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Aerosol Filtration Application Using Fibrous Media—An Industrial Perspective

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Abstract Filtration of aerosol particles using non-woven fibrous media is a common practice for air cleaning. It has found wide applications in industries and our daily lives. This paper overviews some of these applications and provides an industrial perspective. It starts from discussing aerosol filtration theory, followed by a brief review on the advancement of filtration media. After that, filtration applications in respiratory protection, dust collection, and engine in-take air cleaning are elaborated. These are the areas that the author sees as the typical needed ones in China's fast pace economical development endeavor, where air filtration enables the protection of human health, environment and equipment for sustainability.
Keywords aerosol filtration, filter media, fiber technology, respirator, dust collection, engine in-take air cleaning, sustainability

1 INTRODUCTION

Aerosols or airborne particles are present in our environment either by nature or through human activities. They come in many forms such as dust, mist, fume, smoke and fog [1]. These aerosols affect visibility, climate and human health and quality of life. For example, pollen, bacteria and virus carrying aerosols, if inhaled, could lead to severe breathing problem, lung infection and other sicknesses. Particulate and oil mist emissions from engine tail pipe and engine crank case ventilation system are carcinogens, thus are highly regulated in developed countries. Cabin air must be cleaned to remove aerosols and odors inside an airplane to create a healthy environment for the passengers. Meanwhile, aerosol particles are very damageable to machinery relying on clean air or liquid for operation. One straight example is engine intake air for combustion. The many particulate contaminants in air, if not filtered out before introduction to the combustion chamber, could cause non-reversible engine damage instantaneously, especially in a dusty environment engine operates, such as desert, mining plant, construction areas where a fair amount of flying dusts exist.

Understanding aerosol behavior is of significant importance while finding means to remove aerosols from different environment is never taken lightly. Aerosol removal through filtration is simple and economical, and has been a long-standing topic for both academic research and industrial practice for environment and equipment protection. In its essence, aerosol filtration plays a critical role in sustainability since it helps to create a cleaner world when pollution becomes a companion of technology development and economical growth.

However, the process of air filtration is very complex, and many early studies focused on filtration theory. Prof. J.Y. Chen is one of the pioneers who made a difference in this regard. His publication in *Chemical Reviews* in 1955 has been considered as a theoretical milestone [Chen, C.Y., "Filtration of aerosols by fibrous media", *Chemical Reviews*, **55** (3), 595−623 (1955)]. This work, although frequently cited by people involved in aerosol filtration research, is barely visible to those working in Chemical Engineering field where contaminant removal from air is long due for attention.

To celebrate his 90th birth day and near 6 decades of scientific research career by bearing in mind his significant contribution to many aspects of chemical engineering research, the author provides this paper in an attempt to remind and remember the pioneering work of aerosol filtration Prof. Chen and his generation started, which has been carried on by numerous academic and industrial scientists and engineers, to be continued by generations to come in order to protect our world, enable and sustain various product and process technologies for economical growth and human's well being.

2 AEROSOL FILTRATION MECHANISMS

At low dust concentration, aerosol filtration by fibrous media is the most economical means for collecting submicron sized particles from a gas stream with high efficiency. It is used in many applications such as respiratory protection, air cleaning from smelter effluent, processing of nuclear wastes, dust collection at power plants and clean rooms and so on.

Aerosol filtration is a very complex process but fundamental theories are well established regardless of the still existing gaps between theory and experiment. Prof. Jiayong Chen (formerly Chia-yung Chen) had made significant contribution to filtration theory in his 1955 publication as mentioned earlier [2], where he established a semi-empirical screen model to account

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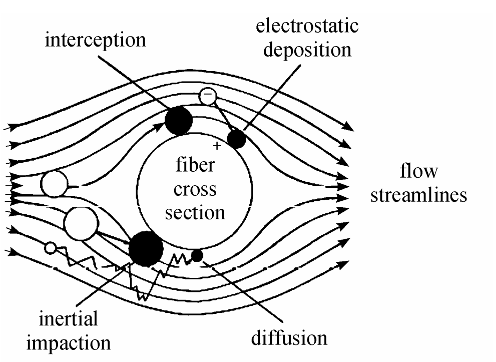
for interference effect of neighboring fibers. His model is considered as one of the milestones of aerosol filtration theory and has been cited for more than 150 times (SCI statistics), including 12 citations in the 21 century. His work covered aerosol removal mechanisms through direct interception, Brownian diffusion and the force of inertia impaction, which is critical to designing air filters with low pressure drop and high filtration efficiency that is practiced routinely today. However, at the time Prof. Chen conducted his work in University of Illinois-Urbana in early 1950s, the understanding of these major mechanisms and quantifying them by mathematical modeling with experimental verification, and by taking into account fiber interaction on pressure drop and capture efficiency in the model, was a very big accomplishment. As previously, sieving was naturally thought to be the main mechanism for particle separation from a gas stream using fibrous media, which was later proven probably the least important for small aerosol particle separation before a surface cake is established. Once the cake is formed, sieving becomes dominant and a filter's life quickly ends because of high pressure drop rise across the filter media.

