Review Article

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Theory and technology of air filtration: review

Abstract

The development of modern science and technology, improving the level of industrialization, increase people's awareness of environmental protection were leaded to the world's demand for filter materials to purify the air. This review presented an overview of air pollutants classification, history of fiber materials, theory of air filtration technology, and traditional air filtration (materials, characteristics, advantages, disadvantages, and standards). In addition, the paper reviewed the mechanisms of filtration, which include diffusion, interception, intermolecular interaction, straining, inertial impaction, gravitation, and electrostatic interaction of particles on the filter surface. Different studies have revealed the possibilities for the utilization of activated carbon fiber in the removal of VOC or odor from gaseous emissions in the air.

Keywords: air pollutants, air filtration, HEPA, purification techniques

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Introduction

Air pollution had become the biggest ecological environment problem, seriously affecting human health and life. It was claimed thousands of lives every year in countries like the USA.[1–14] Europe, Australia, Japan,[15–45] China,[11] and the Netherlands.[18] asthma, nausea, skin irritation, high blood pressure, cancer, birth defects can cause exposure to air pollutants (particulate matter (PM) and gaseous pollutants)[28,30,46–67] along with respiratory and cardiovascular diseases.[58,11,47] The effective control of airborne pollutants, harmful biological agents, allergens, and aerosol particles were the main issues concerned by people. Generally, the diameter of dust particles floating in the atmosphere ranges from 10 nm – 10 µm, which were the main ingredients of air pollution.[1,48,2] A high-efficiency air filter could effectively remove bigger than 0.3 µm particles, but not smaller particles. For air purification, the filtration industry had been looking for a material to prepare a filter medium that could effectively filter particles below 0.3 µm. Nano-fiber materials had attracted people's attention because of their excellent surface-to-volume ratio and potential to be used in filtration.[63,29,39,46,24,2]

Classification of air pollutants

Classification of air pollutants was shown in Figure 1.[5,29] The concentration of pollutants in the indoor atmosphere was 2 -5 times more than concentrations in the outdoor atmosphere.[17] Cooking, heating, smoking, and air conditioning increase PM concentration.[5,65] While in the outdoor atmosphere industrial activities and vehicle emissions were increased PM concentrations.[21,40]

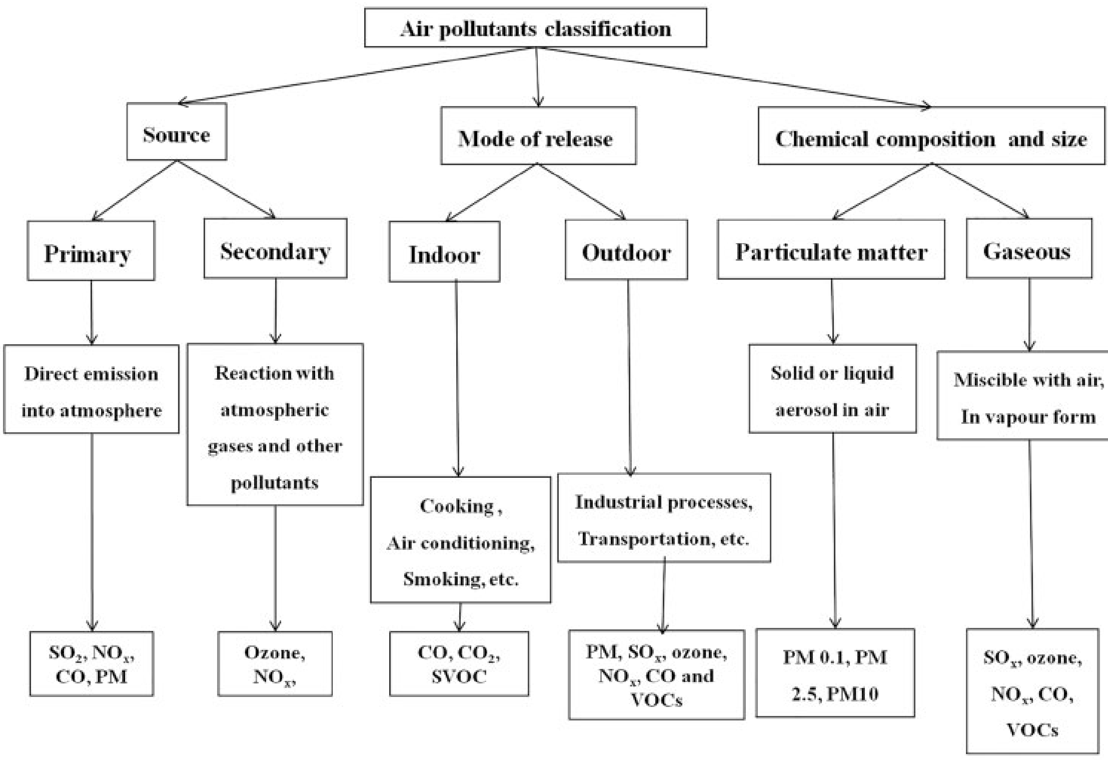

Figure 1 Air pollutants classification and examples.[5,29]

