

# Chapter 4

## Fibrous Layer Filter



### 4.1 Principle of Fibrous Layer Filter

Granular layer, fibrous layer, microporous membrane, membrane covered fibrous layer, screen mesh and perforated plate can be used to remove particles, which are classified as barrier-type filter. This chapter only discusses the fundamental principle of fibrous air filter.

Fibrous layer comprises a fibrous filling layer, nonwoven fabric and filter paper etc.

There are mainly five principles for filtration of particles with fibrous air filter.

#### 4.1.1 *Interception (or Contact/Hook) Effect*

Inside the fibrous layer, fibers locate randomly and form numerous meshes. The number of meshes formed could be dozens or even hundreds of layers. When particles with certain size approach fiber surface when following the streamline, suppose the distance between the streamline (also the centerline of particle) and fiber surface is equal to or smaller than particle radius, particles will be intercepted and then deposit on the fiber surface, which is called interception effect. Sieve effect also belongs to the interception effect.

#### 4.1.2 *Inertial Effect*

Because of the complex arrangement of fibers, streamline will change directions frequently and abruptly when air flows through fibrous layers. When the particle mass is large or its velocity (which could be approximated by air velocity) is large,

by virtue of its inertia, particle will not follow the streamline when air flows around fibers. Therefore, particles will deviate from the streamline when approaching fibers, then collide with fibers and deposit on it. If with the inertial effect, particles do not collide with the frontal surface of fiber but collide within the range of the interception effect, it is two combined effects which capture particles.

### ***4.1.3 Diffusion Effect***

It is much obvious for small particles that show Brownian motion caused by the collision between gas molecules and particles.

At normal temperature, the diffusion distance could be  $17 \mu\text{m/s}$  for  $0.1 \mu\text{m}$  particles, which is several times or even dozens of interspace distance between fibers. This could result in the larger possibility of particle deposition on fiber surface. While the Brownian movement is weaker for particles with diameter larger than  $0.3 \mu\text{m}$  and usually it is not strong enough to make particle deviate from the streamline and deposit onto fiber surface.

### ***4.1.4 Gravitational Effect***

Particles will deviate from the streamline under the influence of gravity when they pass through fibrous layers, which mean they will deposit on fiber surface by gravitational deposition.

The time usage for airflows through fibrous air filters, especially paper filters, is far less than 1 s, so particles with diameter smaller than  $0.5 \mu\text{m}$  will pass through fibrous layers without deposition on fiber surfaces. Therefore, it is reasonable to ignore the effect of gravitational deposition.

### ***4.1.5 Electrostatic Effect***

By various reasons, charge may exist on both fibers and particles, which will cause electrostatic effect and attract particles.

Except for the case of intentional charge on fibers or particles, both fiber charges by friction during the manufacture process and particle charge by charge induction will not exist for a long time. These electric field intensities are very week and the resultant attractive force is too small to be neglected.

With the combined effect of these five principles, there is the minimum efficiency for different kinds of particle diameter or filtration velocities. This is because sometimes the smaller the particle diameter is, the larger the efficiency is, while it is

opposite for other principles. The effect of filtration velocity is also similar.

The quantitative analysis of these five principles and theoretical calculation on efficiency can be found in “*Fundamentals of Air Cleaning Technology*” [1] in detail.

## 4.2 Basic Index for Fibrous Layer Filter

There are four fundamental indexes of the fibrous layer filter.

### 4.2.1 Face Velocity and Filtration Velocity

Face velocity is defined as the air flow velocity passing the cross section of air filter (m/s). It represents the capacity of the flow rate passing through and installed area of air filter.

Filtration velocity is defined as the flow velocity of the air passing through the expanded area of filter media. It represents the ability of air flow passing through filter media, especially the filtration performance of filter media.

Table 4.1 shows the range of filtration velocity for air filters.

The magnitude of filtration velocity through coarse filter could reach m/s, but that of fine filter and high-medium efficiency air filter is usually dm/s. The range of filtration velocity for sub-HEPA filter is 5–7 cm/s, and that of HEPA filter and ULPA filter is usually 2–3 cm/s.

### 4.2.2 Efficiency and Penetration

When weight concentration is used to describe the particle concentration in the air flow, performance is evaluated with arrestance. When particle counting concentration is used, performance is evaluated with particle counting efficiency (such as microscopic counting and light scattering counting). When other physical parameter is used, performance is evaluated with dust spot efficiency or turbidity efficiency etc.

