

Polymeric Nanofibers in Air Filtration Applications

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ABSTRACT

Nanofiber is a broad phrase generally referring to a fiber with a diameter less than 1 micron. While glass fibers have existed in the sub-micron range for some time and polymeric meltblown fibers are just beginning to break the micron barrier, sub-half-micron diameters have been used for air filtration in commercial, industrial and defense applications for more than twenty years.

This paper will discuss a process for making nanofibers, as well as the benefits, limitations, construction, and performance of filters using nanofiber media. In particular, nanofibers provide marked increases in filtration efficiency at relatively small (and in some cases immeasurable) decreases in permeability. In many laboratory tests and actual operating environments, nanofiber filter media also demonstrate improved filter life and more contaminate holding capacity.

Nanofiber filter media have enabled new levels of filtration performance in several diverse applications with a broad range of environments and contaminants. The capabilities of nanofibers will be explored through applications-based performance data. The possibility of applying nanofiber media to a wide range of applications will also be discussed.

1. INTRODUCTION

Polymeric nanofibers have been used in a number of commercial air filtration applications over the last 20 years, and hold promise for technical benefits in an expanding field of filtration applications. This paper will discuss the theoretical filtration benefits of small fibers in air filtration applications, a process for making nanofibers, and real-world applications that demonstrate the practical usage of nanofiber-based filter media.

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2. CHARACTERISTICS OF SMALL FIBERS IN AIR FILTRATION - THEORY

Small fibers in the submicron range, in comparison with larger ones, are well known to provide better filter efficiency at the same pressure drop in the interception and inertial impaction regimes. Figure 1 shows such effect by assuming non-slip flow at fiber surface [9].

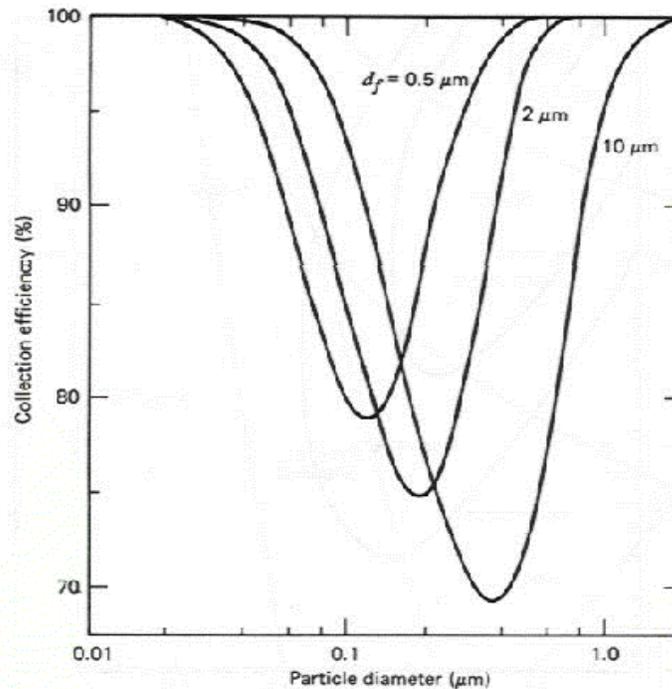


Figure 1: The effect of fiber size on filter efficiency as a function of particle sizes; filter solidity is 0.05 and face velocity is 10 cm/s. Filter thickness has been adjusted so that all three filters have the same pressure drop as calculated [9]

While smaller fiber size leads to higher pressure drop, interception and inertial impaction efficiencies will increase faster, more than compensating for the pressure drop increase. Thus, in the particle size of interest, i.e., from submicron and up, better filter efficiency can be achieved at the same pressure drop, or conversely, the same filter efficiency at lower pressure drop can be achieved with smaller fiber sizes.

For nanometer-scale fibers, a second factor has to be taken into account: the effect of slip flow at the fiber surface [2]. Filtration theory generally relies on an assumption of continuous flow

around the fiber, with a no-slip condition at the fiber surface. The theory starts to break down when the scale of the fiber becomes small enough that the molecular movements of the air molecules are significant in relation to the size of the fibers and the flow field. Using a slip-flow model at the fiber surface can extend the useful range of continuous flow theory. The Knudsen number is used to describe the importance of the molecular movements of air molecules at the fiber surface to the overall flow field. The Knudsen number can be written as

$$Kn = \frac{\lambda}{r_f}$$

where λ is the gas mean free path (the dimension of the non-continuous nature of the molecules), and r_f is the radius of the fiber. When Kn becomes non-negligible, the continuous flow theory, which does not take into account the molecular nature of air, starts to break down. While there is no exact Kn above which slip flow will prevail, it generally needs to be considered when $Kn > 0.1$, and definitely needs to be considered when Kn is around 0.25. For air at standard conditions, the mean free path is 0.066 microns; therefore, for fibers with diameters smaller than 0.5 microns, slip flow must be considered. In slip flow, the air velocity at the fiber surface is assumed to be non-zero. In other words, the air slips at the fiber surface as shown in Figure 2.