In aerosol filtration using a fibrous material, particles are captured through the depth of the porous structure as gas follows path created by the series of interconnected void spaces formed by the microstructure. Particles can be captured through the mechanisms depicted in Fig. 1 as diffusion, interception, inertial impaction, electrostatic interaction, *etc*. Each time the gas stream flows through porous opening, particles have an opportunity to deposit onto the fiber.



Particle deposition mechanisms on filter media structure.

Figure 1 Aerosol filtration mechanism illustration

Particle deposition *via* diffusion results when particles collide with the fiber due to their random Brownian motion. This motion, and hence the degree of particle capture, becomes more pronounced as the particle diameter becomes smaller, especially for particles less than 0.1 μm.

A particle is deposited *via* the interception mechanism if a particle of finite size is brought within one particle radius of the fiber as it follows the flow streamlines around the fiber. Collection *via* this mechanism increases with increasing particle size. Interception becomes the dominant capture mechanism for particles in the 0.1−1 μm and larger size range.

Larger particles collide with the fiber due to the mechanism of inertial impaction, as the particles are unable to follow the curve path of the gas streamline around the fiber. This mechanism becomes an increasingly significant means of particle collection for larger particles and higher gas velocities. This mechanism becomes important for particles larger than 0.3−1 μm, depending on the gas velocity and the fiber diameter of a filter media.

Particles deposit *via* electrostatic-deposition if electrical charges on either the particle or the filter, or both, create attractive electrostatic forces of sufficient magnitude to attract the particle to the fiber surface. Lesser importance mechanisms include sieving and gravitational sedimentation. The particle capturing effectiveness of each mechanism is primarily dependent on the particle size, gas velocity and size of fiber diameter.

A single fiber's efficiency and the overall filter efficiency can be calculated using the following equations:

Single fiber efficiency:

$$\eta_s = \frac{\text{particles collected by fiber}}{\text{particles in volume of air geometrically swept out by fiber}} \tag{1}$$

Overall filter efficiency:

$$\eta = 1 - \exp(-\eta_s S) \tag{2}$$

where S is the filter area factor, equivalent to the projected area of fiber per unit filter area

A typical collection efficiency as a function of aerosol particle size accounting for the different mechanisms is shown in Fig. 2. The overall efficiency is also shown in the same figure where a most penetrating particle size (MPPS) is defined as the one corresponding to the lowest overall filtration efficiency. This is a characteristic size of a filter material, typically around 0.3 μm or lower.

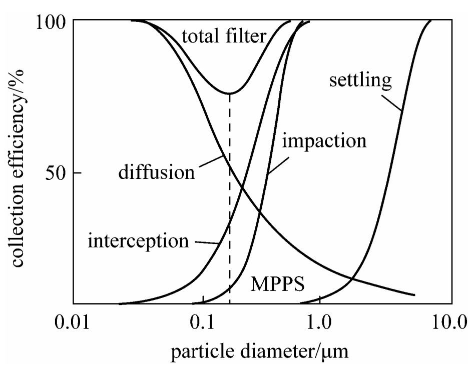
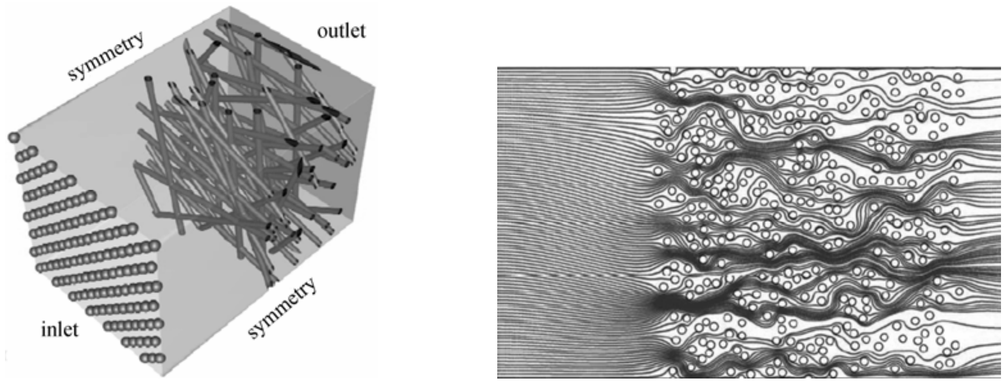