**Table 4.1** Range of filtration velocity for air filters

Type	Coarse filter	Fine filter, high-medium efficiency air filter	Sub-HEPA filter	HEPA filter
Magnitude of filtration velocity	m/s	dm/s	cm/s	cm/s

The most commonly used method is the particle counting efficiency with particle concentrations at both the inlet and the outlet air flow, i.e.

$$\eta = \frac{N_1 - N_2}{N_1} = 1 - \frac{N_2}{N_1} \tag{4.1}$$

where  $N_1, N_2$ —particle concentration at inlet and outlet air flow (pc/L), respectively.

During the performance test on air filter, it is customary to use penetration  $K$ , instead of efficiency.

$$K = (1 - \eta) \times 100\% \tag{4.2}$$

According to author’s calculation [1], under the condition of common distribution of atmospheric dust, when the efficiency for particles with diameter 0.3  $\mu\text{m}$  is 99.91%, the corresponding efficiency for particles with diameter 0.5  $\mu\text{m}$  is 99.994% and that for particles with diameter  $\geq 0.5 \mu\text{m}$  99.998%, which can be approximately considered as “Five 9” or 99.999%.

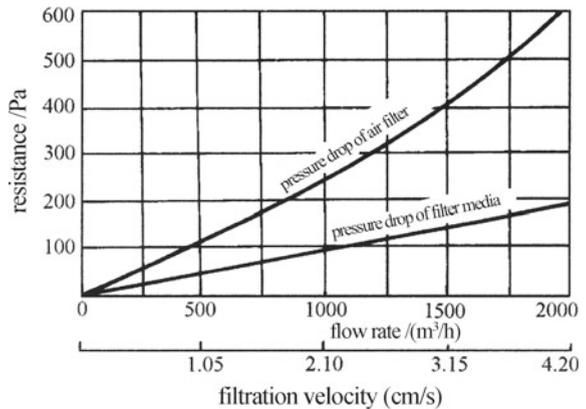
### 4.2.3 Pressure Drop

Pressure drop of air filter is composed of two components: filter media and structure of air filter.

The pressure drop of filter media is linearly proportional to the filtration velocity, while the whole pressure drop of air filter has exponential relationship with the filtration velocity, which can be seen in Fig. 4.1.

Except for reducing the pressure drop of filter media itself, there are other means to reduce the pressure drop of air filter:

**Fig. 4.1** Relationship between pressure drop and flow rate (filtration velocity) for HEPA filter



Expansion of area of filter media;

Reducing the length of air flow channel, this could reduce the air friction resistance;  
Simplification of the entrance and exit of air flow channels, or reducing the air velocities at the inlet and the outlet, this could reduce the local resistance of air flow.

The above three measures are performed at the cost of increasing the filter area or volume. We can also try not to increase or try to increase a little of filter area or volume. There are already successful examples.

#### 4.2.4 Dust Holding Capacity

Dust holding capacity is an index directly related to the life time of air filter. If air filter is allowed to use forever, particles will penetrate through the air filter and reach the leeward side of air filter, which is of course not permitted. Usually there is one restriction. In the early times, the dust weight deposited on air filter is called the dust holding capacity of this air filter, when the final pressure drop of air filter at operation is about two times of the initial pressure drop. It can be expressed as

$$\text{Final pressure drop} = 2 \times \text{Initial pressure drop at related air flow} \quad (4.3)$$

Practice has shown that the larger the final pressure drop selected is, the larger the variation of the flow rate will be (the flow rate will be reduced by more than 50%). For the application where the flow rate should be kept constant, it is difficult to adjust the flow rate. Meanwhile, the energy consumption will be increased too much, which is not cost-effective. And pollution may also be caused (when the quality of air filter is not good, leakage or penetration is likely to occur by the increased pressure drop across the air filter. The gap inside the equipment may also increase the risk of leakage).

Both practice and theory prove that the operational flow rate through the air filter should not reach the rated value. By increasing the number of air filters, it seems that the operational flow rate of each air filter will be decreased. However, the life time of air filter will be prolonged more and the period between replacement cycles can be increased. The energy consumption by air filter during the longer operational period is reduced. With the reduced pressure drop, it is much energy-saving. Meanwhile, the efficiency is much better. Table 4.2 shows the relationship between the operational flow rate and the life time [1].