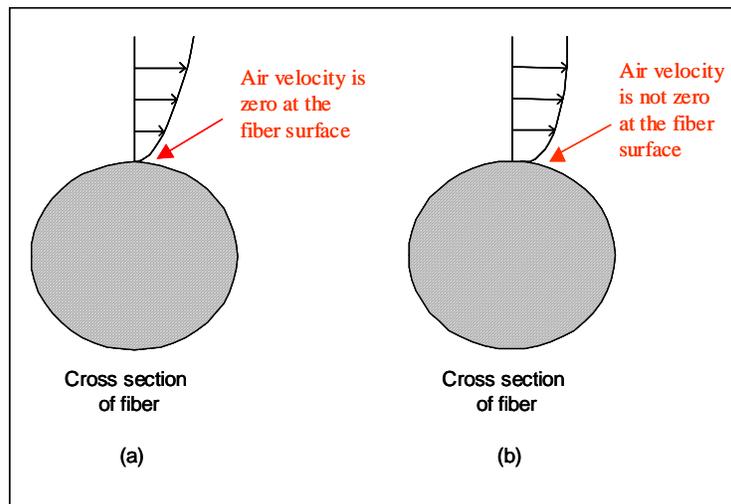


Figure 2: Velocity profiles at the fiber surface for (a) non-slip flow; and (b) slip flow

Due to the slip at the fiber surface, drag force on a fiber is smaller than that in the case of non-slip flow, which translates into lower pressure drop. On the other hand, the slip flow makes the portion of the air flowing near the fiber surface larger than that in the case of non-slip flow, which translates into more particles traveling near the fiber, resulting in higher diffusion, interception and inertial impaction efficiencies. The effects of slip flow on pressure drop and efficiency can be further illustrated by applying mathematical equations such as those by Stechina and Pich [15, 11] in their valid range, although such results are not presented here as

they are beyond the scope of this paper. Thus, the benefit of achieving better filter efficiency at the same pressure drop actually accelerates when fiber sizes are reduced below half micron.

Therefore, due to the dependence of efficiency and pressure drop on fiber sizes, and due to the benefit of having slip flow at the fiber surface, small fiber sizes such as those of 0.2 to 0.3 micron are highly desired for filtration applications.

3. METHOD FOR MAKING NANOFIBERS

Polymeric nanofibers can be made using the electrospinning process, which has been described in the literature [4, 16] and in patents [6]. The basic configuration is shown in Figure 3.

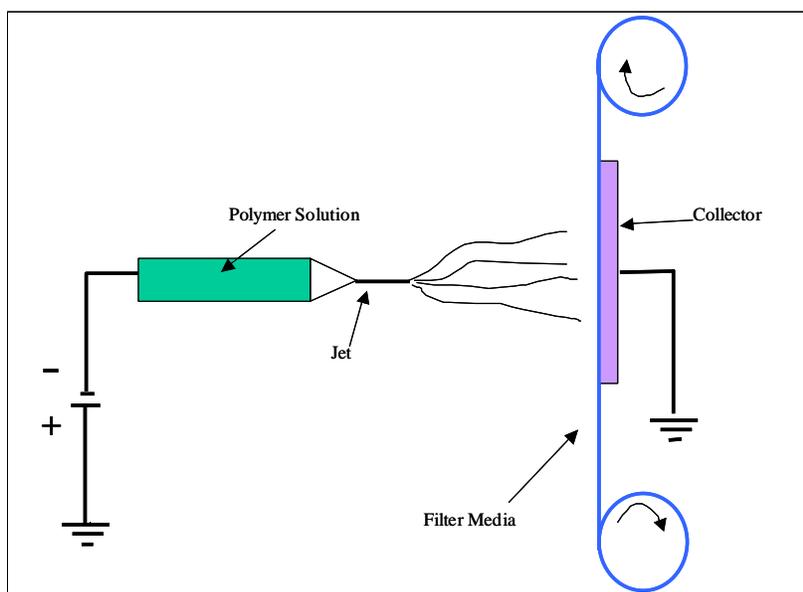


Figure 3: Schematic of the electrospinning process

Electrospinning uses an electric field to draw a polymer solution from the tip of a capillary to a collector. A voltage is applied to the polymer solution, which causes a jet of the solution to be drawn toward a grounded collector. The fine jets dry to form polymeric fibers, which can be collected on a web (sometimes called a nanoweb). The electrospinning process has been documented using a variety of polymers [3, 12]. By choosing a suitable polymer and solvent system, nanofibers with diameters in the range of 40-2000 nm can be made.

4. EXAMPLES OF ELECTROSPUN NANOFIBERS

Figure 4 is a scanning electron micrograph (SEM) of electrospun nanofibers. The fibers are approximately 250 nanometers in diameter. As the fibers themselves have a small diameter, the thickness of the nanoweb can likewise be quite small, with a thickness of four nanofiber diameters approaching only one micron. The thin nanoweb has limited mechanical properties that preclude the use of conventional web handling and filter pleating equipment. As a result, nanofiber webs have been applied onto various substrates. Substrates are selected to provide appropriate mechanical properties to allow pleating, filter fabrication, durability in use, and in some cases, filter cleaning. Substrates are often chosen to resemble conventional filter materials, which allows the use of conventional filter media pleating and element handling equipment.

