bags is comparatively large, the pressure drop increases. The decrease of pressure drop of filter material cannot offset the increase of pressure drop of structure. Meanwhile, when the number of bags is large or they are too long, the two walls of neighboring bags almost contact each other under the effect of airflow. So it is meant to increase the filtration area by increasing the bag number, but the result is different. It can be improved by setting formed line inside the bag or setting frame outside the bag. With the formed line, walls of bags will be tightened and bags will not be stretched outside. With the frame, walls are kept from stretching outside. For the filtration velocity between 0.2 and 0.5 m/s, the pressure drop can decrease by 30–50%. There are similarities between folded air filters and the bag filter.

If no frame is placed, with the same total filtration area, the more the number of bag is (or the smaller the bag is), the narrower the airflow channel is, and the larger the structural pressure drop is. Since the pressure drop of filter material is the same, the total pressure drop increases. This is consistent between experiment and theoretical analysis [6].

### 4.13 Foam Air Filter

Foam air filter is a combination of individual pin hole. Membrane between pin holes is melted with the chemical treatment, so that air can flow through it. It is then used as filter material. Foam plastic filter is one example. It is composed of three dimensional net skeletal frames, whose cross section is not circular. The size of this skeletal frame differs a lot. When the skeletal frame is considered to be fibers inside the filling layer, the filtration efficiency can be derived with the application of fibrous filtration mechanism [39]. Figure 4.40 is the calculation plot for efficiency. In the figure, the number of pores is counted with microscopic after the surface of foam plastic is dyed.

The usage of foam plastic filter is rare.

![Fig. 4.40  Calculation plot for efficiency of foam plastic air filter](image)
4.14 Electrostatic Cleaner

In this section, the mechanism and device of electrostatic precipitation will not be introduced comprehensively. Only one kind of popular electrostatic precipitation equipments – electrostatic cleaner is presented.

4.14.1 Application of Electrostatic Cleaner

In the turbulent cleanroom, eddy current forms near the four corners of rooms because of the limit of air supply mode, where the cleanness cannot be improved by air distribution. Because of the eddy current and the dust source, the cleanness of the room will be greatly influenced. In order to reduce the particle concentration in these regions, local cleaning equipment can be used.

Air is cleaned when the local air goes through the air cleaner repeatedly. The pressure drop of electrostatic cleaner is very small, and it is usually only 10–20 Pa. The axial fan can be used and the noise level is low. Besides it has the advantage of flexibility and convenience to use. So it is especially suitable for self-purification of indoor air. In the past, the electrostatic cleaner was called electrostatic self-purifiers in China.

If a layer of activated carbon filter is added into the electrostatic cleaner, it also has the effect of gas and carbon dioxide adsorption. Now this kind of electrostatic cleaner can be used as self-purification in rooms where the air cleanness is required. For example, it can be applied in meeting room, guest room, and living room. Test has shown that when an electrostatic cleaner with two-stage ionization and efficiency of 95% operate in room with area 25 m² for 1.5 h, the dust concentration reduces to 1/8 of the original value, and the colony count becomes 1/6 of the original value.

In cleanrooms, electrostatic cleaner should not be used as final filter, which has already specified in related standards. This is because the air delivery rate is very small. Moreover, particle resuspension caused by power failure, shutdown of the device, and discharge will cause unexpected result. It efficiency is less than that of sub-HEPA filter and HEPA filter. It is mainly used in the air handling system of fresh air.

4.14.2 Working Principle of Electrostatic Cleaner

It is shown in the expression that for given particle group, $u_e$ is proportional to $\frac{n}{d_p}$ when other conditions remain the same. However, as mentioned before, for particles with diameter less than 1 μm, $\frac{n}{d_p}$ is stable. So $u_e$ will approach stable and do not decrease. When it is noticed that the slip correction coefficient $C$ will increase with the decrease of particle size (introduced in Chap. 6), the separation velocity will be a little larger. That means the decrease of $u_e$ becomes stable. Therefore, compared with
other kinds of air filters, electrostatic cleaner is more suitable for capture of fine particles. When particle diameter is larger than 1 μm, \( u_e \) is proportional to \( d_p \) because \( \frac{n}{d_p} \) is proportional to \( d_p \) (because \( n \) is proportional to \( d_p^2 \)).

