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Modeling particle filtration in disordered 2-D domains: A comparison with cell models

S.A. Hosseini, H. Vahedi Tafreshi*

Mechanical Engineering Department, Virginia Commonwealth University, Richmond, VA 23284-3015, United States

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ABSTRACT

In this work, Stokes equations are numerically solved in a series of 2-D geometries comprised of randomly distributed fibers, using the Fluent CFD code. Particle collection due to interception and Brownian diffusion has been incorporated in the CFD calculations by developing two C++ subroutines that run in the Fluent environment. We have also modified the Discrete Phase Model of the Fluent code to correctly predict the effect of Brownian motion on a particle trajectory, and to obtain nanoparticle collection efficiency of a filter medium via the Lagrangian method. Our simulations are aimed at studying aerosol filtration in disordered 2-D fibrous media, and their results are compared with the predictions of existing cell-model-type (ordered 2-D models) semi-analytical correlations, as well as our previous simulation data obtained from 3-D simulations. Our results revealed that disordered 2-D fiber arrangements can be utilized to predict the performance of fibrous filters with reasonable accuracy and CPU time. Collection efficiencies obtained from our 2-D models seem to be marginally lower than those of 3-D simulations, for nanoparticles, and slightly higher, for larger particles. Pressure drop predictions of disordered 2-D media are found to be lower than that of ordered 2-D models, but higher than that of 3-D fibrous models. The latter is found to be in very good agreement with experiment. We have also studied the impact of aerodynamic slip on the collection efficiency of our filter media, and concluded that aerodynamic slip improves the collection efficiency of a filter medium, especially for larger particles.

1. Introduction

Fibrous filters are the single largest mediator of particulate air pollution in commercial and residential environments. For the past 50 years, scientists around the globe have been trying to develop mathematical formulations to predict the performance of fibrous filters and improve their effectiveness. Starting with the work of Kuwabara [1], existing analytical/numerical studies that built the foundation of current filtration theory were formulated using 2-D solution domains, in which the fibers were arranged in either square or staggered (i.e., ordered) positions (e.g. [2–21]). The air and particle flow field were then calculated in a unit cell of such periodic geometries to find analytical expressions for the pressure drop and particle capture efficiency of real fibrous filter media (in which fibers are randomly distributed in 3-D space). Treating a filter medium as an ordered array of fibers in 2-D domains may help in obtaining rough estimates of the pressure drop and collection efficiency of real filter media, but such expressions often need empirical correction factors (each valid for a given range of fiber diameters, particle diameters, or flow hydrodynamic/thermal regimes) to improve their accuracy. We have previously demonstrated the advantages of generating virtual 3-D models that mimic the internal microstructure of fibrous media for simulating pressure drop and collection efficiency [22–30]. Such 3-D models do not necessarily need empirical correction factors, and their predictions can directly be used for product design and development. The problem with 3-D models, however, is that they require excessive computational power, which may prohibit extensive parameter studies, especially in the presence of particle loading. In the current paper, we simulate the pressure drop and particle collection efficiency of fibrous media in large, but 2-D, simulation domains comprised of randomly distributed fibers. Our main objective in this paper is to examine whether or not the simulations conducted in disordered 2-D fibrous geometries can generate predictions comparable to those of 3-D simulations (or those obtained using semi-analytical correlations from the literature). We also investigate the influence of aerodynamic slip on particle collection efficiency and pressure drop, and compare them with existing correlations in the literature.

In the next section, we first describe our algorithm for generating disordered 2-D simulation domains comprised of randomly distributed fibers. We then discuss our governing equations and

* Corresponding author at: Virginia Commonwealth University, Mechanical Engineering Department, 401 West Main Street, P.O. Box 843015, Richmond, VA 23284-3015, United States. Tel.: +1 804 828 9936; fax: +1 804 827 7030.
E-mail address: htafreshi@vcu.edu (H.V. Tafreshi).

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