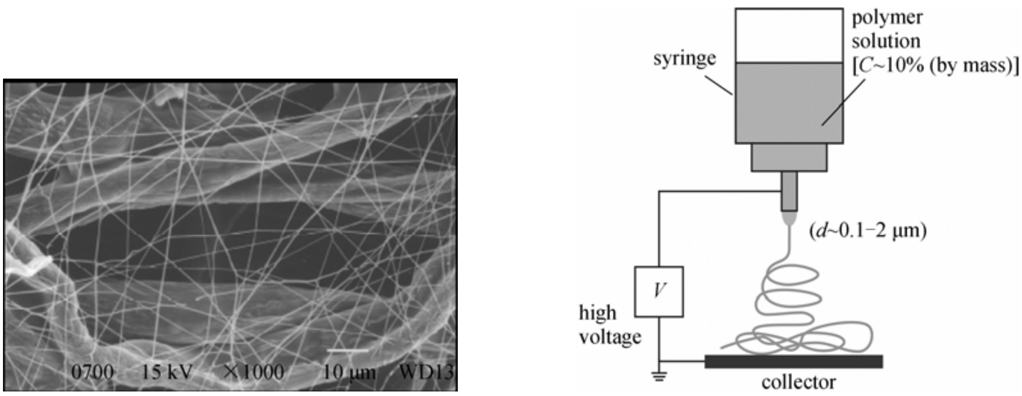
Figure 2 Filter efficiency for individual single-fiber mechanisms and total efficiency [1]

Many filtration models have been established to predict a filter's performance considering fluid dynamics



(a) (b)

Figure 3 An example of using the Eulerian method for calculating particle capturing due to interception and diffusion using 3D simulation domains



(a) (b)

Figure 4 SEM (Scanning electron microscopy) of electrospun nanofiber web on cellulose (a) and schematic diagram of electrospinning process (b)

and the filter's structure using the mechanisms discussed above. Fig. 3 (a) is an example where 3D media structure is constructed for a 3D domain simulation, and particle capture due to interception and diffusion can thus be calculated using Eulerian method and the result is given in Fig. 3 (b) [3].

The more practical model focuses on generating a universal tool to guide filter design without conducting prototype filter build and test, thus saving material, energy, human labor, and ultimately, development time and total cost while reducing waste generation [4]. This kind of work is mostly conducted in industrial labs to help speed up designing filtration systems.

3 ADVANCEMENT IN FILTER MEDIA

3.1 Nanofiber spinning technology

Filter media is the core of aerosol filtration technology. Due to its cheap cost, light weight and ease of handling, both natural and synthetic fibrous material has been the preferred choice for almost every application in aerosol filtration. More often, fiber blend is used to balance filtration efficiency and pressure drop. High pressure drop across a filter translates to the undesired high energy consumption to drive air flow through the filter. One early study shows that when fiber size is reduced, the MPPS shown in Fig. 2 shifts to the left, meaning the total filtration efficiency becomes higher. The increase in filtration efficiency is due to the large surface area per volume available for particle capture, especially for small submicron meter particles. This finding has encouraged a wave of small fiber innovation and commercialization that boost the filtration industry starting from early 1980s.

A traditional aerosol filter media is often made of big and flat cellulose fiber. The microstructure it forms gives large flow path for air molecules. Such filter captures big particles well but allows small ones to pass through. Commercialization of electrospun nanofibers with fiber size ranging 100–2000 nm has made it possible to lay a web of only a few fiber diameters thick on cellulose, thus forming a nanofiber composite filter media as shown in Fig. 4 (a) [5]. Since its debut, this media is widely used for air cleaning to remove aerosol particles, from engine in-take air filtration to power generation equipment gas turbine protection. The media also offers self-cleaning capability for defense equipment and power plant dust collection system, to effectively remove submicron particles with much longer filter service life. Because of its high efficiency and low pressure drop, the service life of a filtration system using this media can be more than doubled than a regular cellulose media.

In electrospinning process, high potential electric field is applied to the polymer solution in the syringe to launch a polymer jet towards the grounded collector as shown in Fig. 4 (b). As the jet travels through the atmosphere, it undergoes bending instability and solvent evaporates to form nanofibers. Electrospinning of submicrometer polymer fibers has seen a tremendous increase in research and commercial attention over the past decade [6]. However, due to the available intellectual property protection for commercialization, industrial efforts have been limited. The alternative is to go back to modify other traditional technologies to make fine fibers typically having fiber size of 1−5 μm. Improvement in meltblowing technology can generate a portion of fibers smaller than 1 μm, all the way down to 0.3 μm. The meltblowing is performed by extruding a polymer melt through an orifice die, and molten filaments are attenuated by hot air to form microfibers.