### 4.14.2.1 Charge on Airborne Particles

Inside the electrostatic cleaner, the electric field usually has two forms: single zone and double zones, which are shown in Fig. 4.41.

For the case of electric field with double zones, ionization electrode and dust collecting electrode are separate. In this way, the voltage of ionization electrode can be reduced from tens of thousands of voltage, which is used in single zone, to ten thousands voltage. Several dust collectors can be used to increase the collecting area. The distance between collecting plates reduces so that the voltage can be as low as several thousands, which is much safer. Therefore, the electrostatic cleaner with double zones is applied in the field of air-conditioning and cleaning system.

The main difference between electrostatic cleaner used in air-conditioning and cleaning system and electrostatic precipitator used in industrial application is the discharge by positive corona instead of negative corona. For positive corona, it is easy to convert from corona discharge into spark discharge. So only lower charge voltage can be exerted, which reduces the generated ozone. For the occupied space, the concentration of ozone generated is limited.

When positive corona is used, high enough DC positive voltage is exerted on the metal wire of ionization electrode, and two sides of polar plates are grounded. In this way, nonuniform electric field is formed near the ionization electrode. A few free electrons in the air obtain energy from the electric field. They collide with air molecules fiercely, which generates collision ionization, and incomplete discharge appears, which is called corona discharge. Around the ionization electrode, a ring of light blue halo could be seen, which is termed as corona. So ionization electrode abounds with positive ions and electrons. Electrons move towards metal wire and neutralize on it, while positive ions move regularly under the effect of electric field, and they attached onto neutral particles when they encounter each other. In this

![Fig. 4.41 Types of electric field. (a) Single area type. (b) Double area type](image-url)
way, particles become positive, which is the first kind of charge mechanism, i.e., electric field charge. Secondly, except for the movement under the effect of electric field, ions have thermal motion. Ions attach onto particles during the process of thermal movement, which makes particles positive. This is called the second kind of charge mechanism, i.e., diffusion charge.

According to the electrostatic theory, electric field charge mainly has influence on the particles with diameter larger than 1 μm. The maximum charge particles can obtain is

\[ q = ne = \frac{kE_1d_p^2}{4} \]  

(4.38)

where

- \( E_1 \) is the electric field intensity in the space of ionization electrode, e.s.u. (300 V/cm = 1 e.s.u.);
- \( n \) is the number of charge;
- \( e \) is the unit charge, \( 4.8 \times 10^{-10} \) e.s.u.;
- \( d_p \) is the particle diameter, cm;
- \( k \) is the coefficient, \( k = \frac{3\varepsilon}{\varepsilon+2} \); the average is between 1.5 and 1.8;
- \( \varepsilon \) is the dielectric constant; the average value is 2–3.

Diffusion charge has the main influence for particles with diameter less than 1 μm, especially less than 0.2 μm. However, no simplified expression has been obtained for the maximum diffusion charge so far. It is known from Eq. (4.38) that the charge on particles with diameter larger than 1 μm is proportional to the square of particle diameter. But with the effect of diffusion charge, the charge on particles with diameter equal to or less than 1 μm is larger than that obtained by Eq. (4.38). So the ratio of charge and its particle size \( \frac{q}{d_p} \) keeps stable. It will not decrease inversely proportional to the square of particle size.

### 4.14.2.2 Capture of Charged Particles

Charged particles enter into the space composed of parallel thin aluminum plates. Since aluminum plates are placed by staggered rivets with one aluminum plate positive and the other grounded, an uniform electric field is formed in the space.

With the Coulomb force in the electric field, charged particles obtain repelling force from the positive plate, and they settle down onto the grounded plate. The repelling force can be expressed as

\[ F_e = QE_2 = neE_2 \]  

(4.39)

where

- \( F_e \) is the Coulomb force;
- \( Q \) is the charge on particle (e.s.u.).
For the flow with small $Re$ (usually less than 1), the pressure drop of spherical particles is obtained by Eq. (6.5). When the pressure drop is balanced with the Coulomb force, i.e., $3\pi\mu d_p v = neE_2$, the motion velocity $u_e$ of particles in the electric field is obtained when the slip correction is considered, which is also called separation velocity or migration velocity. It can be expressed as

$$u_e = C\frac{neE_2}{3\pi\mu d_p} = Ck\frac{E_1E_2d_p}{12\pi\mu} \text{ (cm/s)}$$

where $\mu$ has the cgs unit (shown in Chap. 6), and other symbols have already been explained.