Therefore, it is specified in national standard GB50333-2013 “*Architectural technical code for hospital clean operating department*” that the operational flow rate of the final air filter should be larger than 70% of its nominal flow rate. The life time of air filter will be more than two times. For example, originally two air filters were used and they were replaced each half a year. In one year, they have been replaced twice, so six air filters have been used in total. Now when three air filters are used, they will be replaced once time during one year. Therefore, six air filters are also used in total. But since the pressure drop is smaller, it is much energy-saving. After

operation of two years, there are ten air filters used for the former case, while only nine air filters are used for the latter case.

Therefore, air filter should not be replaced when the pressure drop increases to two times of the initial pressure drop at nominal flow rate. The flow rate will be decreased to a half of the initial value. It seems to be saving, but it is a waste of money in fact. Moreover, it is unacceptable when the flow rate is reduced to a half or even more. Now it is specified in the provision of some standard that air filter should be replaced when the final pressure drop reaches two times of the deigned initial pressure drop or two times of the operational initial pressure drop value.

That is

$$\text{Final pressure drop at replacement} = 2 \times \text{Designed initial pressure drop} \quad (4.4)$$

Or

$$\text{Final pressure drop at replacement} = 2 \times \text{Operational initial pressure drop} \quad (4.5)$$

They are given according to the above principle. Of course, the value of multiple can be adjusted according actual situation. For example, it is specified that air filter can be replaced when the efficiency becomes less than 85% of the initial value or the flow rate reduces to 85% of the initial value.

Moreover, since the filtration area in the air purifier should be as large as possible, its initial pressure drop is very small. According to Eqs. (4.4) and (4.5), the period to replace air filter may be short. A suitable multiple times of pressure drop can be provided by manufacturer by experiment. Then intelligent system can be used in air purifier.

For barrier-type fibrous air filter, the efficiency will not reduce but increase slightly during quite a long period (situation will be different when the deposited dust is too much). Therefore, it is reasonable to replace air filter when the flow rate is reduced to 85% of the nominal flow rate.

It is inappropriate to set the life time of the air purifier when the flow rate is reduced to a half of the nominal value. The standard value 85% commonly used in air cleaning industry should be adopted (for example, in GB50591-2010 “Code for construction and acceptance of cleanroom”, it is specified that the difference between the operational and the designed flow rates of each air supply opening should not be larger than ±15% of the designed flow rate). This problem will be discussed again later.

**Table 4.2** Relationship between the operational flow rate and the life time

Ratio between operational flow and nominal flow rate	0.5	0.7	0.75	0.8	1.0	1.25
Life time $T_0$ under nominal flow rate	$3.5T_0$	$2.15T_0$	$1.91T_0$	$1.7T_0$	$T_0$	$\frac{T_0}{1.7} = 0.59T_0$

## 4.3 Feature of Fibrous Layer Filter

### 4.3.1 *Removing Both Dust and Bacteria*

Fibrous air filter is effective in capturing particles.

Airborne particles can be classified as:

The total suspended particles (TSP): the airborne particles with aerodynamic diameter less than 100  $\mu\text{m}$ ;

The inhalable particles (IP), which is also termed as the floating dust: the airborne particles with aerodynamic diameter less than 10  $\mu\text{m}$ ; It can be expressed as  $\text{PM}_{10}$ ;

Fine particle: the airborne particles with diameter less than 2.5  $\mu\text{m}$ ; It can be expressed as  $\text{PM}_{2.5}$ ;

Bacteria and virus itself are particles. The minimum size of naked virus is 8 nm, and the maximum of which reaches 0.3  $\mu\text{m}$ . The size of naked bacteria is between submicrons to 10  $\mu\text{m}$ . But both bacteria and virus must be attached to carriers. In this case, the size is called as the equivalent diameter.

Based on field measurement, when the density of bacteria is considered  $\rho = 1 \text{ g/cm}^3$  and  $\rho = 1.5 \text{ g/cm}^3$ , the equivalent diameters for deposition of bacteria in ordinary and clean rooms are 5.2 and 3.9  $\mu\text{m}$ , respectively. The equivalent diameter of virus is between 2 and 5  $\mu\text{m}$ , which could be considered 3  $\mu\text{m}$  [1]. For example, the real size of foot-and-mouth disease virus particle is only 25–30 nm. But cascade sampling results show that 65–71% of particles are larger than 5  $\mu\text{m}$ , 19–24% are 3–6  $\mu\text{m}$ , while only 10–11% are less than 3  $\mu\text{m}$  [2].