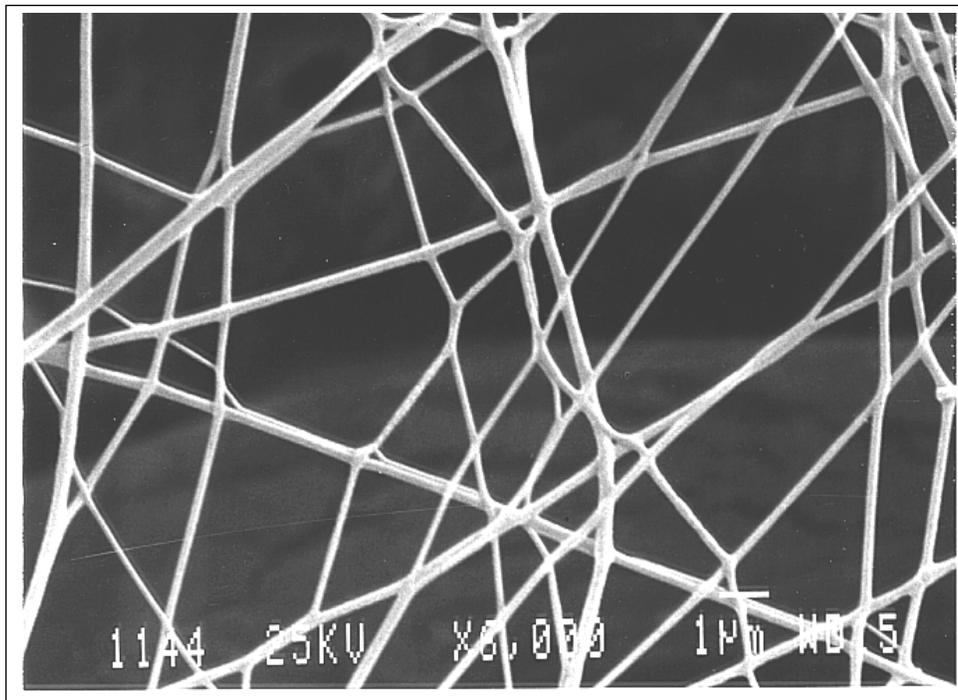


Figure 4: Electrospun nanofibers

Figure 5 is an SEM showing a cross-section of nanofibers electrospun onto a polyester substrate. The substrate is chosen to provide mechanical properties, while the filtration performance is dominated by the nanoweb.

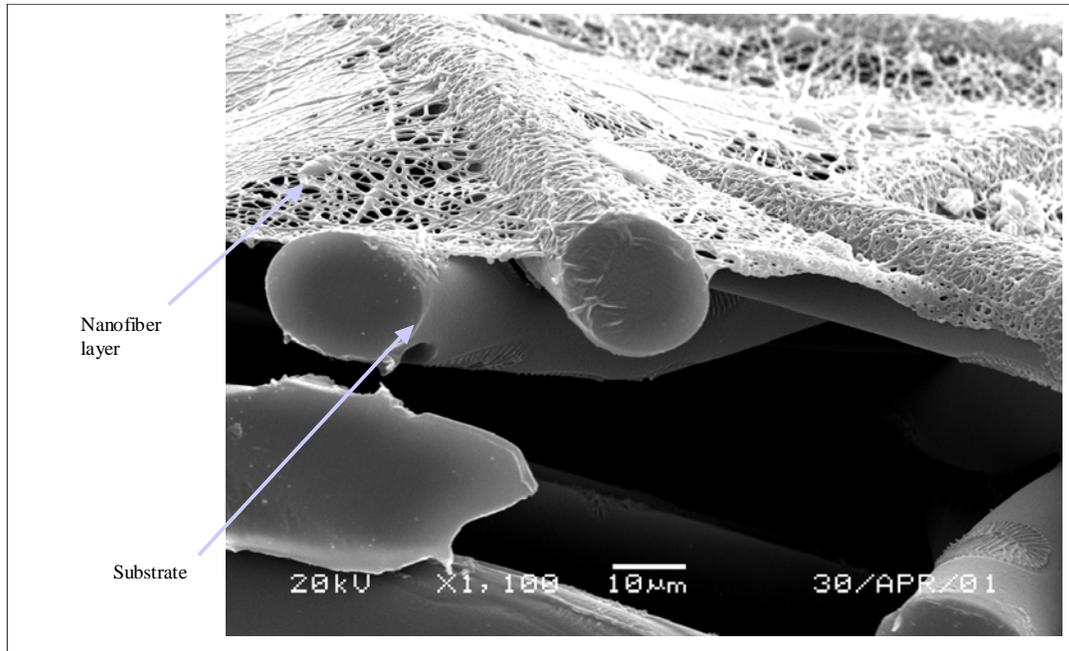


Figure 5: Electrospun nanofibers on a polyester substrate [8]

Figure 6 is an SEM of commercially-available nanofibers electrospun onto a cellulose substrate for air filtration applications. The nanofiber diameter is approximately 250 nanometers, as compared to the cellulosic fiber structure, with diameters exceeding ten microns. This composite filter media structure has been successfully pleated on high-speed rotary pleating equipment with minimal damage to the nanofiber layer.