It is shown in the expression that for a given particle group, $u_e$ is proportional to $\frac{n}{d_p}$ when other conditions remain the same. However, as mentioned before, for particles with diameter less than 1 $\mu$m, $\frac{n}{d_p}$ is stable. So $u_e$ will approach stable and does not decrease. When it is noticed that the slip correction coefficient $C$ will increase with the decrease of particle size (introduced in Chap. 6), the separation velocity will be a little larger. That means the decrease of $u_e$ becomes stable. Therefore, compared with other kinds of air filters, electrostatic cleaner is more suitable for capture of fine particles. When particle diameter is larger than 1 $\mu$m, $u_e$ is proportional to $d_p$ because $\frac{n}{d_p}$ is proportional to $d_p$ (because $n$ is proportional to $d_p^2$).

### 4.14.3 Structure of Electrostatic Cleaner

Electrostatic cleaner is composed of box, power supply, fan, dust collecting electrode, ionization electrode, activated carbon filter, and prefilter. Figure 4.42 shows the structure of domestic JZQ-II electrostatic self-purifier [7]. The box is made by single layer of thin steel plate. With the requirement of air tightness, the box gates are connected with circlip, which is used for the convenience of maintenance.

The ionization electrode is a nickel chrome silk with diameter 0.5 mm. Dust collecting electrode is composed of rigid aluminum alloy plates with thickness 1 mm and inter-plate spacing 6 mm (between opposite plates). Each polar is made of 46 pieces of plates with area of each plate 0.2 m $\times$ 0.23 m. The surface of these plates has been electropolished to get rid of the burr and sharp corner, so the phenomena of spark discharge will not occur and the voltage between plates will be decreased. Figure 4.43 presents the structure of JZQ-1 electrostatic self-purifier with one time ionization method.

The height of JZQ electrostatic self-purifier is 0.8 m and the net cross-sectional area is 0.34 m $\times$ 0.34 m.

During the design of structure, the leakage inside the structure is usually neglected, which will greatly reduce the dust capture efficiency. There are mainly two reasons: one is caused by the electric wire when it goes through holes (such as the separator between layers); the other is the leakage between frame of each layer and box.
Fig. 4.42 JZQ-II electrostatic self-purifier

Fig. 4.43 JZQ-I electrostatic cleaner
It should be noted during the design of structure that two grounded plates must be added at both sides of ionization electrode (metal wire) and dust collecting electrode (metal plate). If both the ionization wire and the electrode plate near the edge are only connected with the power and without being grounded, both the airflow and particles will not be easily ionized and particles will not deposit readily, which will lower the total efficiency.

Since the volume of electrostatic cleaner is small, silicon rectified circuit is used for the power supply. In order to reduce the output voltage of transmitter so as to insulate, four times voltage circuit is usually adopted. Figure 4.44 shows the circuit of JZQ-II electrostatic cleaner. When too much dust has been deposited on the dust collecting plate, the indicator light will turn dark. The plate should be taken out for clean in time so that the dust collecting efficiency will not be affected.

4.14.4 Efficiency of Electrostatic Cleaner

4.14.4.1 Efficiency Expression

The following steps can be used to derive the dust collecting efficiency of electrostatic cleaner when the dust collecting electrode is plate.

Suppose the concentration at $x$ distance from the inlet of dust collecting plate is $N_x$, the airflow velocity between plates is $v$, the total flow rate through the dust collecting plate is $Q$, the total effective area of dust collecting plate is $F$, and the length of plate is $L$. During the time $dt$, the decrease of dust along the dust collecting plate (perpendicular to the flow) equals with the number of deposited particles at this section of dust collecting plate, i.e.,

$$-dN = N_x \frac{u_x F dt}{Q/L}$$
Since

\[ dx = v \, dt \]

We get

\[ \frac{dN}{N_x} = -\frac{F u_e}{QL} \, dx \quad (4.41) \]

When the concentration at \( x = L \), i.e., the outlet concentration, is \( N_L \), and the concentration at \( x = 0 \), i.e., the inlet concentration, is \( N_0 \), integration is performed on the above equation and the following expression is obtained:

\[ N_L = N_0 e^{-\frac{F u_e}{Q L}} \quad (4.42) \]

Then the dust collecting efficiency is

\[ \eta = 1 - \frac{N_L}{N_0} = 1 - e^{-\frac{F u_e}{Q L}} \quad (4.43) \]

### 4.14.4.2 Separation Velocity

It is obvious that \( \eta \) increases with the increase of the separation velocity \( u_e \). For given particles, \( u_e \) mainly depends on the voltage between the ionization electrode and the dust collecting plate.

