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Electrospun Nanofibers for Air Filtration Applications

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Abstract

Activated carbon and fiberglass are widely used in air filtration industry. Nanotechnology field is booming in an exceptionally impressive manner. Nanofibers are one of the unique materials which have one order of magnitude smaller than conventional fibers. The high surface-to-volume ratio, low resistance and enhanced filtration performance make nanofibers an attractive material for many applications such as healthcare, energy and air filtration. Recent advancements in the removal of volatile organic compounds (VOC), nanoparticles and airborne bacterial contaminates in the air are highlighted. The aerosol filtration performances of nanofibers are also presented. The enhanced activity of nanofibers due to the nanosize and their applications such as in protective clothing are highlighted.

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Keywords: Nanofibers; Nanotechnology; Air Filtration; aerosol removal; Protective Clothing Applications

1. Introduction

In the air filtration applications, activated carbon and fibreglass are widely used due to their many potential advantages. Activated carbon is used to remove toxic chemicals through adsorption process, whereas high efficiency particulate air (HEPA) filters are used to filter particles such as lint and other debris from the air. Recently, nanotechnology field created high impact in various fields such as healthcare, energy and environment [1-3]. Some of the nanotechnology products are already commercially applied to use in products such as coatings, sportswear, automotive, sunscreens and textiles. Among the nanotechnology products, nanofibers are one of the unique materials which have been studied as such or in combination with other materials such as textiles and fibreglass [4]. The potential exploration of nanofibers in various fields such as air filtration and protective clothing applications are presented.

2. Applications of Electrospun Nanofibers

2.1. Electrospun nanofibers for the removal of volatile organic compounds

Electrospun nanofibers have been explored for the adsorption of volatile organic compounds (VOC) present in the air by various authors [5-7]. Scholten et al reported that adsorption and desorption of VOC by electrospun nanofibrous membranes

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(ENMs) (Fig. 1) were faster than conventional activated carbon [5]. Cyclodextrins have the ability to form non-covalent host–guest inclusion complexes (CD-IC) with various molecules such as hazardous chemicals and polluting substances. They have been incorporated into poly(methyl methacrylate) PMMA ENMs by Uyar et al and demonstrated that VOC such as aniline, styrene and toluene can be removed [6]. ENMs have also been explored for the adsorption of VOCs in the bio-treatment sewage by Xu et al [7].

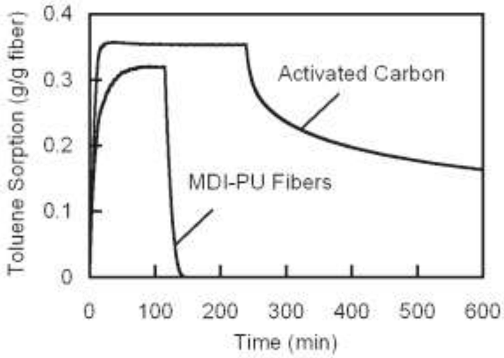

Fig.1. Differing sorption and desorption behavior of toluene with activated carbon and MDI-based PU ENMs at 25 °C. Reproduced with Permission from [5] ACS.

2.2. Filtration Performance of nanofibers

In the conventional HEP) filters, according to filtration theory, non-slip flow is the dominant mechanism. However, when the nanofibrous layer is coated on the conventional filter (Fig. 2), the slip flow mechanism becomes dominant due to the smaller fiber size ability to disturb the air flow [8]. As can be seen from Fig.3a, depth filtration is taking place on the conventional filter media (dust loading), whereas surface loading of dust particles (Fig. 3b) is taking place on the nanofiber coated on conventional filter [8].

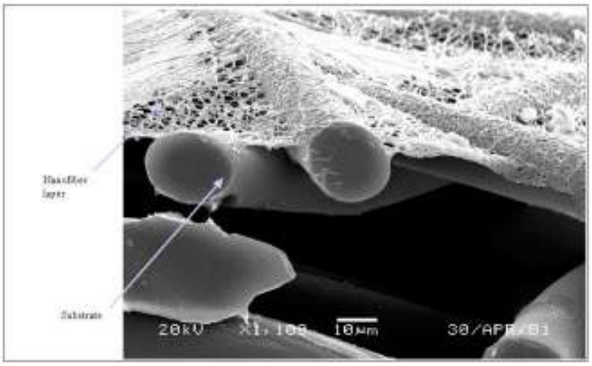

Fig. 2. Electrospun Nanofibers on a polyester substrate Reproduced with Permission from [8] .