The most recent advancement in nanofiber making is the so-called force spinning technology [7]. Fiber size in the range of 100−600 nm can be obtained. However, this technology is still under development: challenges being large-scale production, continuous fiber collection on roll goods and extension to spinning a variety of polymers in addition to polypropylene and nylon.

Figure 5 shows the schematics of fiber formation using the force spinning technology. The polymer solution or melt is forced through the orifices of the spinneret by applying centrifugal force. As polymer solution or melt is ejected through the orifices, continuous polymer jets are formed and are stretched into formation of fine web of fibers due to the applied centrifugal force. The web is collected on the custom designed collector system.

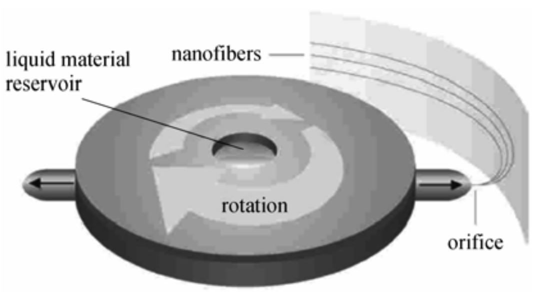


Figure 5 Mechanism of fiber formation in force spinning technology [7]

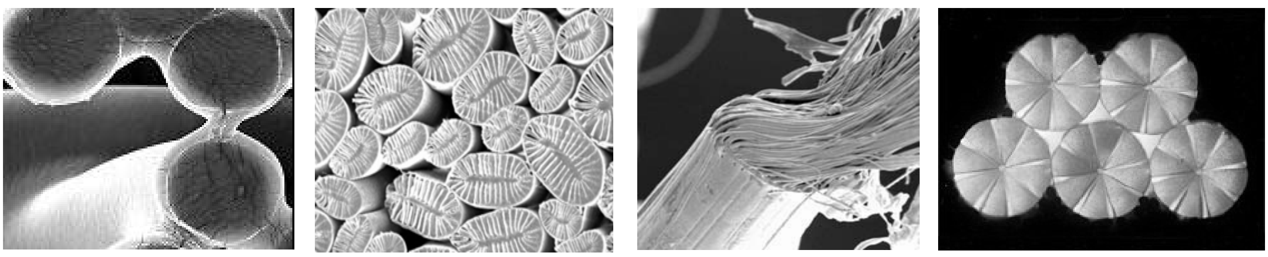
Fiber formation and morphology of the formed web are dictated by solution concentration, melt viscosity, rotational speed, distance between collection system and spinneret and gauge size of the spinneret. By varying these parameters, fine control over the fiber diameter and morphology is possible.

3.2 Multicomponent fiber technology

To date, multi-component fibers have been less used for filtration than meltblown fibers, and they are far less embraced for their small size than electrospun fibers. However, modern melt spinning distribution system technology has clearly demonstrated the capability to produce fibers with smaller size and better consistency than either of the two above techniques. In addition, micron-sized (1−10 μm) and submicron to nano-sized (<1 μm) multi-component fibers can be produced with improved production rates, economics and physical properties over the other systems, and with even broader polymer choice capabilities. Multicomponent fibers sizes of about 40 nm have now been demonstrated at commercially attractive production rates. Multi-component fiber production is available in staple, continuous filament, spunbond, and meltblown processes [8, 9].

By far the most common type of multi-component fibers is bicomponent fibers (consisting of two polymer components). Some common bicomponent fiber cross sections include sheath/core, wing shaped, segmented pie and island-in-a sea fibers as shown in Fig. 6.

Sheath-core round cross section bicomponent fibers have been developed recently for aerosol filtration, especially for mist collection for compressor air filtration and engine crank case filtration [4]. The advantage of using such fibers includes resin-free, self-supportive and high efficiency filtration and oil mist drainage rate, as well as lower pressure drop compared with traditional glass media with resin-bonding. When the sacrificial sheath is dissolved, shaped fibers [Fig. 6 (b)] with wings can be obtained. Preliminary



(a) Round cross section bicomponent fibers (b) Wing-shaped bicomponent fibers (c) Island-in-a sea bicomponent fibers (d) Segmented pie bicomponent fibers

Figure 6 Some common bicomponent fiber cross sections

studies showed that when this area-enhanced fiber is used to construct an aerosol filtration media, significant pressure drop and dust holding capacity advantage can be offered, which translates to significant energy saving at the same filtration efficiency. This kind of media can also act as a prefilter for high efficiency air filter media to improve their dust capacity [10].