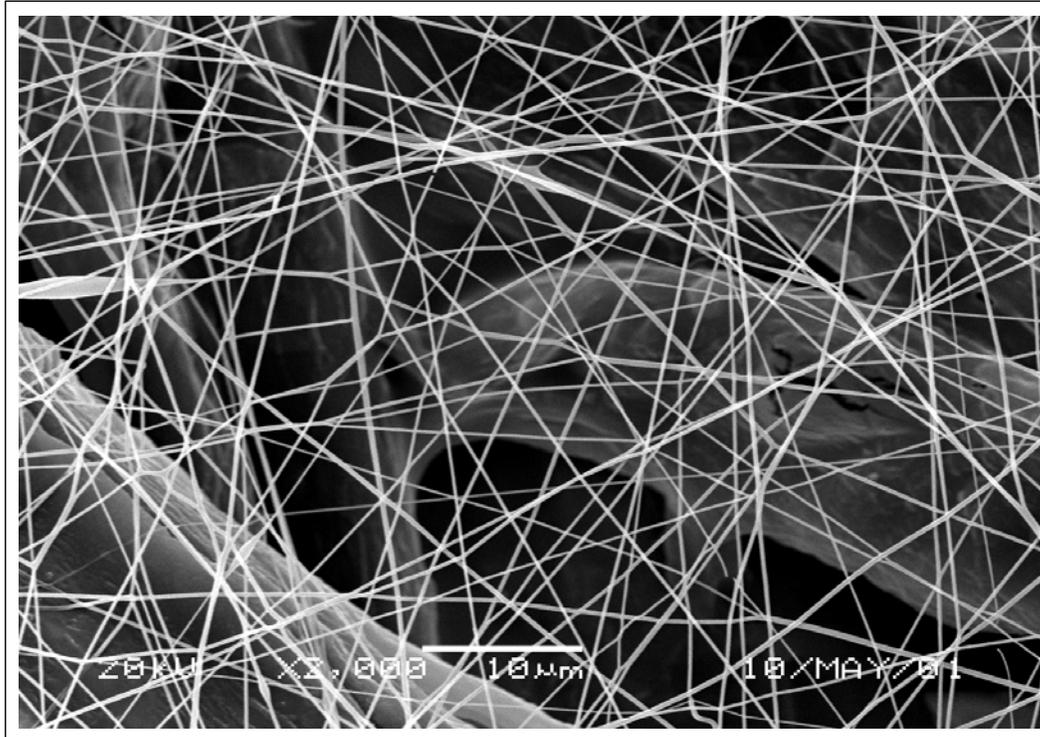


Figure 6: Nanofibers on a cellulose filter media substrate

Controlling parameters of electrospinning allows the generation of nanowebs with different filtration characteristics. Different fiber sizes can be made, some as small as 50 nanometers. Fibers can be put on one side or on both sides of a substrate. Additionally, Figure 7 shows a comparison between a very light layer of nanofibers and a heavier layer of nanofibers. The substrate fibers are more visible in the light application simply due to depth of field limitations of a Scanning Electron Microscope. Nanofibers have been electrospun onto a variety of substrates, including glass, polyester, nylon, and cellulose.

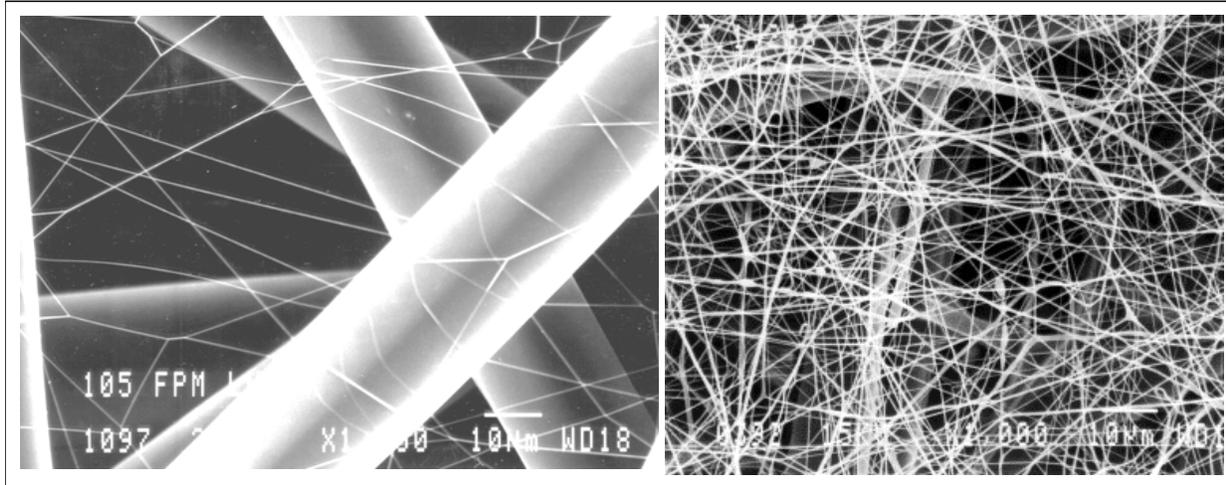


Figure 7: Varying the density of the nanoweb [13]

The filtration properties of nanofibers have been discussed theoretically, and a process for making them has been described. The filtration properties of nanofibers can also be shown visually by reviewing SEM's of nanofiber media that have been exposed to contamination. Figure 8 shows a cellulose media and a cellulose/nanofiber composite media (with nanofibers on the upstream side), both of which have been loaded to the same pressure drop (0.5" w.g.) with ISO Fine test dust. ISO Fine test dust is commonly used for testing engine air cleaners, and contains particles in the size range of 0.7 – 70 microns. The cellulose sample shows depth loading and relatively few submicron particles, while the composite sample shows loading at the nanofiber surface and a significant quantity of submicron particles captured. The composite sample is holding 2.5 times more mass of dust than the cellulose sample [14].

