Electrospun Nanofibers for Highly Efficient Air Filter Applications

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This article will discuss the technical aspects of polymeric nanofibers and their suitability as synthetic materials utilized for air filters. This paper will include an archival research review of producing nanofibers via electrospinning and their properties that incorporate high efficiency for particulate air filtration, which shows potential for industrial use. Finally, we will delve into the commercial large-scale process of synthesizing these filters with Inovenso electrospinning technology.

1 Introduction to Nanofibers

Nanofibers are a form of nanomaterial that can be depicted as long cylindrical bodies with diameters in the sub-micron range. Nanofibers have gained a lot of traction due to their novel and intricate abilities and due to the increased development of research in electrospinning.

There are many properties of nanofibers that attract researchers. Among the most common are extremely fine fiber diameter size, high surface area to volume ratio, and controllable porosity [1]. All of the aforementioned properties are what make nanofibers appropriate for air filtration usage. Nanofibers are also used in industries such as biomedical, HVAC (Heating Ventilation, and Air Conditioning) cosmetics, defense, and energy applications. However, we will only focus on air filtration in this article. A layer of nanofibers possessing mi-nute diameter sizes below 1 micron can act as a sieve for straining particulate matter (PM) that are of similar small sizes. High surface area to volume ratio denotes that the nanofiber layers can be of light-weight and can provide numerous contact points for a large number of particles in the air stream. Controlling the porosity of the nanofiber mesh plays a huge role for the permeability of air particles and prevention of undesirable PMs such as dust, pollen, or even bacteria. As a result, these properties allow nanofibers to be a model specimen for air filtration theory.

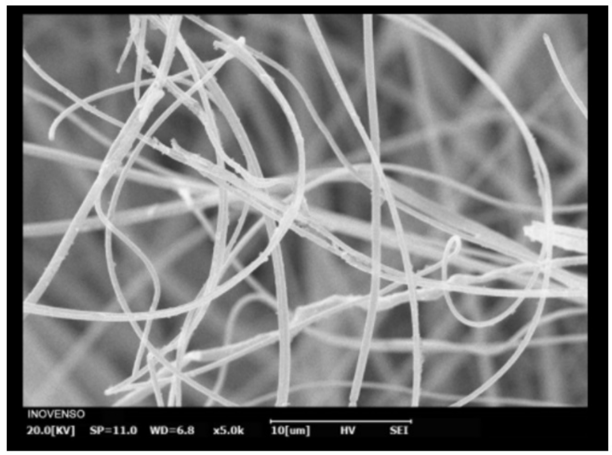


Fig. 1. Scanning Electron Microscopy image of Nanofibers.

2 Electrospinning: Fabrication of Nanofibers

Whilst there are a number of ways to produce nanofibers, electrospinning is the most popular and robust technique. It is essentially an electro-hydrodynamic process where polymeric solutions are influenced under high voltage (typically in range of several kV) and consequently accumulate charge. These highly charged and energetic solutions are dispersed out of a needle/nozzle orifice in a cone shape (this is known as the Taylor cone), and then proceed to form strands of jets. These jets traject towards an electrode of the opposite charge or of neutral charge.

As the strand of jets move towards the target electrode, they are stretched and become thinner and thinner. The trajectory produces somewhat of a 'whipping' motion. This is because of charge repulsion in the jet stream being introduced aerodynamically. The jets solidify while being attracted towards the oppositely/neutrally charged target electrode. The end-product of this process is a mesh of nanofibers deposited on the target electrode. This mesh is actually a network of many nanofibers randomly oriented

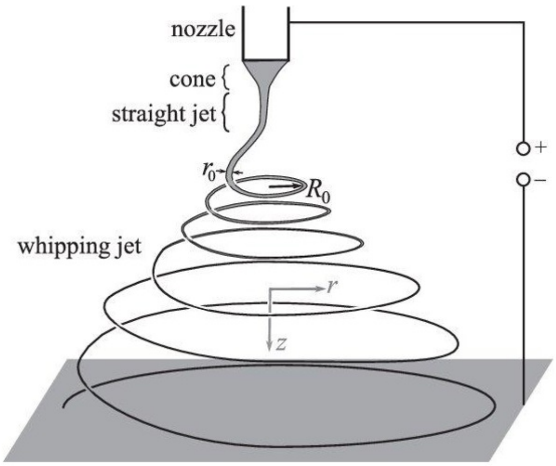


Fig. 2. Diagram showcasing the electrospinning mechanism. Ref image from [2]

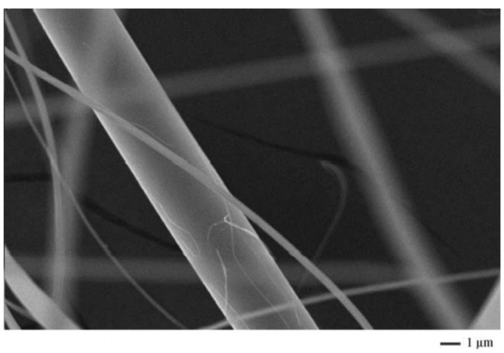


Fig. 3. The larger strands are commercial glass fibers being compared with the smaller electrospun polystyrene nanofibers . Original image taken from [1]

with a particular thickness and porosity that can act as a filter layer. If observed under an SEM, the nanofiber layers will show resemblance to the SEM images of glass fibers that are used in conventional HEPA filters albeit smaller. Electrospinning remains a highly popular technique due to the fact that several characteristics of nanofibers can be controlled by changing crucial parameters of the process, such as the high voltage between the electrodes, the rate at which the solution is being fed into the system, and distance between the electrodes.