No filtration media made from segmented fibers and islands-in-a sea fibers has been reported yet, but individual fibers after dissolving the sea from Fig. 6 (c) (600 islands) can be as small as 300 nm, which has the potential to be used in a matrix of other fibers to enhance aerosol filtration as a depth instead of a surface filtration media as electrospun nanofibers. So far, one US patent was filed in this regard to make nanofibers using islands-in-a sea bicomponent fibers [11].

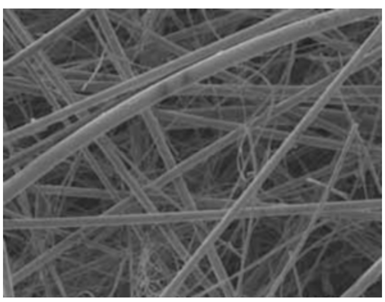
4 AEROSOL FILTRATION IN RESPIRATOR APPLICATION

Respiratory equipment is used throughout the world to provide personal protection from a variety of noxious gases, vapors and aerosol hazards which could cause harm and even death to human, if inhaling wood dust, chemicals, coal dust, pesticide spraying, spray painting and aerosol transmissible diseases such as influenza, diphtheria, SARS (severe acute respiratory syndrome) and swine flu. In contrast, surgical face masks have not traditionally provide protection to the wearers but have been used to keep mouth generated particles from harming a patient in a healthcare situation.

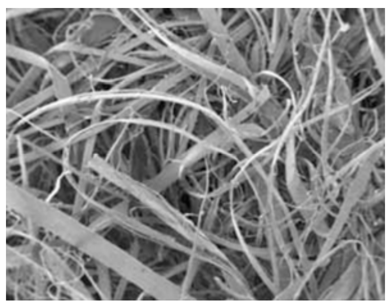
A simple respirator shown in Fig. 7 (a) can collect aerosol particles just like a regular air filter but with very low air flow coming to the mask. Fig. 7 (b) is an elastomeric half face piece cartridge air purifying respirator. The non-woven media used in respirators can be highly efficient glass fibers [Fig. 8 (a)], split film fibers [Fig. 8 (b)], meltblown fibers [Fig. 8 (c)] and expended PTFE (polytetrafluoroethylene) membranes [Fig. 8 (d)]. However, over the last 60 years, for dust and mist respirators, electrostatic air filter media have been the overwhelming choice for almost every respirator manufacturer. While such filters are

(a) Face mask (b) Cartridge respirator

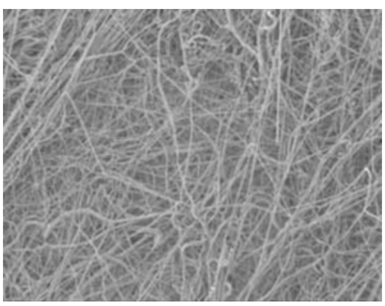
Figure 7 Typical respirator seen on the market



(a) Glass fibers



(b) Split film



(c) Highly charged meltblown fibers

(d) E-PTFE membrane

Figure 8 Available media for respirators [13]

macroscopically electrostatically neutral, microscopically there are charges of either sign balanced within the nonwoven structure which generate electrostatic fields strong enough to capture even uncharged particles. The cartridge respirator can be stretched to give careful protection against multiple hazards. It can handle not only dust and mist, but also threat agents. The cartridge filter normally has multiple layers for different functionalities as shown in Fig. 9. The removal of the agent was brought about by its physical adsorption onto activated charcoal having an extraordinary large surface area as high as 300–2000 $m^2 \cdot g^{-1}$. Further increased protection can be achieved by impregnating the charcoal with substances such as copper oxide since it reacts chemically with certain threat agents [12].

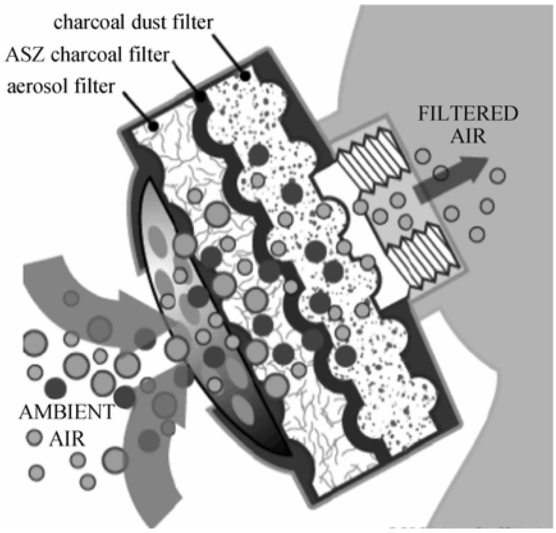


Figure 9 Illustration of cartridge respirator filter structure

The future development and evaluation of respirator will center on the removal of nanoparticles and agglomerates since the special properties of nanoparticles give rise to recent concerns about the potential health hazards posed to workers or users that are exposed to them [13]. The respirator will also become smart and adaptive to the environment it exposes, to not only remove with high efficiency and high capacity the threatening aerosols including toxic agents and bioaerosols, but also to detect the kind of toxins that are captured or inhaled, so quick and correct medical response can be initiated in case of medical emergency.