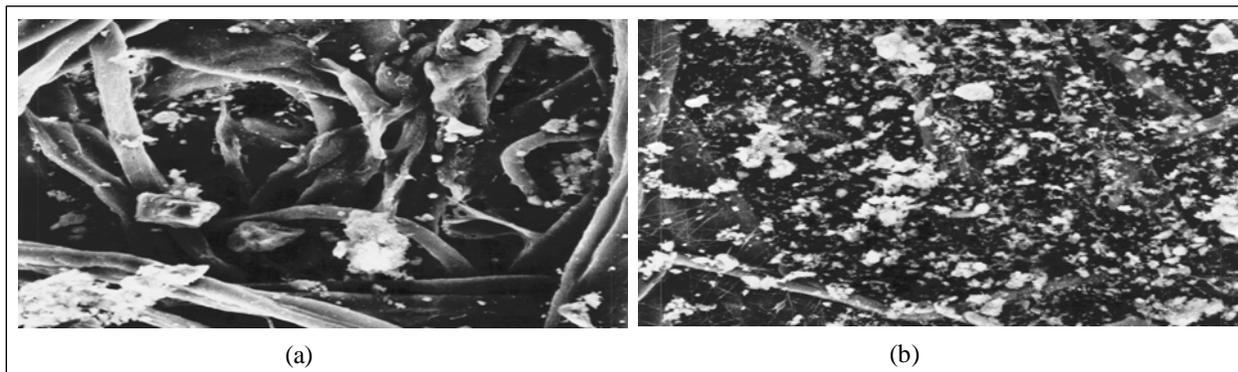


Figure 8: ISO Fine dust loading on (a) cellulose and (b) cellulose/nanofiber composite [14]

Figure 9 shows a composite media sample that has been exposed to a submicron sodium chloride contaminant, with particles in the size range of 0.01 to 0.5 microns. The nanofibers are covered with the salt particles, while the larger substrate fiber has collected relatively few of the submicron particles [13]. Increased filtration efficiency for submicron contaminants can be achieved with nanofibers.

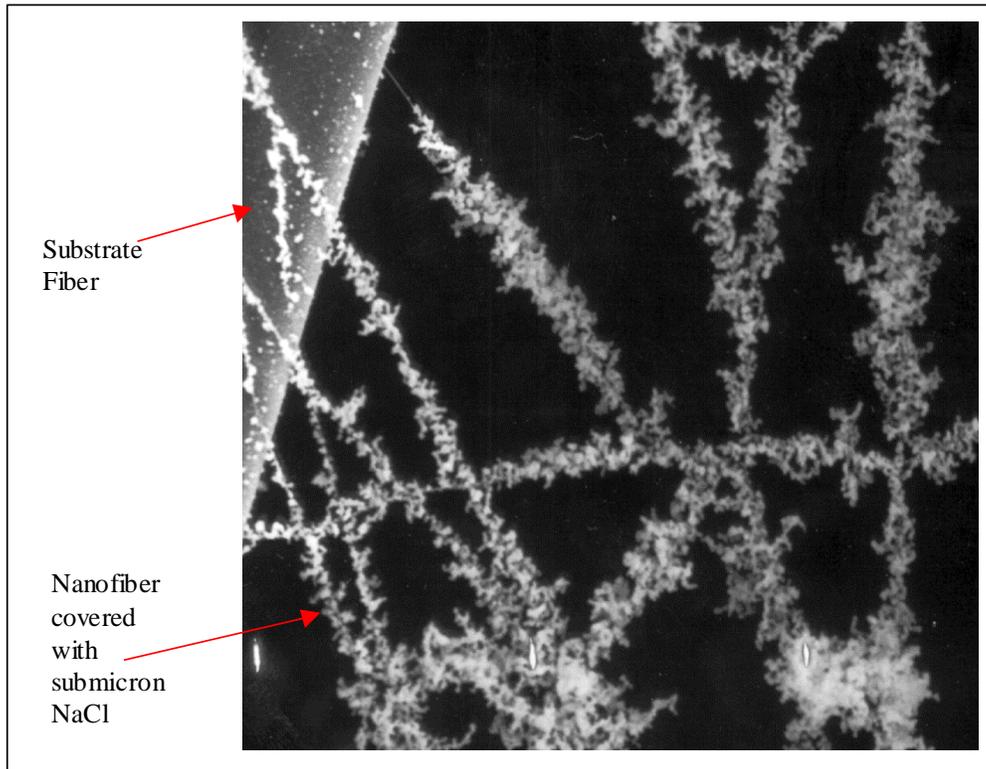


Figure 9: Loading of submicron NaCl on a composite nanofiber structure [13]

5. EXAMPLES OF APPLICATIONS USING NANOFIBERS

Nanowebs have been used in a variety of air filtration applications. This section will discuss some of the unique attributes of nanofibers through an examination of their performance in two different applications.

