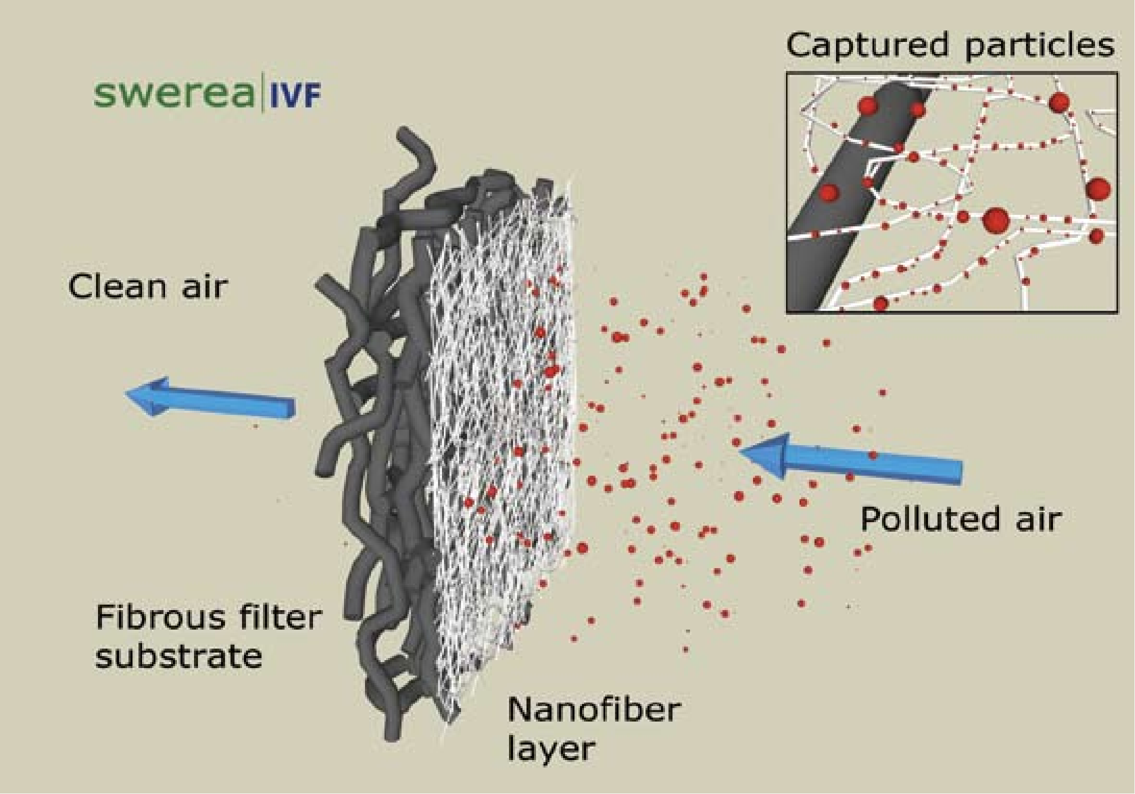

Figure 1. Schematic illustration of nanofiber air filtration. Air polluted with small particles which are efficiently stopped due to the large surface area of the nanofiber layer. Inset: Particles that are much smaller than the pores of the filter are attracted to and captured on the surface of the fibers.

Nanofibers – small fibers with big potential

Jonas Engström, Anna Thorvaldsson, Bengt Hagström, Pernilla Walkenström, Swerea IVF AB

www.swereaivf.se

Jonas Engström
Senior scientist at Swerea IVF. Finished his PhD in 2006 with a thesis titled "Functional compolymers of polyvinylpyrrolidone". Has since then worked with electrospinning and crosslinking of polymers. Expert on material science with a specialization in polymer organic chemistry.

Anna Thorvaldsson
PhD-student at Swerea IVF. Finished her Master of Science in biotechnology in spring 2006. The studies focused on biopolymers (DA-work) and molecular biology. Has thereafter worked with electrospinning of nanofibers for biomedical applications.

Bengt Hagström
PhD in Mechanical Engineering. Expert on polymer processing, polymer melt rheology and melt spinning of fibers. Manager of the Functional Fibers group at Swerea IVF.

Pernilla Walkenström
Adjunct professor in Textile Technology at University College of Borås, The Swedish School of Textiles. Manager at Textiles and Plastics department, Swerea IVF. Finished her PhD 1996, focusing on "Phase distribution of mixed biopolymer gels in relation to process conditions". Has since then worked with biopolymers, gel formation phenomena, followed by fiber spinning processes.