5 COAL DUST COLLECTION

5.1 Baghouse collectors

Thermal power plants (coal-fired power plants) use coal as their fuel. To handle the coal, each power station is equipped with a coal handling plant. Coal dust emission must be removed effectively and efficiently to protect the working environment and reduce equipment wear as well as cleanup and maintenance costs of the plant. A dust collection system shown in Fig. 10 is typically constructed to achieve this, and filter bags are used to separate dust particulates from dusty gas streams through large fabric bags, commonly known as baghouses. They are typically made of woven or felted cotton, synthetic, or glass-fiber material in either a tube or envelope shape. Fabric filters are one of the most efficient and cost effective types of dust collectors available and can achieve a collection efficiency of more than 99% for very fine particulates [14]. Traditional fabric bags are made of needle punched polyester fabric.

Baghouses are characterized by method for their

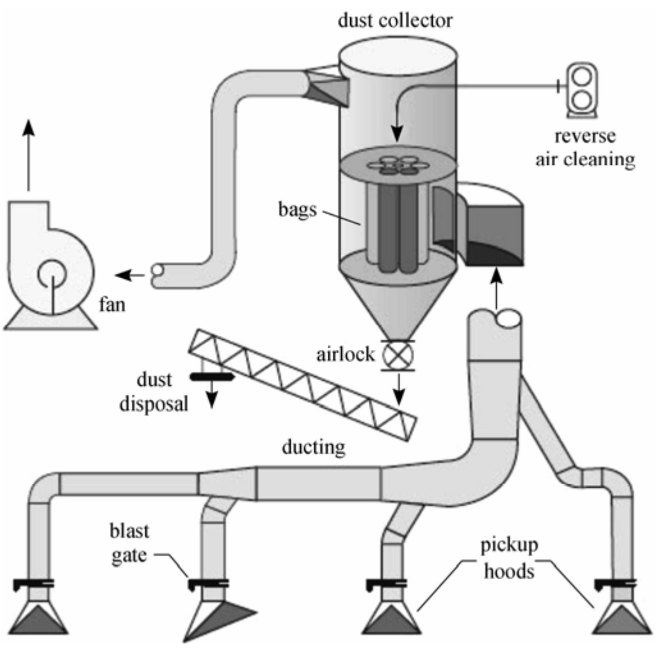


Figure 10 Dust collection system

cleaning after a period of operation by either shaking, reverse air, or pulse jet and sonic. Taking reverse air for example, air flow gives the bag its structure. Dirty air flows through the bag from the inside, allowing dust to collect on the interior surface. During cleaning, gas flow is restricted from a specific compartment. Without the flowing air, the bags relax. The cylindrical bag contains rings that prevent it from completely collapsing under the pressure of the reverse air. A fan blows clean air in the reverse direction. The relaxation and reverse air flow cause the dust cake to crumble and release into the hopper. Upon the completion of the cleaning process, dirty air flow continues and the bag regains its shape.

Recent advances in dust collection system design focus on baghouse material optimization for easier cleaning and extended service life, and the use of cartridge filters to replace the baghouse and minimize the size of the dust collector while maintaining the same efficiency and capacity for energy, material, as well as operational cost saving.

Traditional polyester bags are produced with a needling process that creates larger pores where dust can embed into the fabric, inhibiting cleaning and reducing bag life. Extended service bags are engineered with a unique hydroentanglement process that uses water to blend the fibers. This process provides a more uniform material with smaller pores, better surface loading, and better cleaning. These advantages provide twice the operating life before bags need to be replaced due to pressure drop surge, lowering maintenance and operating costs and raising baghouse dust collection to a whole new level.

The more advanced bag material technology is to laminate expended PTFE membrane or hydrophobic nanofiber web on the needle punched polyester to enhance filtration efficiency and to promote self-cleaning for applications at regular temperatures. On the other hand, temperature resistant bag materials such as polyimide is aggressively pursued, once the cost is lowered to an acceptable level, its application is expected to surge for hot gas treatment.