Therefore, the opinion that fibrous air filter can only remove dust but cannot remove virus is not established.

It is shown from Fig. 4.2 that very few viruses can penetrate through air filter for most of viruses [3]. This means the efficiency is very high. Therefore, the efficiency for virus is not necessarily smaller than that for bacteria.

As for the worry about the penetration of microorganism through filter media or reproduction on filter media, people will consider to put some additives on the filter media for sterilization, which is unnecessary [1]. Taking the flu virus which people are worried about as an example, they can survive on surfaces of the stainless steel and the plastic for 24–48 h, but the survival period on surfaces of the paper and the handkerchief is less than 8–12 h [4]. This is because this kind of virus is not adapted to comparatively high relative humidity environment.

### 4.3.2 *No Selectivity for Removing Dust and Bacteria*

Dust particles include conductive and non-conductive, with water content or without water. Bacteria include plant bacteria, Bacillus, cocci, spore bacteria and fungi.

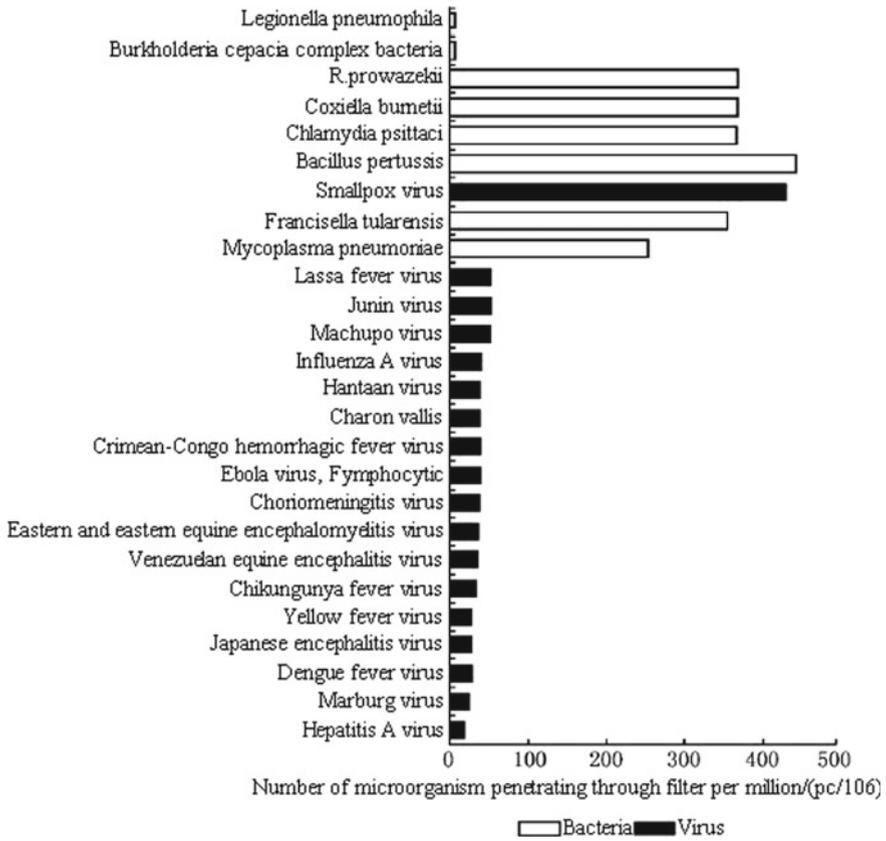


Fig. 4.2 Penetration of air filter for various kinds of microorganism through air filter

According to the ISO definition, fog is the general term for the droplet suspension in air. The combination of fog and a large amount of fine solid particles is called haze. In other words, haze contains water content (water, dissolved liquid of sulfate and nitrate etc.). High-voltage electrostatic adsorption is not a suitable means for removing conductive particles and water-containing particles.

Different bacteria have different sensitivity levels for UV ray, which can be seen in Table 3.1 of Chap. 3. Therefore, the sterilization performances of UV irradiation on different kinds of bacteria are different.

However, for barrier-type fibrous air filter, there is no selectivity for the “identity” of different particles. Instead, it only cares about the size of particles.