Introduction

Nanofibers prepared by electrospinning are polymer filaments with diameters ranging from several micrometers to a few nanometers. The thin diameters of such fibers give them a very high surface-to-volume ratio, a property that makes them ideal for producing very porous materials with a number of potential application areas.

In lab-scale electrospinning, a polymer solution is typically placed in a syringe and subjected to a strong electric field between the needle tip and a collector. If the electric field strength is sufficient, it will deform the pendant drop at the tip of the needle enough to eject a jet of solution which will travel towards the collector. On its way towards the collector, the jet will stretch immensely. Simultaneously, the solvent will evaporate, leaving a porous nonwoven sheet of very thin polymer fibers on the collector surface.

A broad division of the application areas for nanofibers is Bioengineering, Environmental Engineering & Biotechnology, Energy & Electronics, and Defense & Security.[1] To review all of these areas would be a vast undertaking that could fill a complete journal issue of its own. This report will give an introduction to the research on nanofibers in technical textile applications, which are part of the work at Swerea IVF, namely nanofibers in air filtration, sound absorption, tissue engineering, and wound care. A separate article will describe our research on large-scale production of nanofibers.

Nanofibers in air filtration

Air filters are commonly misunderstood as functioning solely by sieving particles from the air stream. However, the sieving mechanism is only one of several mechanisms involved in the capturing of particles from the air stream. In fact, particles that are much smaller than the pores of the filter are captured on the surface of fibers as shown in the inset in Figure 1.

For nanometer-scale fibers, the air velocity at the fiber surface is not zero which causes the air to "slip" at the fiber surface. This effect decreases the drag force on each fiber, which in turn lowers the pressure drop over the filter. Furthermore, the slip flow makes the portion of air passing near the fiber surface large, resulting in more particles passing near the fiber surface and thus to be captured. In other words, the nanofibers increase the efficiency of the air filter without requiring more energy for pushing the air through the filter. Diagram 1 below shows this increased efficiency for a filter substrate (class F5) covered with nanofibers.

As can be seen in Diagram 1, a nanofiber layer (~1 g/m^2, blue curve) increases the particle retention efficiency of an F5 substrate (pink curve) to a level that surpasses a filter of class F9 (red curve). Still, the pressure drop is merely increased from 44 Pa to 84 Pa, which is only half of the pressure drop for the corresponding F9 substrate (164 Pa). Obviously, the possibility of increasing filter efficiency in this way could be of enormous benefit for the society. Today, research in this area is focused on the development of large-scale production of nanofibers and ways to overcome the low mechanical strength of the nanofibers. Another issue is the adhesion of the nanofibers to the substrate which is often insufficient for many filter applications.

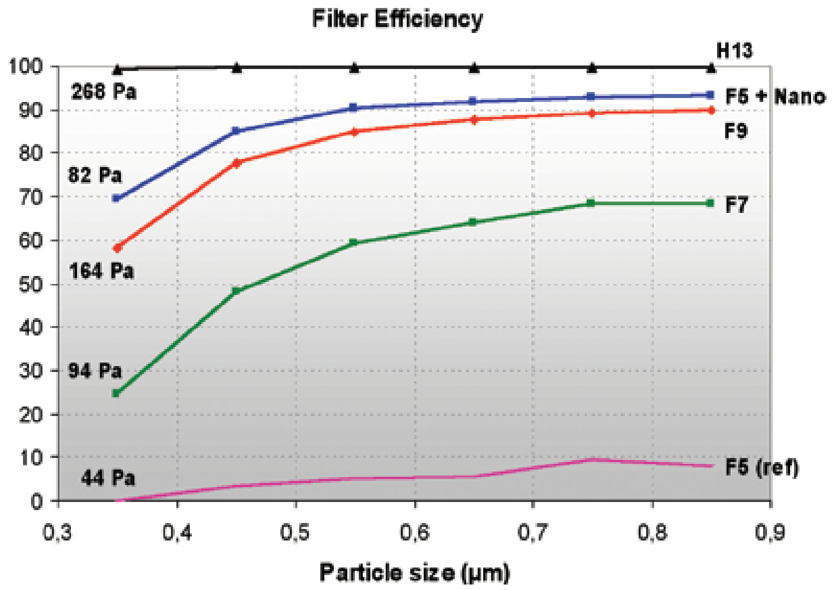

Diagram 1. Particle retention and pressure drops for various filter substrates. F5 (ref), F7 and F9 = Filter substrates of filter class F5, F7, and F9 respectively; F5 + Nano = filter substrate of filter class F5 with a layer of nanofibers; H13 = filter substrate of class HEPA 13 (high efficiency particulate air [filter]).