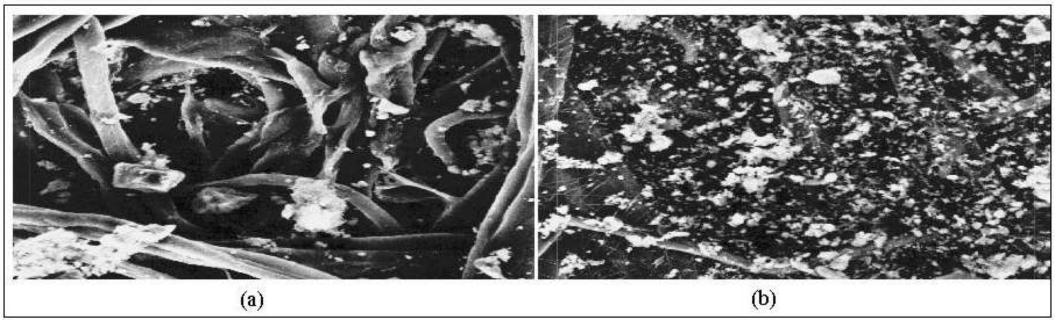

Fig.3. ISO Fine dust loading on (a) cellulose and (b) cellulose/nanofiber composite. Reproduced with Permission from [8].

Fractional efficiency of nanofibrous and micron filters against the aerosol particle diameters between 10–500 nm were determined by Podgorski et al [9] . The fiber diameters of the filter 1,2,3, and 4 are 10µm, 2 µm, 700 nm and 100 nm, respectively. The most penetrating particle sizes (MPPS) determined for filter 1,2,3, and 4 were 366 nm, 199 nm, 140 nm, and 54 nm, respectively. Fig. 4 shows that decreasing the fiber diameter increases the fractional efficiency of the filter [9].

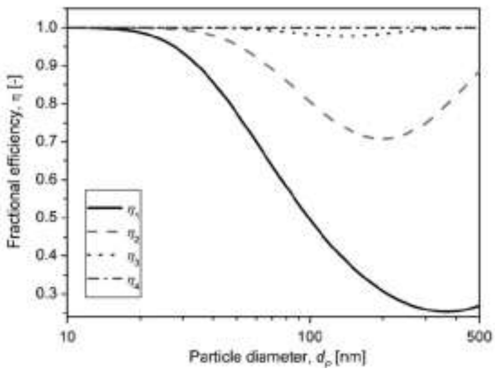

Fig. 4. Calculated fractional efficiency for four considered filters (η_1, η_2 η_3 η_4 represents the fractional efficiency of filter 1,2,3 and 4, respectively). Reprinted with permission from [9] Elsevier .

The effect of processing parameters on the fiber morphology and pore size distribution of the ENMs and their performances test by pressure drop and aerosol collection efficiency was evaluated by Park et al [10]. Recycling of polystyrene (from expanded polystyrene) for the purpose of nanofibers fabrication was carried out by Shin et al and nanofiber performance in the coalescence filtration of oil droplets from air was compared with HEPA filter performance [11]. Heikkila et al studied the optimum coating thickness of polyamide nanofibers required to improve the filtration efficiency. They reported an efficiency of over 95% (0.16 µm Particles) for 0.5 g/m^2 coating [12]. Electrospinning of chitosan and polycarbonate nanofibers by air blowing technique was carried out and air flow tests conducted for air filtration studies indicated that they can be potentially applied for air filtration applications [13-14].

Zhang et al have recently reported that one of the ways to compensate the inferior parts in nanofiber mat to preserve structural entity would be to stack multiple thin layers of nanofiber mats. They achieved enhanced quality factor for ENMs than the conventional HEPA filter and military standard filter [15]. Generally, handling and preserving structural integrity of ENMs are difficult as due to their delicacy in nature. Moreover, they tend to expose to various kinds of actions such as airflow, water flow and dust particle deposition. During such conditions, use of support layers is supposed to be a solution to overcome this issue. Patanaik et al fabricated composite media and reported that there were not much changes in filtration efficiency and pressure drop for the composite media after cyclic compression, whereas these changes were appreciable when deposited over nonwoven support [16].

Recently, electrostatic charging technologies have been studied to prepare filter media with more open structure resulting in lower pressure drops to achieve high efficiency of 99.97 % with energy savings, whereas in conventional high efficiency particulate air filters (HEPA), fine fiber diameter has been used at the expense of high pressure drops. Boehmite nanoparticles were incorporated into ENMs and studied as a new electret filter media by Yeom et al [17]. They showed that significant improvement in the electrostatic surface potential and submicron aerosol capture efficiency can be achieved without significant changes in the air flow resistance

Leung et al electrospun polyethylene oxide nanofibers with average diameter of 208 nm on micron sized filter. They reported that the MPPS (NaCl aerosol size ranging from 50 to 480 nm) decreased from 140 to 90 nm when nanofiber packing density was increased from 3.9 to 36×10^{-3}. They also reported that the filtration efficiency was decreased when face velocity was increased from 5 to 10 cms^{-1}. They also observed that nanofiber packing density have much effect on MPPS rather than nanofiber layer thickness [18]. Hung et al studied the effect of fiber diameter on capture efficiency and pressure drop. They observed that when fiber diameter was reduced from 185 to 94 nm, the filtration of 50–500 nm nano-aerosol can be achieved only with significant increase in the pressure drop. They also observed increased filtration efficiency when nanofiber basis weight (W) was increased from 0.042 to 0.333 gm^{-2} [19].