When the voltage of the dust collecting plate increases, the electric strength in the space between dust collecting plates also increases, which will increase the separation velocity. However, when the electric strength between dust collecting plates is too high, the phenomena of electrode discharge are likely to appear. Even through the electropolishing, the surface of plates will inevitably unsmooth, especially burr exists near the edge. Even through the surface is very smooth, discharge will occur when a large dust especially fiber deposits on the surface, which will decrease the electric strength rapidly. During the process of discharging, sounds with cracking will be heard. For common manufacturing level, the electric voltage of the dust collecting plate can be increased to 7,000–8,000 V, which is equivalent to the electric strength about 1 kV/mm.

When the voltage of the ionization plate is elevated, particles will be charged more, which increases the separation velocity \( u_e \). But the extent of voltage increase is limited by the manufacturing precise. Too much voltage will cause electric discharge. So the voltage is usually less than 15,000 V.

The separation velocity \( u_e \) calculated from Eq. (4.40) is only a theoretic value. In practice there are many influencing factors which are not included in this equation. These influences include: distribution of air and airborne particles at the cross section between plates, movement characteristic of air in the channel, coagulation of particles, and re-entrainment of particles deposited on plates.
the actual separation velocity is much less than theoretical value. Research performed on industrial electrostatic cleaner shows that the actual velocity is half of the theoretical value. But the situation is better for electrostatic cleaner used in air cleaning system, because the distance between dust collector plates is small, and velocity is small so that the flow is laminar. The particle size distribution at inlet is comparatively uniform. So the disturbance extent on \( u_e \) is small. Therefore, the actual separation velocity of electrostatic cleaner is a little higher than that of industrial electrostatic cleaner.

### 4.14.4.3 Effective Length of Dust Collector Plate

For the given height (width), the larger the effective area is, which corresponds to the larger length, the higher the efficiency derived by Eq. (4.43) is. The effective area of plate mentioned in literature means the area which is effectively used in structure. According to the expression of efficiency, efficiency will reach 100\% when the area is large and the plate is lengthy. But in reality not all the area of the plate along its length can collect dust efficiently. Test on JZQ-I electrostatic cleaner with length 30 cm shows that only 2/3 of the area along the length collect dust. If all the particles are deposited on the plate along this 2/3 length, the efficiency of this electrostatic cleaner approaches 100\%, while in fact it is only 70–80\% which can been seen from the comparison table about efficiencies. This is not caused by the length of plate which is not long enough so that particles do not have time to deposit but by part of particles which is not charged or whose electric charge is not enough. For particles whose charge is not enough and \( u_e \) is small, it is effective to prolong the length of dust collector plate. However, for particles which are not charged at all, they will not be deposited on plate even when its length is prolonged. Since particles without charge do exist, a concept “effective length of dust collector plate” is proposed. It means that under certain electric field, only certain part of the plate has effect on dust collecting. When it is longer than this length, the efficiency of the left part of the plate cannot be described by Eq. (4.43), which implies that no more particles can be captured or not all the particles can be collected.

Why do some particles carry very few charges or no charges? According to the theory of electric corona discharge, there are mainly two reasons:

1. Since the electric ionization polar is a metal wire, the electric field with high electric strength only appears near the small distance around it, while the electric strength far from it is very weak. For the latter situation, the movement velocity of ions is very slow and the air in that region is not ionized (If all the air between plates is ionized, the electric field will be penetrated when spark discharge appears and short electric circuit is formed, thus the electrostatic cleaner stops).
2. As mentioned before, with certain voltage of electric ionization polar, the ionization strength for air is fixed and the charge amount is determined. If the dust concentration of air entering electrostatic cleaner is high, charge on every particle is not enough or some particle cannot be charged at all.
It is obvious that the former reason is mainly for electrostatic cleaner. From the above analysis, if the effective length of dust collector is measured, the actual separation velocity can be derived from the dust collector efficiency.