### 4.3.3 Broad Spectrum of Efficiency, Large Range and High Efficiency

Barrier-type fibrous air filters cover the range from coarse (the simple screen is not included) to ULPA filters, which is shown in Table 4.3.

The particle diameters used in test are different. For example, for HEPA filter or air filters with performance better, the Most Penetrating Particle Size (MPPS) should be used. For air filters with performance worse than HEPA filters, the particles with diameter  $0.4\ \mu\text{m}$  should be used. Therefore, there is a certain degree of relativity for the comparison table above. For the air cleaning equipment made in China, the name or symbol of air filter should be indicated according to Chinese national standard at first. Then the equivalent symbol with foreign standard should be indicated. It should not only indicate the latter symbol.

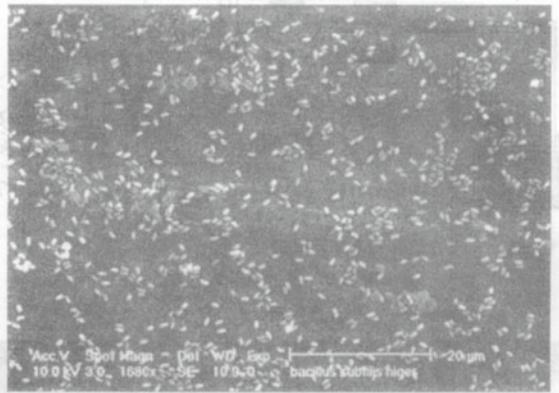
It is already shown in Chaps. 2 and 3 that the efficiency of air purifier with electrostatic and UV irradiation will usually decay gradually with the operational time. However, the efficiency of fibrous air filter will not decay but increase slightly, which could be considered constant.

It is already shown in Chaps. 2 and 3 that the efficiency of high-voltage adsorption and UV irradiation on particles or bacteria is within an extremely small range, such as “One 9” (90%). But the efficiency of HEPA filter on bacteria is larger than that for particles with diameter  $0.3\ \mu\text{m}$  or  $\geq 0.5\ \mu\text{m}$ . Table 4.4 shows the measurement result in negative pressure isolation ward [5]. The efficiency of HEPA filter on bacterial particles could be larger than that of particles by one magnitude.

This is because the linear length of the naked bacteria is about  $1\ \mu\text{m}$  and the width is about  $0.5\ \mu\text{m}$ , which is shown in Figs. 4.3 and 4.4 [6].

Spore has a very strong ability of resistance to ultraviolet irradiation, so the sterilization efficiency is relative low. But for air filters, it only cares about the size of the particles, regardless of whether there is spore or not. The bacterial removal efficiency of HEPA filter could reach “seven 9”. It is incomparable by other methods.

**Fig. 4.3** Electron microscopic photograph of *Bacillus subtilis* spores (Amplification magnitude 1700 times)



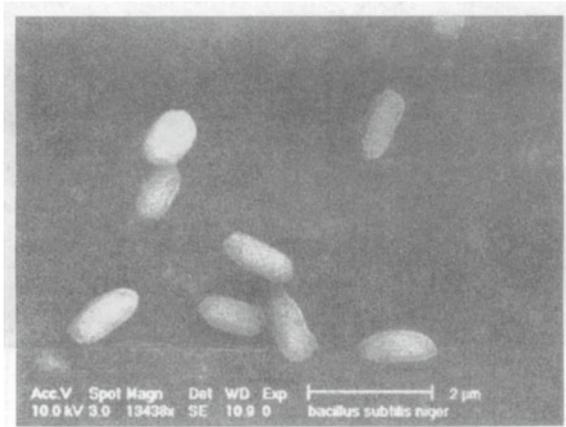
**Table 4.3** Efficiency range of fibrous air filters