Pulse-Clean Cartridges for Dust Collection Applications

An attribute of nanofiber media that has not been modeled is dust cake release, or “self-cleanability”. An experiment was completed to investigate the self-cleanability of nanofiber media. This experiment was designed to emulate a pulse-cleaned cartridge dust collector application. Dust collectors are commonly used in industrial environments where airborne particulate matter needs to be removed to protect people or processes. Some common applications for dust collectors are woodworking, sanding, painting, welding, and grinding operations.

A cartridge element test system was assembled and is shown schematically in Figure 10. Clean air enters the system through a HEPA filter, is combined with a dust stream, and is supplied through a series of ducts to the filter element. Filtered air then exits the test system through another HEPA filter and exhausts through a blower outlet. The ducts were specifically designed to provide airflow to the filter element with a uniform velocity profile. A compressed-air manifold and pulse valve allow pulse-cleaning of the filter element. Dust is fed into the system with a screw-type metering dust feeder. Dust that has been collected and pulse-cleaned from the filter element is recycled through the use of an air lock valve at the bottom of the filter element test chamber.

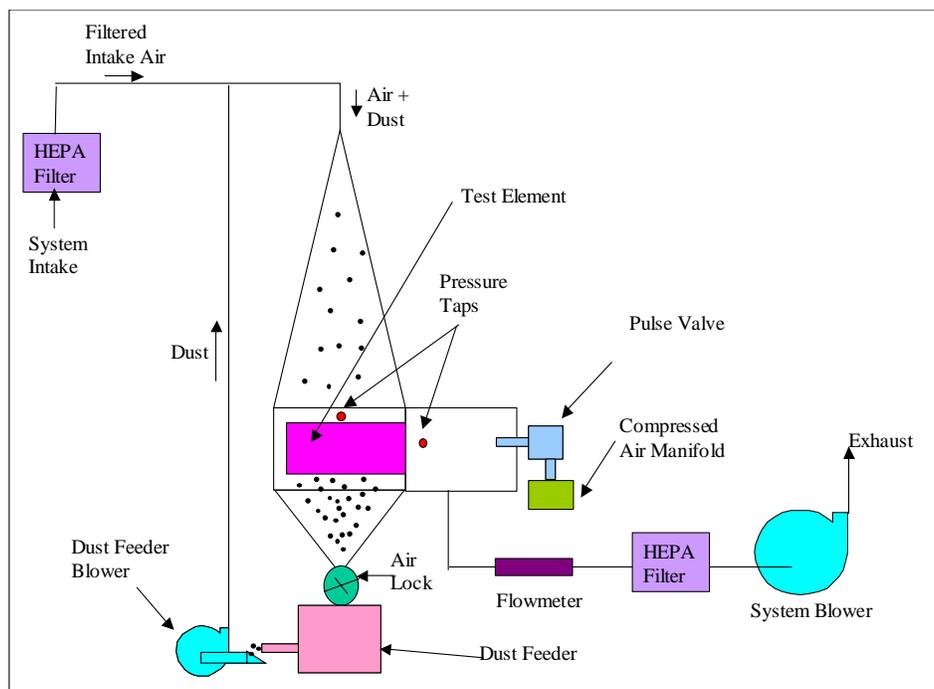


Figure 10: Schematic of pulse-clean test system

The air flow of this system was set to 890 ft³/min, which is approximately one to three times higher than a typical dust collection cartridge installation.

Atomite dust was chosen as the contaminant for this testing, which is manufactured by Imerys (France) and is commercially available from a number of sources including George C. Brandt Co. Atomite dust is a free-flowing calcium carbonate powder with an irregular shape. The size distribution of Atomite dust is shown in Figure 11. The dust feed rate was set to 10 grains/ft³ (0.65 grams/ft³), which is 5-10 times higher than the dust concentration of a typical dust collection cartridge application.

Particle Size, microns	Percent by Weight
< 1.0	25%
1.0 – 2.5	25%
2.5 – 5.0	30%
5.0 – 10.0	18%
10.0 – 15.0	2%

Figure 11: Atomite particle size distribution [1]

The system was set up to pulse every 10 seconds for a 10 millisecond duration at a manifold pressure of 70 psig. This pulse signature was used to simulate the pulse in a typical cartridge-style dust collector.

Cylindrical cartridge filters typical of the industrial dust collection industry were fabricated with a diameter of 13.84 inches and a height of 26.00 inches. At a pleat height of two inches, this configuration incorporated 254 square feet of media. These cartridges were then installed into a test system, as shown in the schematic in Figure 10.

Filters containing three different media varieties were tested: a cellulose media, a cellulose/synthetic blended media, and a cellulose media with a nanofiber treatment. Specifications for the three media varieties are shown in Figure 12. The resulting pressure drop data is presented in Figure 13. The nanofiber/cellulose composite media maintains a lower pressure drop as compared to the other two media varieties tested. As dust collection cartridges are typically changed when a terminal (maximum) pressure drop is reached, the lower pressure drop of the composite media defines a longer service life. Filters utilizing this kind of media have been installed in many pulse-clean dust collection applications and have anecdotally confirmed the empirical lab data shared here.