5.2 Cartridge collectors

Cartridge collectors use perforated metal cartridges that contain a pleated, nonwoven filtering media, as opposed to woven or felt bags used in baghouses. The pleated design allows for a greater total filtering surface area than in a conventional bag of the same diameter. The greater filtering area results in a reduced air to media ratio, pressure drop, and overall collector size.

Cartridge collectors are available in single use or continuous duty designs. In single-use collectors, the dirty cartridges are changed and collected dirt is removed while the collector is off. In the continuous duty design, the cartridges are cleaned by the conventional pulse-jet cleaning system. The advancement in filter media and package design makes it possible to shrink the size of a cartridge collector by 50%–100%. This is achieved by using nanofiber media and a new filter shape developed in late 1990s firstly by Donaldson Company, trade-marked as PowerCore technology. It consists of fluted channels alternatively sealed at one end as shown in Fig. 11. This straight through airflow design and high density filtration system eliminates the hollow center of conventional cylindrical filters, thus saving space, reducing system restriction, extending filter life and reducing overall maintenance cost [4].

6 ENGINE INTAKE AIR FILTRATION

Innovative vehicle designs and increased

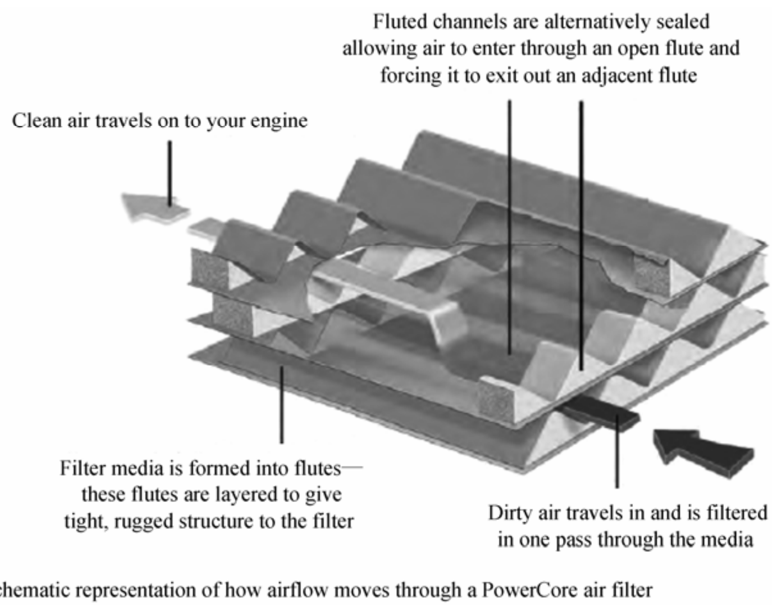


Figure 11 Fluted air flow channel makes compact filter packaging possible [5]

environmental awareness call for new engineering solutions for on-road and off-road vehicle components. Diesel engine air intake suppliers are facing increasing challenges as vehicle manufacturers demand higher performance in a smaller volume while minimizing life-cycle costs [5]. The challenge is mostly determined by the design and performance of the air filter. The air filter removes contaminant from the air in order to protect the engine from damaging wear. Engine wear rates have been calculated to decrease by a factor of 10 when high efficiency air filters are used in place of standard efficiency filters.

Major progress in engine-intake air filtration recently has been made by introducing in line, flow through fluted and pleated filters, and nanofiber filter media as already mentioned in dust collection applications as the PowerCore technology, which has marked its 10th anniversary of commercialization and the sale of its 10 millionth filter [15] in the first half of year 2011. The fluted and pleated in-line, reduced-volume filters, provide high filtration performance while occupying less space. In these designs, almost the entire volume of the filter housing accommodates the filter media. The use of nanofibers on the media surface has allowed the thickness and density of the media to be reduced thereby decreasing the pressure losses through the media and the amount of material used. These nanofibers also show very high initial efficiency compared to standard cellulose media which only achieves its targeted efficiency level after it has built up a sufficient dust cake on its surface.

Figure 12 shows an air induction system, in which nanofiber media is used in the air filter. However, nanofiber filter media is not an emerging technology any more [16]. It was first introduced for industrial application in 1981. It reached on and off road diesel engine application in 1993. In 1995, the self-cleaning pulse jet air cleaner was developed for military applications in high dust concentration environment. There are still challenges such as cost, chemical compatibility, durability, nanofiber layer adhesion and uniformity, and some hazards associated with solvent removal and disposal. As the use of nanofiber filter media expends, these manufacturing issues are being aggressively addressed.