### 4.14.4.4 Flow Rate

It is obvious that the less the flow rate of electrostatic cleaner, the higher the efficiency is. But for particles without charge, efficiency will become stable when the flow rate is less than a certain value.

### 4.14.5 Electrostatic Cleaner with Two-Stage Ionization

According to the above analysis, in order to increase the efficiency of electrostatic cleaner with one-stage ionization, the extent of particle charge must be increased. So author proposed a scheme “two-stage ionization” which put two electric fields in series. With this method, air molecules not ionized in the first electric field will be likely to be ionized in the second electric field. In the late of 1960s, Institute of HVAC at China Academy of Building Science and the former Tianjin Medical Equipment Factory invented and manufactured JZQ-II electrostatic cleaner together, which adopted this method.

It is meaningless if the height of the equipment with two-stage ionization is two times that of the original equipment. According to the above analysis, the effective dust collector length under the given conditions is about 0.2 m. So the length of dust collector of JZQ-II electrostatic cleaner is 0.2 m under the condition of compact structure, which is the same as that of the one-stage ionization.

With the scheme of two-stage ionization, the predicted effect of electrostatic cleaner is realized. Related experimental data are presented in the following tables.

Table 4.27 is the experimental data about the relationship between efficiency and voltage of dust collector.

Table 4.28 is the experimental data about the relationship between efficiency and velocity between plates of dust collector.

Table 4.29 is the experimental data about the relationship between efficiency and capacity of capacitor in the rectifying circuit.

The influence of capacity of capacitor in the rectifying circuit on efficiency is large. When the capacity is small, the decrease of voltage on each octave band pressure level will be large, which reduces the particle capture efficiency, while increasing the capacity will smooth the wave profile after rectifying and the effective voltage approaches the summit value. But it is not safe if the capacity of capacitor was too big. For JZQ-II electrostatic cleaner, it is feasible to choose 8,800 μF as the capacity of capacitor.

According to Eqs. (4.38) and (4.40) with the cgs unit and 1 e.s.u. of $E_1$ and $E_2$, the separation velocity for the condition with $c = 1$, $k = 2$ (for oil mist from the
transformer, \( k = 1.5 \); for marble particles, \( k = 2.4 \), and both \( E_1 \) and \( E_2 \) are 1 e.s.u.

becomes

\[
\nu_c = \frac{2d^2E_1E_2}{12\pi \times 1.8 \times 10^{-4}d} \approx 0.03E_1E_2d \times 10^4 \text{ cm/s}
\]

When \( d = 0.5 \times 10^{-4} \text{ cm}, \ c = 1.3, \ E_1 = 14,000 \ \text{V} \approx 46.5 \ \text{e.s.u.}, \) and \( E_2 = 7,000 \ \text{V} \approx 23.3 \ \text{e.s.u.}, \) the derived separation velocity is \( \nu_c = 21 \ \text{cm/s} \) (which is equivalent with the calculation result based on average particle size of atmospheric dust).

According to Eq. (4.40), the relationship between \( \frac{F_{Nu}}{Q} \) and \( \eta \) is

| \( \eta \) (%) | 60 | 70 | 80 | 90 | 95 | 99 |
|----------------|----|----|----|----|----|----|
| \( \frac{F_{Nu}}{Q} \) = \( \frac{\nu_c}{v} \) = \( B \) | 0.9 | 1.21 | 1.6 | 2.3 | 3.0 | 4.6 |
Suppose the effective cross-sectional area of the cleaner is \( S \) and the velocity at the cross section (the velocity between dust collecting plates) is \( v \), we could get:

\[
\frac{F u_e}{Q} = \frac{E u_e}{v} = B
\]

So

\[
u_e = \frac{BV}{S}
\] (4.44)

For JZQ-II electrostatic cleaner, we know

\[
\frac{F}{S} = \frac{(46 - 2) \times 0.2 \times 0.23}{0.1} = 20
\]

where 46 is the number of dust collecting surfaces. Each dust collecting plate has two surfaces. Since the most outer two sides do not play a role, they are not included and the total number of dust collecting surfaces is 44. So the actual separation velocity of each section for given efficiency can be calculated, which is shown in Table 4.23.

From Table 4.30, the average of actual separation velocity is 0.12 m/s, which is slightly higher than half of theoretical separation velocity. It is consistent with the aforementioned analysis.