	Basis Weight	Permeability	Thickness
Cellulose	70 lb/3000 ft ²	13 ft/min at 0.5 in w.g.	0.012"
Cellulose/ Synthetic Blend	94 lb/3000 ft ²	14 ft/min at 0.5 in w.g.	0.013"
Cellulose + Nanofibers	70 lb/3000 ft ²	14 ft/min at 0.5 in w.g.	0.011"

Figure 12: Media specifications for pulse-clean testing

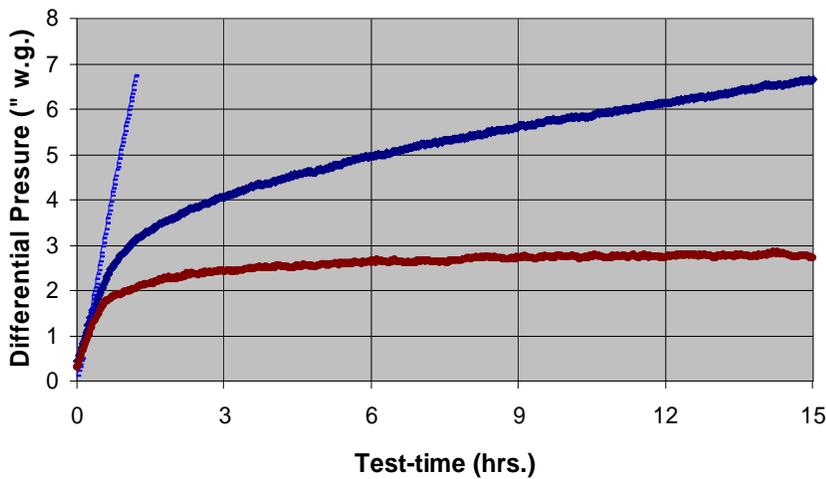


Figure 13: Pressure drop as a function of time (loading) for three different filter media in pulse-clean testing

Nanofiber Filter Media in Cabin Air Filtration of Mining Vehicles

Airborne contamination in the personnel cabins of mining equipment is of concern to mining workers, mining companies and government agencies such as the Mine Safety and Health Association (MSHA). Recent work with mining equipment manufacturers and the MSHA has shown that nanofiber filter media can further reduce cabin dust concentration compared to standard (cellulose) filter media [7, 10].

Two gravimetric particle sampling devices were used on a Caterpillar 992G wheel loader, one placed just inside the cab and the other just outside the cab, both very near the cab fresh air filter. The performance of standard cellulose intake and recirculation filters were compared with composite cellulose/nanofiber intake and recirculation filters on subsequent days in August, 1998 at Kaufman North Pit in Clearfield County, Pennsylvania. Filter media specifications are shown

in Figure 14. Results of the study are shown in Figure 15. It can be seen that a significant increase in filter efficiency was observed with the installation of the composite filters, thus providing an improvement in worker protection.

	Basis Weight	Permeability	Thickness
Cellulose	67 lb/3000 ft ²	58 ft/min at 0.5 in w.g.	0.013"
Cellulose + Nanofibers	67 lb/3000 ft ²	40 ft/min at 0.5 in w.g.	0.013"

Figure 14: Media specifications for mining cab study

Filter	Outside Dust mg/m ³	Inside Dust mg/m ³	Dust Reduction %
Cellulose			
Submicron	0.031	0.010	68%
Respirable	0.441	0.060	86%
Cellulose + Nanofibers			
Submicron	0.037	0.003	92%
Respirable	0.361	0.025	93%

Figure 15: Filter performance comparison in 992G wheel loader cab [7, 10]

Evaluation of filter life in a field application can be challenging due to the changing external environment and the influence of environmental factors on filter loading (dust concentration and particle size distribution, relative humidity, temperature). To compare the filter life of a cellulose filter to a cellulose/nanofiber composite, a laboratory test system was used. A schematic of the test system is shown in Figure 16.