In addition to the PowerCore technology, which is protected by almost 30 featured patents, other companies have come up with their own fluted air filter design and compete in the market place for engine in-take air filtration. The major players include Cummins, Mann-Hummel and Baldwin, and their products are pictured in Fig. 13 [16]. These highly compacted

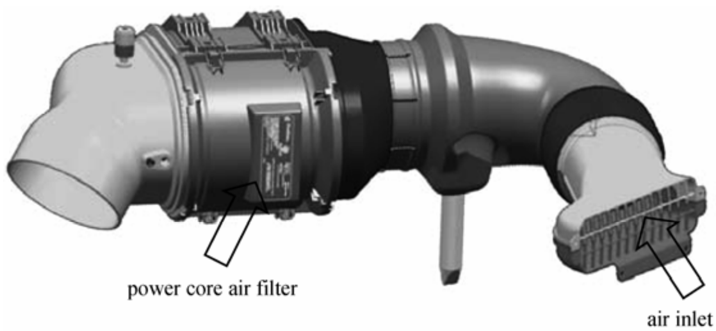


Figure 12 Example of engine in-take air filter system

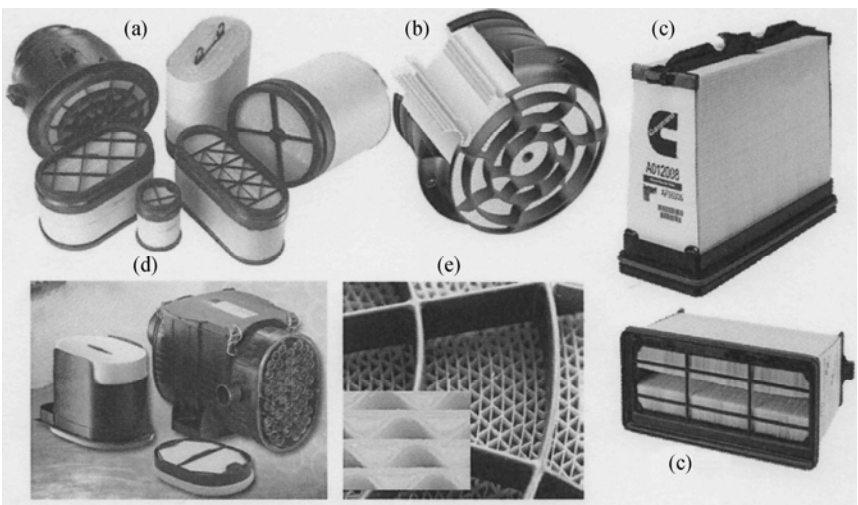


Figure 13 In-line fluted and pleated air filters (a) PowerCore (Donaldson), (b) Channel flow (Baldwin), (c) Direct flow (Cummins), (d) PicoFlex (Mann-Hummel), (e) Block of flutes [16]

filter system are becoming even smaller and lighter today due to OEM's (original equipment manufacturers) requirement to fully use the hood space and integrate multiple mechanical and electrical functionalities for fuel economy and emission reduction. In the foreseeable future, these technologies are expected to be used in the majority of new built diesel engines for both on-road and off-road vehicles to meet the ever stringent emission regulations worldwide.

7 CONCLUSIONS

Aerosol filtration has seen enormous advancement in the past decades based on customers' increasing demand for small size, high efficiency, and low pressure drop of a filtration system. Emission regulation also drives the evolution of filter media technology as well as filter configuration optimization. It is anticipated that the demand can only become stronger for human health protection and sustainable growth. Since filtration systems are to be challenged by different aerosol contaminants in different environment in the real world, developing robust filtration technology with better flexibility and functionality without significantly increasing the cost is expected to be the future trend. However, this can only be achieved by applying the existing knowledge, understanding the limitation of current technology, and interfacing with other disciplines to explore the possibility of the next big thing in aerosol filtration. In my personal opinion, breakthrough technologies may come from three aspects: (a) a deeper level of aerosol characterization, not only to understand its size and size distribution, but also to learn about its chemical-physical properties, especially for bio-aerosol that threatens human health directly; (b) fiber technology. Nanofibers will be further explored in terms of method, material capability and cost reduction. However, nanofiber with purposely designed functionalities such as anti-microbial, structural features and environmental compatibility are something major to consider; (c) media technology. This looks like an extension of fiber technology on the surface, but they do differ significantly in that media technology covers more ground and is more complicated. Process engineering is pivotal to the success of filter media making in order to gain specific media properties consistently to meet the various requirements. Disruptive technologies may come from new process design and process integration based on, but not necessarily limited to the already existing technologies such as dry and wet laid, spunbond, meltspinning, electrospinning, meltblowing, as well as fiber splitting to take advantage of multicomponent fibers for filtration.

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