3 Air Filtration Theory

Air filtration theory dictates several mechanisms that explain how particulate matter is filtered. Among them, four major mechanisms responsible for air filtration are; diffusion, inertial impact, interception, and electrostatic attraction. Diffusion occurs during filtration when a small particle diffuses into the vicinity of the fiber and does not advance

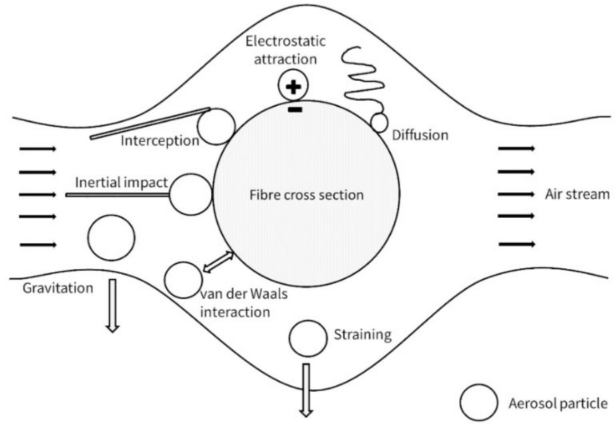


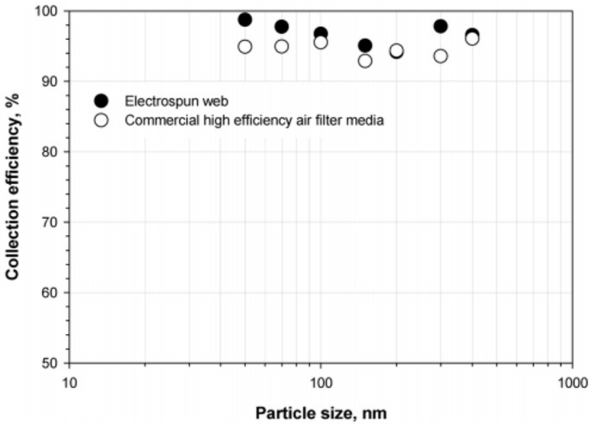
Fig. 4. Overview of several Air filtration mechanisms on cross-section (aerial view) of a single nanofiber strand Ref image from [4]

forward. Inertial impact is when the particle lands directly right into a fiber. Interception mechanism occurs when a particle is in a flow but comes in physical contact with a fiber, causing it to slow down and stop. Electrostatic attraction is different from the mechanical mechanisms as charged fibers attract PMs electrostatically.

In commercial air filters, PMs are generally stopped by electrostatic attraction of the fibers. These filters are made with the standard charged glass fibers. Although efficient, these fibers rely more on electrostatic attraction as their fiber diameter is larger than nanofibers. This is a downside from using glass microfibers, as electrostatic charge decreases over time. Nanofibers incorporate the mechanical filtration processes mentioned above and can also be potentially charged via corona-charging for inducing electrostatic attraction capabilities as-well as shown by Leung and Sun [3].

3.1 Air Filtration

There are many types of air filters. They can be categorized as coarse, fine, or highly efficient. Coarse filters are designed for filtering large objects such as sand or hair, while fine and highly efficient filters are designed for smaller PMs. However, highly efficient filters namely the HEPA and ULPA filters have an efficiency of over 99 %. High efficiency comes at the cost of higher pressure drop. It is essential for an air filter with good filtration efficiency to have minimum pressure drop. Common air filters are comprised of either glass fiber media or synthetic fiber media. Glass fibers are made by the pultrusion method, where silica glass is melted and pulled out as continuous filaments of fiber. The synthetic fiber material is usually poly-propylene melt blown into fibers. Both methods produce fibers in the micron scale, however nanofibers can be used as a filter media for the same purpose.



Comparison of collection efficiency of an electrospun web manufactured at 50 kV and 50 RPM with a commercial high efficiency air filter media.