Chinese standard	Symbol	Efficiency E under nominal flow rate (%)		EU standard	
				EN779	EN1822
Coarse filter 4	C4	Standard artificial dust, arrestance	$50 > E \geq 10$	G1	
Coarse filter 3	C3		$E \geq 50$	G1–G2	
Coarse filter 2	C2	Particles with diameter $\geq 2.0 \mu\text{m}$ , particle counting efficiency	$50 > E \geq 20$	G2–G3	
Coarse filter 1	C1		$E \geq 50$	G3–G4	
Medium efficiency filter 3	Z3		Particles with diameter $\geq 0.5 \mu\text{m}$ , particle counting efficiency	$40 > E \geq 20$	G4–F5
Medium efficiency filter 2	Z2	$60 > E \geq 40$		F5–F6	
Medium efficiency filter 1	Z1	$70 > E \geq 60$		F6–F7	
High efficiency filter	GZ	$95 > E \geq 70$		F7–F9	
Sub-HEPA filter	YG		$99.9 > E \geq 95$	F9	H10–H11
HEPA filter	A	Sodium flame efficiency	$99.99 > E \geq 99.9$		H12–H13
HEPA filter	B		$99.999 > E \geq 99.99$		H14
HEPA filter	C		$E \geq 99.999$		U15
ULPA filter	D	Particles with diameter $\geq 0.1\text{--}0.3 \mu\text{m}$ , particle counting efficiency	$\geq 99.999$		U16
ULPA filter	E		$\geq 99.9999$		U17
ULPA filter	F		$\geq 99.99999$		U17

**Table 4.4** Efficiency of HEPA filter on particles and bacteria measured in negative pressure isolation ward

	Efficiency for particles with diameter $\geq 0.5 \mu\text{m}$	Efficiency for <i>Bacillus subtilis</i> and spore
HEPA filter B	99.999	99.99997
HEPA filter C	99.99994	99.999997

**Fig. 4.4** Amplified electron microscopic photograph of *Bacillus subtilis* spores (Amplification magnitude 13,500 times)



Air filter such as HEPA filter is made of filter media paper with thickness 0.25–0.3 mm. The media is formed by 100 layers of fibrous network. Even though the particle capture efficiency for each network layer is less than 10%, the total efficiency may reach five 9. So it is not surprising for the high efficiency of HEPA filter.

### 4.3.4 No Side-Effect

The barrier-type air filter will not produce any harmful substance (particles or gases), electromagnetic field, or chemical reaction. It is a mechanical barrier.

In German standard DIN1946-4 (2008), it was pointed out for air cleaning device that “During the operation of the unit, it is not allowed for any harmful substances to volatile into the unit, even the use of antibacterial filter or filters containing special material”. Air filters containing the antibiotics and the lysozyme belong to these special material. Therefore, during the episode of SARS, ASHARE Journal stated not to support the chemical filter. It repeatedly warned to carefully use antibacterial products. It has been pointed out in Chap. 2 that the afore-mentioned German standard does not allow to replace the HEPA filter with electrostatic filter, which has already specified in Chinese standard GB50333 in 2002.

Similarly, UV irradiation cannot be considered as the best assistant. Or even it is thought to replace air filter. The negative evaluation of ultraviolet (shown in

**Table 4.5** Evaluation of sterilization method with UV rays by GMP at home and abroad

GMP	Provisions	Evaluation
WHO	17.34	“.....Because of the limited performance of ultraviolet, it cannot be used to replace chemical disinfection method”
	17.65	“.....UV irradiation must not be used as the final disinfection method”
EEC (European Economic Community)	Appendix 1:70	“.....Usually UV irradiation cannot be used as the sterilization method”
EU (European Union)	Appendix 1:70	“.....Usually UV irradiation is not an acceptable sterilization method”
China, 2010 version	Appendix 1:43	“.....Ultraviolet disinfection cannot be used to replace chemical disinfection”

Table 4.5) by Good Manufacturing Practice (GMP) at home and abroad should attract our thinking [7].

So after literature review, Memarzadeh pointed out at last that ultraviolet germicidal irradiation (UVGI) is not recommended for air management before air recirculation from airborne isolation rooms. It also is not recommended as a substitute for HEPA filtration [4].

The above material and the evaluation by U.S. EPA cited in Chap. 1 provide the proof for the view stated in “*ASHRAE Position Document Filtration and Air-Cleaning Devices*” published by ASHRAE in 2015 [8]. It means that barrier-type fibrous air filter may be the only choice for air purifier. The above point of view is:

This Position Document addresses the health consequences of filtration and air cleaning. Data from refereed archival literature are used to form summary statements on performance as well as the positions with respect to specific technologies. One key statement is that, at present, there is only significant evidence of health benefits for porous media particle filtration systems. For a few other technologies, there is evidence to suggest health benefits, but this evidence is not sufficient to formulate firm conclusions. A key position is that filtration and air-cleaning technologies are not recommended for use if they produce significant amounts of contaminants that are known or expected to be harmful for health.