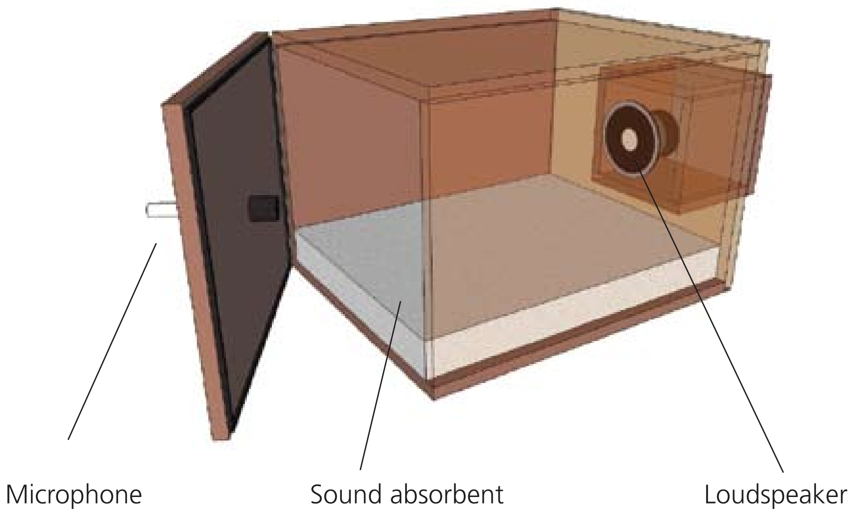

Figure 2. Analysis equipment constructed for quick and cheap qualitative evaluation of sound absorbing properties for thermobonded nonwovens (as shown) and woven fabrics (measured when hanging on a metal rod).

Nanofibers in sound absorption

Environmental noise from sources such as traffic, industries, construction and public work, as well as noise from indoor sources like ventilation systems and office machines, is an ever growing problem to human health. Not only can noise cause hearing impairment, sleeping disorder and stress, it can also reduce learning ability and performance capacity. One way of dealing with this problem is to use sound absorbents near the source of noise or in the premises where people reside in order to create a suitable acoustic environment. Research has shown that nanofibers have very attractive sound absorption properties. Sound absorbents based on nanofibers can have a higher absorption factor compared to traditional absorbents. However, the acoustic mechanism responsible for this effect is not fully understood. During 2008, Swerea IVF administered a project in collaboration with three Swedish companies to investigate the use of nanofibers in sound absorbents. The aim of the project was to enhance the companies' existing sound absorbents (thermobonded nonwovens or woven fabrics) by integration with electrospun nanofibers. In this project, a tool was needed to determine what properties of existing absorbents would be appropriate for use in conjunction with nanofibers. Therefore, customized analysis equipment was constructed as shown in Figure 2.

This equipment provided a quick and cheap method for selecting suitable absorbents for nanofiber deposition. In each measurement a loudspeaker connected to an mp3-player played 50 seconds of white noise. Simultaneously, a microphone connected to a sound card and a computer recorded the sound. Different absorbents were compared qualitatively by comparing the difference in sound pressure level within the empty box and the corresponding level with an absorbent placed inside the box (see Figure 2). Further analyses of the acoustical characteristics for these absorbents were performed according to standardized procedure at SP Technical Research Institute of Sweden. Diagram 2 shows typical measurement results obtained from the analysis equipment that was constructed within the project. A good sound absorbent will lower the sound pressure level and thus show large negative numbers. A thermobonded nonwoven material covered with a layer of nanofibers curve below the corresponding curve for a substrate without nanofibers.

