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Modeling performance of thin fibrous coatings with orthogonally layered nanofibers for improved aerosol filtration

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ABSTRACT

Advances in nanofiber fabrication techniques (e.g., electrospinning) have come to allow control over fiber distribution and orientation such that an ordered coating with fibers arranged in layers orthogonal to one another can potentially be produced. Such coatings can serve as a nano-sieve that can be designed and placed on the downstream side of a conventional nonwoven fibrous filter to enhance its performance (collection efficiency for a given pressure drop). This paper presents a thorough analysis of the performance characteristics of these thin coatings to guide the fabrication process in terms of the coatings' microstructural properties. In particular, we have found a correlation such that, for coatings composed of a given fiber size, there exists a corresponding particle size for which a coating's performance becomes independent of variations in fiber-to-fiber spacing (i.e., coating's non-homogeneity). We have also found that a coating's performance improves when its mass is distributed across more than one pair of orthogonal layers.

1. Introduction

The most common method of removing particles from a fluid stream is via fibrous filters, which are generally characterized by two basic parameters: collection efficiency and pressure drop [1–3]. Nonwoven filters are made by randomly depositing fibers on top of one another to produce a fibrous structure with very small "openings," making the medium permeable to air (or water) but impermeable to particles. Because of this randomness in the orientation and position of the fibers (anisotropy and non-homogeneity), there must always be a greater number of fibers in a medium than is actually needed to filter particles of a given diameter range. Obviously, the presence of additional fibers translates to additional friction with the flow and therefore results in increased pressure drop. Fig. 1a illustrates an "ideal" medium (a nano-sieve) that can potentially be designed to filter a specific range of particles with a minimum number of fibers (i.e., for a minimum pressure drop), in contrast to a conventional fibrous structure as shown in Fig. 1b (the prefix "nano" in this paper is used to refer to fibers with submicron diameters, as it is the convention in filtration industry). Obviously, producing fibrous structures consisting of orthogonal nanofibers is not a trivial task. However, the possibility of using the electrospinning process for producing such structures has already been demonstrated by many investigators (see for instance, ref. [4,5] for AC-electrospun and ref. [6] for DC-spun orthogonal fibers). Of course, large-scale production of filter media with controlled fiber orientation and fiber spacing is a challenge to be overcome in the future. Generally speaking, nanofiber media cannot be used as a stand-alone filter due to their lack of mechanical strength. However, they can be used as a thin coating deposited on the front and/or back surface (upstream and/or downstream side) of a filter medium composed of larger fibers, to enhance its overall performance (see e.g., [7,8]). This paper is aimed at establishing the theoretical framework for design and development of thin nanofiber coatings composed of orthogonal fibers. In particular, our objective is to provide a means for guiding the fabrication of nano-fiber coatings in terms of fiber spacing and fiber diameter for improving the capture efficiency of the filter against particles of a given diameter range. This is especially important when considering the fact that nanofibrous coatings consisting only of a few layers cannot constitute homogenous "media" as has traditionally been the basis for the existing analytical and/or empirical expressions for predicting the performance of fibrous filters in the literature. Our group has also recently simulated the stability of superhydrophobic coatings of this scale against elevated hydrostatic pressures for submersible surfaces, and observed superior performance with surfaces consisting of orthogonal fibers [9,10].

In this paper, we start our discussion by considering virtual fibrous coatings composed of alternating horizontal layers, each consisting of randomly distributed parallel fibers oriented in the x or y direction (Section 2). In Section 2, we will also cover the numerical method that we utilized to determine the flow field through our coatings, discuss the Lagrangian particle-tracking method used to predict particle deposition across the coatings, and explain our means of minimizing numerical errors associated with the simulations. To reduce the statistical uncertainty of the results generated in our parameter study and improve the

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