### 4.3.5 *No Decreased but Increased Efficiency*

During the effective use of air filter, the efficiency usually does not decrease but increase with the increase of dust loading. Of course, when there are too much deposition of particles, the air filter is out of the period of effective use. This is different from the electrostatic purifier in Chap. 2.

### ***4.3.6 Little Influence of Air Velocity on Efficiency of Equipment***

Because the filtration area of the filter media can be far larger than the face velocity of the equipment, the influence of face velocity on efficiency could be reduced. The face velocity of electrostatic purifier is or slightly less than the air velocity passing through, so it is not applicable to the situation with larger amount of flow rate.

### ***4.3.7 Relative Cheap Price***

The unit with air filter or the air supply outlet with air filter is much cheaper and simpler than these with nano-photocatalysis, electrostatic adsorption etc.

### ***4.3.8 Regular Replacement with Certain Pressure Drop Value***

The fibrous air filter has the resistance, which is often considered as one factor in the criticism. As mentioned before, although the resistance of electrostatic purifier or UV irradiation or nano-catalysis itself is very small, they cannot be used alone. Coarse or fine air filter must be installed at the entrance, whose resistance at nominal flow rate could reach 50 Pa according to standard specification. In order to prevent the leakage of UV rays and particles, air filters with higher efficiency are usually placed at the exit of the UV germicidal irradiation unit. In one product, even HEPA filter is added. For safety reason, air filter or even HEPA filter is set at both the entrance and the exit. Table 4.6 shows the pressure drops of several electrostatic purifiers by Mao [9]. When W-type air filter was added downstream, the pressure drop was very high. Therefore, it is incorrect in the generally speaking that the pressure drop of electrostatic purifier or UVGI unit is less than fibrous air filter. The pressure drop of the whole unit should be used for comparison.

With the improvement of structure, the pressure drop of the fibrous air filter can be reduced greatly. Table 4.7 shows the pressure drop of ultra-low resistance and high-medium efficiency air filter invented by author, which has particle removing efficiency 85% ( $\geq 0.5 \mu\text{m}$ ) and bacterial removal efficiency more than 99%. It was measured by the National Center for Quality Supervision and Test of Building Engineering.

When the structures of air filter and equipment are improved, the structural resistance could be greatly reduced and the life time becomes longer. The new patented product is available now.

For the patented outdoor air cleaning unit in the II-type clean operating room, the coarse filter is self-cleaning and its resistance is extremely small, and there is no final pressure drop. The pressure drop in the section for fine and high-medium efficiency

**Table 4.6** Measurement result of initial pressure drop for air purifier

No.	Flow rate (m <sup>3</sup> /h)	Initial pressure drop of air filter (Pa)			
	(Face velocity m/s)	Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 3+W filter
1	800 (0.8 m/s)	2.9	2.9	2.9	170.6
2	1000 (1.0 m/s)	4.9	4.9	3.9	215.8
3	1200 (1.2 m/s)	7.8	6.9	4.9	274.6
4	1500 (1.5 m/s)	10.8	10.8	7.8	337.4
5	1800 (1.8 m/s)	14.7	13.7	11.8	419.7
6	2000 (2.0 m/s)	18.6	18.6	14.7	488.4
7	2500 (2.5 m/s)	27.5	29.4	22.6	635.5
8	3000 (3.0 m/s)	39.2	41.2	33.3	788.5
9	3600 (3.6 m/s)	55.9	59.8	49.0	994.4

**Table 4.7** Pressure drop of ultra-low resistance and high-medium efficiency air filter

Air velocity (m/s)	0.31	0.41	0.52	0.61	0.71	0.79	0.89	0.99
Pressure drop (Pa)	8	10	12	13	15	17	19	21

*Note* Data were from the test report from the National Center for Quality Supervision and Test of Building Engineering and measurement result from Hong-hong Pan, Guo-qing Cao et al.

filter (or sub-HEPA filter) at nominal flow rate is only 14 Pa. Because the filtration area is expanded, the service life is greatly prolonged.

The pressure drop of sub-HEPA filter media is much less than that of HEPA filter media. With the appearance of HEPA filter media with novel material, the pressure drop could be reduced by one third.

As for the replacement of air filter, it is much convenient and safer than the replacement of components for the multiple layer and in-series air purifier introduced in Chap. 1, or the cleaning of electrostatic purifier. The cleaning of non-woven fibrous material will consume a lot of water and it is time-consuming. Moreover, the original performance will also be greatly reduced.

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