History of fiber materials

In 1940, a glass fiber filter material was prepared in the United States. From the 1950s to the 1970s, fiber filter materials developed rapidly, and HEPA (High-Efficiency Particulate Air) filters using glass fibers were applied to the purification of indoor air.[32] To further improve, high-efficiency filters were used, and the filtration efficiency of particles ≥ 0.3 µm reaches 99.998%. Subsequently, an ultra-high efficiency filter (ULPA) was developed by Japan; the filtration efficiency of 0.1 µm particles could reach as high as 99.9955%.[61]

Technology theory of air filters

The theory of classical filtration was developed in the 19th century. Filtration and micro-porous filter theories were summarized in Table 1.

Table 1 Development process of filtration theory[37]

Researcher	Achievement
Robert Brown, Beginning of 19th century	Brownian movement
Freundlich	Penetrating particle size of particles range: 0.1 – 0.2 µm
Sell	Improved Albrecht theory
Kaufmann	First derived the fiber filtering formula
Langmuir	Filtration theory of interception and diffusion
Davies	Isolated fiber theory
Friedlander	Summarized diffusion deposition with bigger Reynolds number
Yoshioka & Clarenburg	A mathematical theory of fiber filter micro-porous structure
Payet & Renoux	The classical theory
Rosner	Particle dispersed on the surface of a single fiber
Thomas	Theoretical and experimental researched air filters under blocking condition

Filtration mechanisms included diffusion, intermolecular interaction, interception, straining, inertial impaction, gravitation, and electrostatic interaction of particles on the filter surface[10,29] (Figure 2).

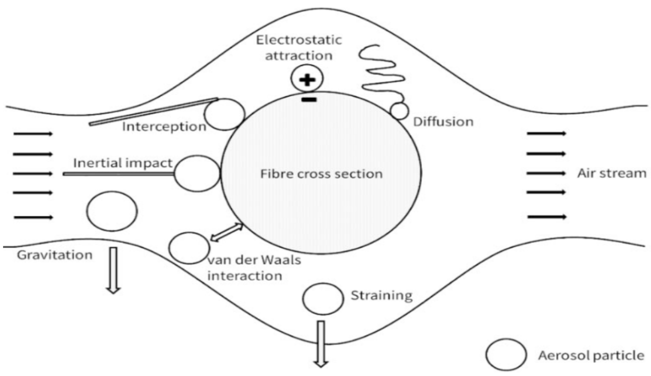

Figure 2 Schematic diagram of single fiber capture mechanisms.[37,29]

HEPA filters were captured Particles in five ways[13]:

a) Sieve effect

This effect stoped large particles (> 5 µm in size) on a filter.

b) Inertial impaction

It took place when large particles were unable to adjust to changes in the flow around fibers (Figure 3a).

c) Interception

It occurred when a particle (0.1- 1 µm) came within the particle radius of a fiber (Figure 3b).

d) Diffusion

Very fine particles (< 0.1 µm) would collide with gas molecules and create a random path through the media as shown in (Figure 3c).

e) static charge

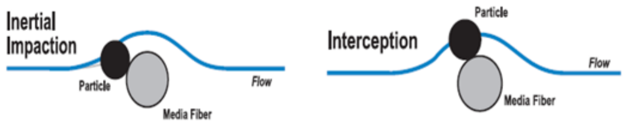

Figure 3a Inertial Impaction. Figure 3b Interception.

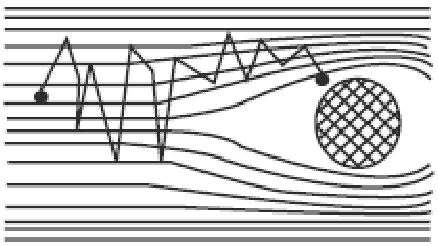

Figure 3c Brownian diffusion.

Figure 3 Ways of trapping particles in fine non-woven HEPA type filter media.[13]

A charge would build up when the air stream passes over the fiber. The fiber material would play a part in how much charge will get built. The geometry and humidity in the air would affect how much charge the fiber will hold.

HEPA filters were getting rid of contaminants and impurities from atmospheric air. HEPA filters could clear the air from dust, pollen, pet dander, smoke, and almost all pollutants present in the air. But HEPA filter was extremely fragile and needs to be shipped, stored, and handled in the same manner as delicate instrumentation.[8,13] HEPA filters were used in a wide variety of applications. Filters could be used for office equipment to remove toner dust to applications for industrial vacuum cleaners for asbestos removal.[6] HEPA filters were also used in surgical operating rooms, and other critical medical air filtration to prevent the spread of airborne bacterial and viral organisms.[33]

Types of air filtration: Filter was a better choice to capture air pollutants. Its efficacy depended on air pollutant type and capturing mechanism.[25,53]

Porous membrane filter: Porous membrane filter: it was membrane matrix, such as polytetrafluoroethylene (PTFE) which contains many small pores.[66,64] This kind of material had a high filtration effect, low air flux, and high air resistance.