For JZQ-II electrostatic cleaner with two-stage ionization method, the comparison of its turbidity efficiency measured by photoelectric turbidimeter with the foreign similar products is shown in Table 4.31.

In terms of efficiency, results obtained by the turbidimetry method are usually smaller than that of dust spot method and weighing method. So the performance of JZQ-II electrostatic cleaner is better than that presented in Table 4.31.

For simplifying the structure, cylindrical electrostatic cleaner appears in the market. Thin metal plate is used to make the cylinder with circular or hexagonal cross section. It acts as the grounding plate. Circular electrode with cusp is placed in the center of cylinder, where high-voltage electrostatic is applied. It becomes the high-voltage discharging electrode in the electrostatic field, which is shown in Fig. 4.45.

But the efficiency of this kind of cylindrical electrostatic cleaner is very low. Table 4.32 shows the test data from Mao Huaxiong [40].

| Air velocity (m/s) | Actual separation velocity (m/s) | Theoretical separation velocity (m/s) |
|-------------------|---------------------------------|-------------------------------------|
| 0.66              | 0.09                            |                                     |
| 1.2               | 0.14                            |                                     |
| 1.4               | 0.12                            | 0.21                                |
| 2                 | 0.12                            |                                     |
### Table 4.31 Comparison of efficiency for the same kind of electrostatic cleaner

| Country                                      | Air velocity (m/s) | Measurement method | Efficiency (%) | Remark                                      |
|----------------------------------------------|--------------------|--------------------|----------------|---------------------------------------------|
| JZQ-I type in China (with once ionization)   | 0.51               | Particle counting method | 72.0           | Measured with the same instrument           |
|                                              |                    | Turbidity method    |                |                                             |
|                                              |                    |                    | 80.6           |                                             |
| China JZQ-II type (with twice ionization)    | 0.66               | Turbidity method    | 99.3           |                                             |
|                                              | 1.20               | Turbidity method    | 99.1           |                                             |
|                                              | 1.40               | Turbidity method    | 96.9           |                                             |
|                                              | 2.00               | Turbidity method    | 91.4           |                                             |
| UK (with once ionization)                    | 0.50               | Turbidity method    | 75–80          |                                             |
| Japan (with once ionization)                 | 1.25               | Turbidity method    | 72.8           |                                             |
|                                              | 2.00               | Turbidity method    | 69.7           |                                             |
|                                              | 2.00               | Turbidity method    | 85             | Data from the same sample product          |
|                                              |                    | Dust spot method    | 90             |                                             |
| Former Soviet Union (with once ionization)   | 2.00               | Turbidity method    | 80–85          | Data from the same product in literature    |
|                                              |                    | Gravimetric method  | 98.5           |                                             |
| Former Federal Germany (with once ionization)| 1.70               | Gravimetric method  | 99             | Data from the same sample product          |
|                                              |                    | Dust spot method    | 90             |                                             |
|                                              | 2.00               | Dust spot method    | 83             |                                             |
| UK (with once ionization)                    | 1.70               | Dust spot method    | 90             | Data from the same sample product          |
|                                              | 2.20               | Dust spot method    | 80             |                                             |

#### 4.15 Special Air Filters

##### 4.15.1 Activated Carbon Filter

More attention has been paid on the influence of chemical pollution inside cleanrooms (please refer to Chap. 7), so people starts to care about activated carbon filter.
Activated carbon filter has functions of both physical adsorption and chemical adsorption, so in fact it is an adsorber. The adsorption ability of activated carbon has selectivity. For these chemical substances which cannot be removed by physical adsorption mechanism, different chemical agents must be used as adsorbent during the process of impregnation. With the chemical reaction between adsorbent and adsorbate, the property of adsorbate is modified and it becomes nontoxic and harmless. Many monographs and literatures have introduced the general application of activated carbon filters, which will not be mentioned in this section. Only several aspects are emphasized here:

1. At present there are three kinds of activated air filters. One is the activated carbon particulate filter where the size of particle varies from small to large. The second is activated carbon particles with diameter 0.5 mm pasted on multiply layers of porous polyurethane foam material. Since the air permeability of foam material is good, its pressure drop is smaller than that of the former kind and the corresponding adsorption efficiency reduces. The third is activated carbon fibrous filter by carbonization of fibrous media. It is thin, and both the pressure drop and adsorption efficiency are comparatively small.