Fig. 5. Filtration comparison of PA 6,6 with a glass fiber air filter over a range of different particle sizes [5]

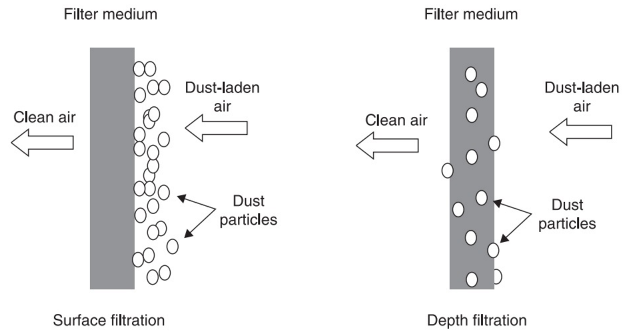


Fig. 6. Surface and depth loading filtration comparison [7].

3.2 Nanofiber Filtration Media

Nanofibers are considered to be the key materials for the next generation of industry standard filtration medias. Multinational companies such as Donaldson and Parker Hannifin are manufacturing filters with nanofibers. The reason for such attention in the market is because nanofibers display a handful of advantages over conventional filter material.

3.2.1 Lower Fiber Diameter

As mentioned prior, nanofibers have very small diameters, this property indicates advanced fiber filtration, which means high efficiency of mechanically capturing unwanted particles and allowing clean air to pass through. Traditional meltblown synthetic materials or fiber glass materials tend to be larger. In a study conducted by Park and Ok from the Korea institute of Energy Research, they tested and compared the filtration efficiency of a commercial high efficiency filter with an electrospun nylon 6,6 sample and found that the electrospun fibers showed overall greater performance [5].

3.2.2 Lower Pressure Drop

In air filters, the pressure drop should not be too high as when these filters are placed into HVAC systems they need to be energy efficient so that the ventilation does not require high power to operate and push air through. What causes the pressure to drop as the air stream enters and exits the filter is actually the air molecules bombarding the fibers as they move past the filter. These air molecules lose momentum which in turn reduces air flow resulting in a decrease of pressure.

Nanofibers have the benefit of following the slip flow regime when air passes through. To elaborate, air molecules impact the nanofibers at less constancy (larger slip flow) due to their small fiber diameter size. When the air molecules do come in contact they retain most of their velocity resulting in less hindrance to the air flow and lower pressure drop [6].

3.2.3 Longer Filter Life

In regular filter media, captured particles seep into the pores of the filter layer. These particles block the pores which cannot be easily cleaned and because of the blockage the pressure drop will increase to a degree that the ventilation system will require higher power for circulating air. Thus rendering the filter to be highly inefficient over time and needing to be replaced. This is known as depth loading, when penetrating particles load into the filter [7].

Generally, nanofibers need to be placed on substrates, e.g non-woven media, as they tend to be soft and require a support layer. Since the nanofiber layer is on top of the support layer, the captured particles like dust pile up on the surface and can be cleaned via backward pulse or by simple dusting. The filters can then be re-used. This is known as surface loading where the unwanted particles accumulate on the surface. As nanofiber filters do not have depth loading, they tend to be usable for a longer period of time.

3.2.4 Potential Modifications

Electrospun nanofibers can be post-treated or customized to add potential functional properties to air filters. For example, electrospinning nanofibers with silver nanoparticles may introduce air filters to have an antimicrobial layer that can not just capture but help kill bacteria and viruses. The electrospinning solution can be altered with other additives or the process can be advanced in way to add new features to the nanofiber filters, such as the adsorption of Volatile Organic Compounds (VOCs) for removing odors which is same application as active carbon filters [8][9].

4 Large-Scale Electrospinning of Nanofibers

One major obstacle that is present with manufacturing via electrospinning is the overall low throughput of nanofibers. Traditional electrospinning has a low production rate as fiber jets emit out of a needle from a small orifice. Consequently materials produced by electrospinning can be

Fig. 7. Top image: Display of the NS 416 Industrial Machine Bottom image: A rod showcasing electrospinning.

difficult to mass-produce at an industrial scale. Inovenso (Istanbul, Turkey) has designed a patented hybrid electrospinning technology that can produce electrospun nanofiber media at a large scale while retaining high quality fibers with small diameter sizes.

The industrial scale machine is a multi-nozzle system, where each nozzle has a unique reservoir-base design that has production rate four times that of the normal needle. The nanofibers are collected on a non-woven substrate in a roll-to-roll system that can run in shifts. The NS 416 machine nanospinner can be seen in figure 6, there are 4 rods with 51 nozzles on each rod. The nozzles on the rod disperse the jet solution onto the substrates. With the right substrate, nanofiber layer, and optimized recipes, electrospun air filter media can be mass-produced.

5 Summary and Conclusions

Nanofibers can be made via electrospinning. Nanofiber structures show appealing properties such as small fiber diameter, high surface area to volume ratio, and porosity. All of these characteristics lead nanofibers to be the suitable candidate for use as the media for air filters. Companies such as Donaldson and Parker Hannifin currently produce such nanofiber products. Nanofiber filters have potential advantages over the conventional filter media, such as high efficacy of mechanical filtration, lower pressure drop due to slip-flow, longer filter life because of surface loading, and the ability to modify and add functional properties like antimicrobial layers.

6 References

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