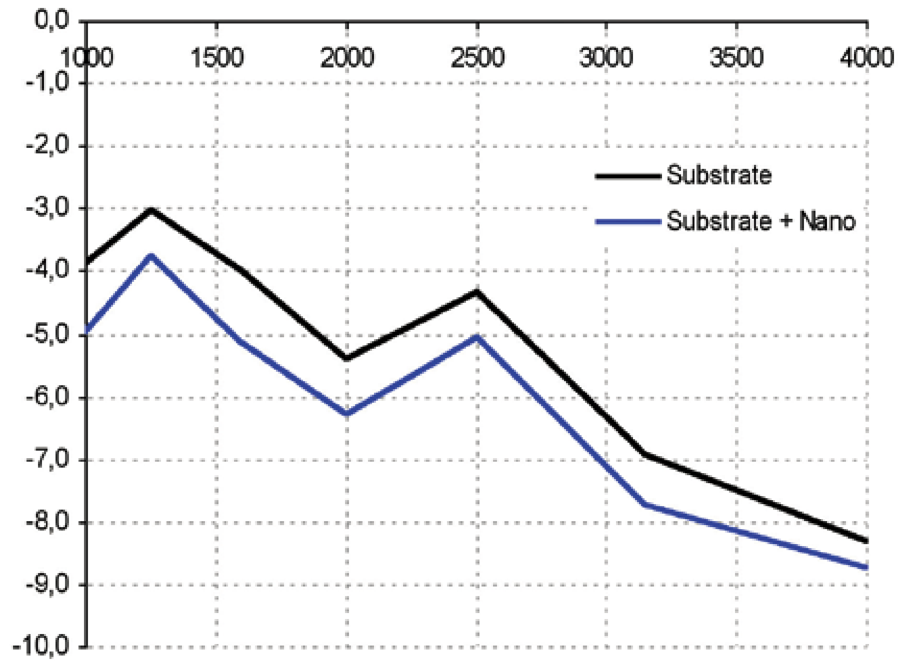

Diagram 2. Typical measurement results for a thermobonded nonwoven absorbent (Substrate) and the corresponding substrate covered with a layer of nanofibers (Substrate + Nano).

Results from the corresponding measurements on woven fabrics with or without nanofibers showed the same tendencies.
As can be seen from the discussion above, the use of nanofibers in sound absorbents is very promising. Still, further research on the fundamental mechanisms responsible for the enhanced sound absorption of nanofibers is needed.

Nanofibers in tissue engineering

Tissue engineering is the re-growing of body tissues and organs and a field with intense research mainly driven by shortage of organ donors. For successful creation of new organs, suitable cells and nutrients for the cells are crucial and represent entire research areas in themselves. The activities of Swerea IVF in tissue engineering focus on developing new scaffolds which are needed to provide the cells with a surface that can support and promote cell growth. In the human body this function is provided by the extracellular matrix.

The main advantage of electrospun nanofibrous scaffolds in tissue engineering applications is their body-mimicking structure, i.e. the resemblance between the electrospun nanofibers and the extracellular matrix.[2,3] Furthermore, the large surface area of the nanofibers enables efficient functionalization, e.g. surface modifications or incorporation of particles such as growth factors, drugs or other biomolecules.[2] Also, electrospinning is a flexible method allowing close control of the morphology of fibers and scaffolds using parameters such as electric field strength, polymer feed rate, polymer concentration, etc.[2,3] This is especially useful in tissue engineering as different cells have different requirements on their environment for optimal growth.

Many studies indicate that cell adhesion and proliferation is enhanced on nanofibers compared to microfibers. However, there are disadvantages of electrospun scaffolds as they generally have small pore size and limited porosity.[2] The porosity of an electrospun scaffold is normally 70-80%. This is most often not enough for adequate cellular infiltration into the three-dimensional scaffold as the pore size required for cellular infiltration is usually at least in the order of a cell, i.e. about 10µm. Often even larger pores, up to several hundred micrometers, are required.[2,3,4] Using porogens (e.g. salt or wax particles) or blowing agents are two ways of increasing the scaffold porosity. However, these methods can cause problems with interconnectivity of the pores and collapse of the structures upon extraction of the particles. In recent years it has been seen that mixing nano- and microfibers is a viable option for increasing the scaffold porosity.[2,5,6] The microfibers then provide a porous structure while at the same time the benefits of the nanofibers can be efficiently utilized.

A new way of creating highly porous scaffolds with a combination of nano- and microfibers has been developed at Swerea IVF and is based on electrospinning nanofibers onto single microfibers (Figure 3).[6] The nanofibers are then present to enhance cell adhesion and spreading, although by collecting them on a microfiber they can easily be formed into any shape, size, and most importantly, into scaffolds of any porosity.

