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On the importance of fibers' cross-sectional shape for air filters operating in the slip flow regime

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A B S T R A C T

In this paper, we investigate the effects of fibers' cross-sectional shape on the performance of a fibrous filter in the slip and no-slip flow regimes. The slip flow regime is expected to prevail when fiber diameter is comparable in size to the mean free path of the gas molecules (about 65 nm at normal temperatures and pressures), whereas the no-slip flow regime describes the aerodynamic condition of flow through media with large fibers. Our numerical simulations conducted for flow around single fibers with different geometries indicate that, while the collection efficiency is only weakly affected by the cross-sectional shape of nanofibers, the fiber drag (i.e., permeability of the media) can be considerably influenced by the fiber's shape. Simulating the flow field around nano- and microfibers with circular, square, trilobal, and elliptical cross-sections, it was found that the more streamlined the fiber geometry, the lower the fiber drag caused by a nanofiber relative to that generated by its micron-sized counterpart.

1. Introduction

With the recent advancements in electrospinning and melt-blowing processes, the production of nanofibers is becoming increasingly viable (even though the term nanofiber should in principle be used for fibers with a diameter smaller than 100 nm, it is a common practice in the filtration community to use this term for fibers smaller than one micrometer, and for the sake of convenience, we follow this convention here). Nanofibers can significantly improve the performance of an ordinary air filter thanks to their minute dimensions, which promote a phenomenon called aerodynamic slip. In a fibrous filter, aerodynamic slip takes place when the fiber diameter is comparable to the mean free path of the gas molecules (e.g., 65 nm for air at normal temperatures and pressures). In such conditions, collisions between the gas molecules and the fibers become so infrequent that the gas can no longer be considered a continuum phase with respect to the fibers. Aerodynamic slip results in a significant decrease in the drag force exerted on a fiber. This leads to a lower pressure drop caused by a filter comprised of nanofibers when compared to another filter with the same collection efficiency, but made up of microfibers.

The permeability and particle collection efficiency of nanofiber filter media have been vastly studied in recent literature. Such studies include, but are not limited to, numerical simulations of Maze et al. [1], Hosseini and Tafreshi [2–4], Wang and Pui [5], Wang et al. [6], Zhao and Povitsky [7], Przekop and Gradon [8] as well as the experimental work of Podgorski et al. [9], Wang et al. [10], and Shin and Chase [11]. Since the infancy of filtration theory about fifty years ago, fibers have always been assumed to be circular. There are many analytical, numerical, and empirical correlations that have been developed for filters made up of circular fibers. There are also a few studies dealing with non-circular microfibers (i.e., fibers with diameters greater than a few micrometers), such as the work of Lamb and Costanze [12], Sanches et al. [13], Raynor [14], Fotovati et al. [15], Cheung et al. [16], Dhaniyala and Liu [17]. However, despite the abundant number of studies dealing with microfibers, no work has been dedicated to exploring the performance of media made of non-circular nanofibers. Our hypothesis in this work is that a fiber's cross-sectional geometry becomes significantly more important when the air is in the slip flow regime, as the streamlines tend to better conform to the actual shape of the fiber in the presence of aerodynamic slip. Our objective in this work is to highlight the importance of a fiber's cross-sectional shape in calculating a filter's pressure drop and collection efficiency in slip and no-slip flow regimes. We examine our hypothesis using numerical simulations, and we validate our simulation results with published studies in the literature, where available. In the next section, we briefly describe our governing equations, boundary conditions, and numerical schemes considered in this study. Our results and discussions are given in Section 3, followed by our conclusions in Section 4.

2. Governing equations and numerical schemes

Our simulations are conducted for a single fiber placed in a square unit as shown in Fig. 1. Fibers with circular, square, elliptical, and

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