2.3. Removal of Nanoparticles in the air by ENMs

The nanofibers have the ability to capture very small nanoparticles in the air stream due to their efficient mechanism of Brownian diffusion and interception. Maze et al reported through simulation data that the filtration efficiency of the ENMs for nanoparticles can be improved by decreasing the fiber diameter and increasing the flow temperature of the air [20]. In another study, Wang et al compared the filtration of nanoparticles by nanofiber filters with conventional fiberglass filters. They demonstrated that the nanofiber filters have better figure of merit for particles larger than about 100 nm compared to conventional fiberglass filters, whereas nanofiber filters do not perform better than conventional fiberglass filters for particle sizes smaller than 100 nm [21]. Recently, tortuously structured polyvinyl chloride (PVC)/polyurethane (PU) ENMs with high abrasion resistance (134 cycles), comparable air permeability (154.1 mm/s), high filtration efficiency (99.5%), low pressure drop (144 Pa) performance (300–500 nm sodium chloride aerosol particles) and lightweight (less than 21 g/m^2) was reported by Wang et al [22].

2.4. Nanofibers in Protective Clothing (PC) Applications

Water vapour transport properties of ENMs were found to be comparable to textile materials and hence they can be applied in protective clothing applications. Although increased filtration efficiency for aerosol was observed for ENMs, relatively higher pressure drop was reported [23]. Reactive organic materials ((3-carboxy-4-iodosobenzyl) oxy-b-cyclodextrin) [24] and nanoparticles [25] have been incorporated into nanofibers by mixing with polymer solutions followed by simple electrospinning and tested for the decontamination of chemical warfare agents (CWA). The decontamination efficiency of such ENMs was found to be much higher than conventional activated charcoal. Simple mixing of nanoparticles into polymer solution led to the formation of nanoparticles aggregates and thereby catalytic activity was reduced. In order to overcome this problem, electrospraying technique was utilized to spray nanoparticles and was combined with electrospinning technique, whereby nanoparticles were made available on the nanofiber surfaces [26-27] by Sundarrajan et al. However, the nanoparticles on such nanofiber surfaces are not stable. Sundarrajan et al overcame this problem by electrospinning the polymers with functional groups such as poly(ethylene imine) and cellulose [28-29].

Facini et al explored nylon nanofibers as the potential candidate for the filtration of nanoparticles in protective clothing applications. A thin coating of nanofibers over textiles provided 80% retention of 20 nm nanoparticles and over 50% retention of 200nm size nanoparticles, which was further improved to 99 % efficiency by increasing the thickness of the nanofibers [30]. Electrospun nylon 6 nanofibers deposited over nylon/cotton woven fabric was evaluated for 300 nm NaCl particles filtration efficiency in PC applications by Zhang et al [31]. They achieved an efficiency of greater than 99.5% without sacrificing air permeability and pressure drop [31]. Electrospinning technique in combination with electrospraying has been utilized in water-soluble nanofilters to be used in the collection of biological micro- and nano-aerosols by Morozov et al [32].

2.5. Nanofibers as Antimicrobial Filters

The incorporation of antimicrobial agents such as Silver with nanofiber is known to exhibit antimicrobial properties to the filters. Neeta et al reported antimicrobial (E. coli and P. aeruginosa) activity for poly(vinyl chloride) PVC, cellulose acetate (CA) and polyacrylonitrile (PAN) nanofiber membranes containing Ag nanoparticles [33]. Electrospun PAN ENMs upon treatment with hydroxylamine led to the formation of –C(NH2) N–OH groups, which were subjected for the coordination of Ag+ ions followed by Ag nanoparticles formation by Zhang et al [33]. They reported that the ENMs containing Ag+ and Ag particles were highly active against microbes and also possessed sufficient transport properties for air filtration applications [34]. Antibacterial nylon nanofiber with Ag and the antibacterial activities of the nanofibers against Escherichia coli (Gram-negative) and Staphylococcus aureus were reported by Montazer et al [35].

3. Conclusion

The use of glass fibers and charcoal based filters can be replaced with functional nanofiber based filters or functional nanofibers combinations. Such filters can improve filtration efficiency, non selective and extended protection duration. The ability of nanofibers filters either alone or along with conventional filters for the removal of VOCs, nanoparticles and bacterial contaminates in the air is very promising. Such removal will reduce the man-made pollution in breathing air and avoid health problems like asthma and lung diseases.

4.Acknowledgements

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