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Nonwoven fiber filter: it was a kind of material that had high porosity, high air flux, and low filtration efficiency.[15,22,23,52,59,62]

a) HEPA (High-Efficiency Particulate Air)

HEPA filter could remove at least 99.97% of dust, pollen, mold, bacteria, and any airborne particles with a size of 0.3 µm.[7,43]

b) ULPA (Ultra-low particulate air)

It was captured PM with filtration efficiency[53] (99.999%). These filters had the form of wet-laid papers, nonwoven fabrics, and air-laid glass fiber. These media contained low solids content, fiber volume < 10 % of the volume of the media. Its thickness was from mm to cm. Non-woven filtres were made from inorganic and organic fibers including wood pulp, cotton, or rayon.[12,20] It had a mean flow pore (MFP) of 1 - 500 um.[49]

Nano-fibres: it was a new kind of filter material in recent years, which was developed by nano-technology. it had small fiber diameters with nano-scale pores, high specific surface area, and high van-der Waals forces.[31,34,36,56,63,67,27,9,66,57,64,52]

Materials of air filtres

Glass fiber material was used in 1940 as an air filter in the United States. The HEPA filter was used in the 1970s, with super fine glass fiber. It could achieve an efficiency of 99.9998% for ≥ 0.3 µm PM.[38]

a. ACF (Activated carbon fiber) was developed in 1970 by the Japanese. Due to its advantages, it was considered to be one of the best air purification materials in the 21st century. It was with a uniform pore size distribution, high stripping speed, short adsorption trip, large adsorptive capacity, effective absorption pore, and easy regeneration.[3]

b. In the late 1980s was born nano-technology (nano-fiber). It had surface tension, surface energy, and a larger specific surface area. These increased the deposition of PM from airborne on the fiber surface and increase efficiency.[56]

c. A ULPA filter (Ultra Low Penetration Air Filter) was produced in the early 1990s by US Company Lydia. It was made from superfine glass fiber, which could be achieving an efficiency of 99.999999% for 0.1 µm PM.

d. TiO_2 (Nano-titanium dioxide) was photo-catalytic material. it was used to eliminate hazardous gases. its mechanism of working depends on excitation energy by UV (Ultraviolet), where when TiO2 material absorbed UV rays it leads to oxidation-reduction reaction, formation of strong oxidizing hydroxyl radicals and superoxide anionic radicals which could degrade nitrogen oxides (NOx), volatile organic compounds (VOCs) , sulfur dioxide (SO_2), ammonia (NH_3), carbon dioxide (CO_2), and carbon monoxide (CO), etc.[36]

High-efficiency particle air filter (HEPA): It was made from microfibers borosilicate in form of a pleated sheet. Its media was a glass and polymer blend, and it was pleated to provide more material in a smaller space. The pleats were separated by aluminum baffles. This combination was installed into an outer frame made from board aluminum or stainless steel.[35] Different types of HEPA filters were shown in Table 2.[13]

Table 2 Types of HEPA Filters[13]

Types	Application	Efficiency
A	Industrial, non-critical	99.97 % for 0.3 µm
B	Nuclear containment	99.97 % for 0.3 µm
C	Laminar flow	99.99 % for 0.3 µm
D	Ultra-low penetration air (ULPA)	99.9995 % for 0.12 µm
E	Stopping toxic, nuclear, chemical, and biological threats	100.00%

Air filter characteristics: The factors affecting the purification characteristics of air filtration materials were examined in different studies.[12,54,26,37] The researchers found that air permeability and porosity were important properties for filtration. There was an extreme relationship between air permeability and porosity, as the porosity increases, air permeability increases also. In previous studies, another relationship had been investigated between air permeability and non-wovens structural characteristics (weight, density, thickness, and fiber diameter). Air permeability of fabric was affected by weight more than the thickness followed by density.[12,4,19] The previous studies were mentioned that filtration efficiency was affected by fiber charge density and face velocity more than other factors. Where, efficiency increased with increasing fiber charge density and efficiency decreased with decreasing face velocity.[37] The main atmospheric air pollutants could be divided into suspended particulate matter (SPM), volatile organic compounds (VOCs), and microorganisms. The effect of individual purification techniques on atmospheric air pollutants was listed in Table 3.[61] Table 4 shows the characteristics of different purification technologies in building environments. A summary of different atmospheric air filtration techniques and efficiency was listed in Table 5.