2. The problem of invalid layer exists in the activated carbon filters. Invalid layer is meant to adsorb a certain amount of chemical pollutants. The larger the activated carbon particle is, the thicker this layer is. This problem is usually ignored.

### Table 4.32 Fractional efficiency of cylindrical electrostatic cleaner with atmospheric dust (%)

| Flow rate (m³/h) | Face velocity (m/s) | ≥0.3 μm | ≥0.5 μm | ≥0.7 μm | ≥1.0 μm | ≥2.0 μm | ≥5.0 μm |
|-----------------|---------------------|---------|---------|---------|---------|---------|---------|
| 800             | 0.8                 | 19.8    | 22.6    | 35.9    | 41.2    | 53.0    | 84.7    |
| 1,000           | 1.2                 | 14.1    | 16.1    | 23.7    | 29.3    | 50.0    | 69.4    |
| 1,800           | 1.8                 | 7.6     | 9.0     | 15.8    | 21.0    | 37.5    | 58.2    |
| 2,500           | 2.5                 | 4.8     | 6.8     | 11.0    | 14.7    | 28.8    | 54.1    |
| 3,000           | 3.0                 | 3.9     | 5.7     | 9.9     | 21.5    | 36.8    | 38.2    |
| 3,600           | 3.6                 | 3.6     | 5.6     | 10.7    | 22.6    | 28.4    | 37.1    |
Figure 4.46 shows the theoretical relationship between the invalid layer thickness and the amount of pollutant adsorbed. When the amount does not reach a certain value, it is called the non-protective time. Figure 4.47 is the result performed with cyan chloride [41].

The existing of this invalid layer is related to the adsorption mechanism of chemical pollutant by activated carbon. When polluted airflows through activated carbon, the pollutant diffuses towards the whole surface of activated carbon particles.
Then it goes towards to the pore interior surface of the particles and the surface of pores. So chemical reactions occur inside the particle interior surface to decompose the pollutant by adsorption of pollutant molecules and between adsorbed chemical pollutant and chemical agent (catalyst) dipped with activated carbon or between adsorbed oxygen and water. If several adsorption mechanisms inside a layer with certain thickness do not have enough time to play a role, for example, pollutant only diffuses onto the particle surface while they do not have time to diffuse towards the interior surface of pores and then adsorbed and decomposed, but it has already penetrated this layer, the pollutant concentration cannot be reduced to allowable value or has no time to be reduced at all, this layer is called invalid layer. If the activated carbon is within the invalid layer, there is no effect of adsorption.

With certain physical and chemical property of activated carbon and temperature/humidity conditions, the thickness of invalid layer is only related to the specific velocity and pollutant concentration. When both the specific velocity and concentration are fixed, the thickness is constant, which is not related to the thickness of whole activated carbon layer.

3. Since the pressure drop of activated carbon filter filled with particulate activate carbon is very large, the allowable specific velocity cannot be very large. Therefore, it is necessary to understand the specific velocity-pressure drop characteristic of this kind of activated carbon filter.

4. When the activated carbon filter is designed to be circular cylinder, it has been proved by the author that the performance is better when the polluted air flows from outer towards inside, which improves the amount of adsorption [40].

4.15.2 Antibacterial Filter

Since the risk of microorganism becomes higher, antibacterial filters develop in the USA and Japan. This kind of filter is made by adding bactericidal substance in the filter media. However, doubt about its effectiveness exists.

One kind is only to spray the additive onto the surface of filter media, so not all the filter layer have the ability to kill bacteria. The second kind is only to add bacteriostatic agent, which cannot kill the bacteria and instead may cultivate the ability of drug resistance of the bacteria. The third kind may generate some gaseous substance or odor which is harmful for people.

It should be emphasized, which will also be introduced in Chap. 9, that it is difficult for the bacteria captured on the windward side of the HEPA filter made by inorganic material to reproduce and even penetrate. Only with the suitable conditions of temperature and humidity, they are likely to survive. So the final conclusion of the necessity to use the antibacterial filter has not been reached. ASHRAE has warned as for this issue and suggests using antibacterial product in HVAC system cautiously, so as not to produce any chemical pollution and new harm to the indoor environment and people.
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