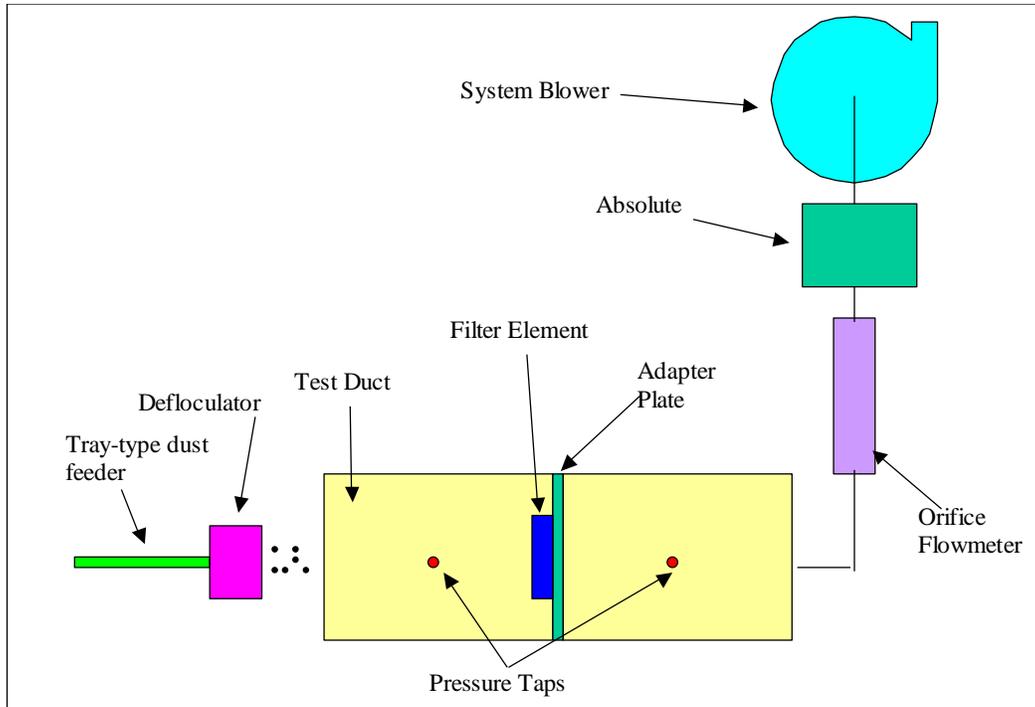


Figure 16: Laboratory test system schematic for mining cab filter loading tests

Panel filters were constructed to the same dimensions as those used in the field test: 26.12" x 5.37" x 2.19", containing 186 two-inch deep pleats. Four filters were tested, two containing the standard media and two with the high efficiency nanofiber media.

SAE Fine dust was fed at a rate of 2.1 g/min to each filter element. The air flow rate was set to 75 cfm. Pressure drop data as a function of the amount of dust fed was recorded, and is presented in Figure 17. Testing was terminated when the pressure drop of the filter element exceeded 1.5" w.g., which is the pressure drop at which mining cab filters are typically changed or cleaned. It can be seen that the increase in particle removal efficiency detailed in Figure 15 was achieved without a corresponding decrease in filter life or significant increase in initial pressure drop. Anecdotal evidence from field trials supports the data presented here.

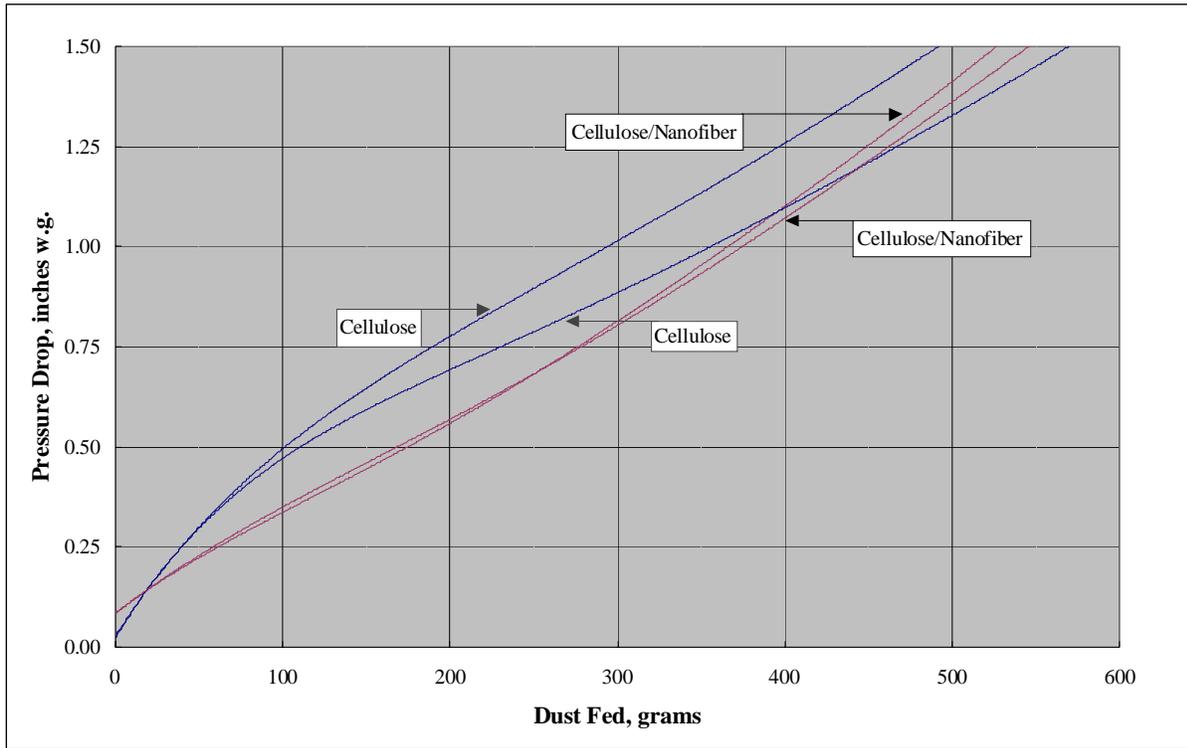


Figure 17: Laboratory results for mining cab filter loading tests

6. CONCLUSION

The theoretical and practical benefits of using nanofibers in composite filter media have been explored, and a method for making nanofibers has been discussed. Nanofibers can provide an improvement in filter efficiency without a substantial increase in filter pressure drop. They have proven to enhance the life of filters in pulse-clean cartridge applications for dust collection, and increase the efficiency of air filters for personnel cabins of mining vehicles.

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