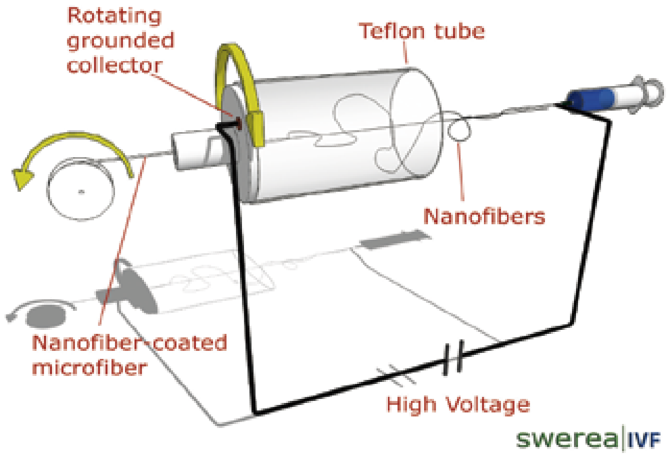

Figure 3. Electrospinning of nanofiber-coated microfibers

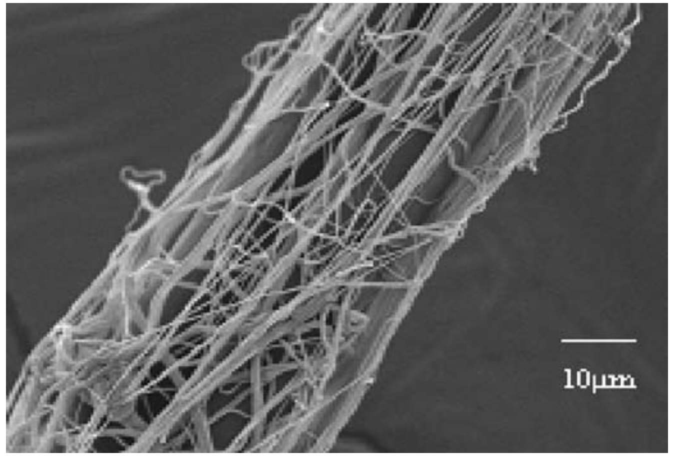

Figure 4. Nanofiber-coated microfiber

The nanofiber-coating can be obtained by using a grounded collector rotating around the microfiber, as illustrated in Figure 3. As the collector rotates the electric field follows, hence forcing the nanofibers to collide with, and be collected upon, the microfiber. The result is a microfiber coated with nanofibers, as seen in Figure 4. The nanofiber-coated microfiber can then be formed into scaffolds of any size, shape and porosity.

In collaboration with Chalmers University of Technology and the Sahlgrenska University Hospital, scaffolds of 95-97% porosity were electrospun and a preliminary cell study with chondrocytes was carried out to investigate the infiltration of cells into the scaffolds.[6] The results showed greatly enhanced cellular infiltration in scaffolds of nanofiber-coated microfibers compared to scaffolds of only nanofibers. Furthermore, the study showed that the porosity of the scaffolds containing nanofiber-coated microfibers could be carefully tailored, important for creation of optimized scaffolds to be used in tissue engineering applications.

The research in the area of tissue engineering is intense and a lot of progress has been made in the last couple of years. However, there are still many obstacles to overcome before tissue engineered products can be regularly found on the market and being routinely used in patient care.

Nanofibers in wound care

The body-mimicking structure of electrospun matrices can be utilized not only in tissue engineering, but also in wound care applications to improve the healing of a wound as it promotes the re-growth of tissue.[2] Incorporation of drugs or bioactive molecules is also important in this context.[7] Depending on the morphology of the fibers and the choice of material the degradation behaviour of the fibers, and thereby the drug release, can be modified.[7] A sustained controlled release is usually beneficial in wound care as it limits or prevents the initial burst effect seen in traditional injection of drugs. Also, incorporating the drug into a fiber matrix allows a very specific and local delivery of the drug, decreasing the amount of drug required for desired effect.

Using biodegradable nanofiber matrices adds an additional benefit to electrospun wound care products since removal (sometimes painful) of the product is unnecessary. By choosing an appropriate material the nanofibers allow the healing to occur, while at the same time degrading and leaving behind only waste compounds that the body can take care of by natural means.[2,7]

References

1.
Ramakrishna, S., *An Introduction to Electrospinning and Nanofibers; World Scientific*, 2005.

2.
Boudriot, U.; Dersch, R.; Greiner, A.; Wendorff, J. H., *Artificial Organs 30*, 785, 2006.

3.
Matthews, J. A.; Wnek, G. E.; Simpson, D. G.; Bowlin, G. L., *Biomacromolecules 3*, 232, 2002.

4.
Telemeco, T. A.; Ayres, C.; Bowlin, G. L.; Wnek, G. E.; Boland, E. D.; Cohen, N.; Baumgarten, C. M.; Mathews, J.; Simpson, D. G., *Acta Biomater 1*, 377, 2005.

5.
Pham, Q. P.; Sharma, U.; Mikos, A. G., *Biomacromolecules 7*, 2796, 2006.

6.
Thorvaldsson, A.; Stenhamre, H.; Gatenholm, P.; Walkenstrom, P., *Biomacromolecules 9*, 1044, 2008.

7.
Cui, W.; Li, X.; Zhu, X.; Yu, G.; Zhou, S.; Weng, J., *Biomacromolecules 7*, 1623, 2006.