Table 3 Effect of individual purification techniques on main types of pollutants[37]

Purification techniques	Main pollutants			
	Suspended particles	Volatile organic pollutants	Microorganisms	
	Dust, pollen, secondary pollutants, etc.	Formaldehyde, benzene, etc.		
	Diameter: 0.01 – 100 µm	Diameter: 0.01 – 100 µm	Bacteria	Virus
			Diameter: 0.2 – 10 µm	Diameter: 0.01 – 0.3 µm
Filtration	Effective	None effective	Effective	None effective
Adsorption	Partially effective	Highly effective	Partially effective	None effective
Water washing	Effective	Partially effective	None effective	None effective
Electrostatic precipitation	Effective	Not obvious	Partially effective	None effective

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Table 4 characteristics of different purification technologies in building environments[37]

Technologies	Pollutants	Advantages	Disadvantages	Efficiency
Fiber filtration	- Particles	- Low cost	- High resistance	100.00%
	- Microorganisms	- Convenient installation		
Electrostatic	- Particles	- High efficiency	- Efficiency decline after dust discharge	50%
	- Microorganisms	- Wide range		
Activated carbon adsorption	- All pollutants except biological	- Multiple sources	- Saturation	
		- High efficiency	- Resistance	

Table 5 Summary of air filtration techniques[37]

Air filtration technique		Effective particles diameter	Efficiency (%)
Fibrous filter	Medium filter	> 0.3 μm	60 – 90
	HEPA	> 0.3 μm	99.99
	ULPA	0.12 – 0.17 μm	99.999
	Glass fiber	2 - 10 μm	99
	Nano-fiber	< 0.3 μm	> 99.99
Trombe wall		< 10 μm & < 0.01 μm	99.4 for PM10
Bio-filter	A dynamic botanical air filtration system	VOCs	> 33 for toluene
			90 for formaldehyde
	Integrated bio-filtration system		99
Electrostatic air filter	Electrostatic air filter	< 0.1 mm	82 - 94
	Electrostatic precipitators	> 0.1 mm	Lower than HEPA
Cold plasma air filter		< 0.1 mm & VOCs	85 - 98

Air filter standards

Table 6 presents the air filter classifications standards according to the EN 779: 2012 standard[16] and GB/T14295:2008-2016.[37]

Table 6 Air filter classification according to EN779:2012 and GB/T14295:2008-2016[16]

Classification according to	Category	Filter class	Final pressure drop (Pa)	Average capture (Am) of industrial dust (%)	Average efficiency (Em) of 0.4 μm particles (%)	Minimum efficiency (Em) of 0.4 μm particles (%)
EN779:2012	Coarse	C1	250	50 ≤ Am < 65	-	-
		C2	250	65 ≤ Am < 80	-	-
		C3	250	80 ≤ Am < 90	-	-
		C4	250	90 ≤ Am	-	-
	Medium	M5	450	-	40 ≤ Em < 60	-
		M6	450	-	60 ≤ Em < 80	-
	Fine	F7	450	-	80 ≤ Em < 90	35
		F8	450	-	90 ≤ Em < 95	55
		F9	450	-	95 ≤ Em	70

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Table Continued...

Classification according to	Category	Filter class	Rated wind speed (m/s)		Purification efficiency (%)		Initial pressure drop (%)
			Air filter	Filter media			
GB/T14295:2008-2016	Sub high	YG	1	0.053	Diameter ≥0.5 μm	99.9 > E ≥ 95	≤120
	High medium	GZ	1.5	0.1	-	95 > E ≥ 70	≤100
	Medium 1	Z1	3	0.2	-	70 > E ≥ 60	≤80
	Medium 2	Z2	-	-	-	60 > E ≥ 40	-
	Medium 3	Z3	-	-	-	40 > E ≥ 20	-
	Coarse 1	C1	2.5	1	Diameter ≥ 2.0 μm	E ≥ 50	≤50
	Coarse 2	C2	-	-	Standard artificial dust weight efficiency	50 > E ≥ 20	-
	Coarse 3	C3	-	-	-	E ≥ 50	-
	Coarse 4	C4	-	-	-	E ≥ 50	-

Conclusions

Air filtration materials and techniques become essential in our life to reduce and eliminate high levels of atmospheric air pollutants, which affected human health and the environment. The advantages of classical fibrous filters were low cost, simple structure, and high efficiency. Although, they were characterized by high maintenance costs, filter colonization, and high-pressure drop. To overcome the disadvantages of classical physical filters need to be coated with chemicals or nano-particles. In addition, researchers were found single filtration techniques ineffective in presence of multiple atmospheric air pollutants types. Thus, they have suggested a combination of filtration techniques with other purification technologies to improve their efficiency to remove or eliminate pollutants.

Conflicts of interest

The author state that there is no conflict of interest.

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