Influence of fiber orientation on the transverse permeability of fibrous media

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(Received 6 April 2009; accepted 29 July 2009; published online 28 August 2009)

In this work, we study the influence of in-plane and through-plane fiber orientations on a fibrous medium's transverse permeability. Three-dimensional virtual geometries resembling the microstructure of fibrous media with different fiber orientations are developed to be utilized in permeability calculations conducted by numerically solving the Stokes equations in the void space between fibers. Results of our simulations are compared to existing experimental and analytical studies from literature and excellent agreement is observed. We, in particular, demonstrate that the transverse permeability of a fibrous medium is independent of in-plane fiber orientation but increases with increasing deviation of the fibers' through-plane angle from zero. Our findings somewhat disagree with some of the conclusions made by Stylianopoulos *et al.* [Phys. Fluids **20**, 123601 (2008)]. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3211192]

I. INTRODUCTION

Fibrous media are essential parts of many biological, chemical, and mechanical systems. Fibrous materials are mechanically strong, structurally flexible, and yet highly permeable. Permeability of fibrous media has been vastly studied for the past decades and there are many publications reporting on its variations as a function of flow regime and/or media's microstructure.[1–9]

Microstructure of disordered fibrous materials, in general, can be considered to fall into three major categories: Unidirectional structures, where axes of all cylindrical fibers are parallel with one another (e.g., Refs. 1, 2, and 10–12), layered structures, where axes of cylindrical fibers lie randomly in parallel planes often perpendicular to a fluid flow (e.g., Refs. 1, 4–9, and 13–16), and three-dimensionally isotropic structures, where fiber axes can be randomly oriented in any direction in the three-dimensional (3D) space (e.g., Refs. 1–3, 6, and 17). Even though fibrous materials have been widely studied in the past, there has been no study in literature specifically devised to examine the effect of fiber orientation in fibrous media except for the recent simulations of Stylianopoulos *et al.*[18] These authors developed 3D fibrous media with three different levels of fiber orientations and compared the permeability of their 3D isotropic structures with those of their moderately and highly oriented media. In the current paper, we present our numerical simulation developed to investigate the effects of in-plane and through-plane fiber orientations on the transverse permeability of fibrous media. We also compare our work with that of Ref. 18 and discuss some of the observed discrepancies. Here, we also model fibrous media with fibers of orthogonal orientations across layers and compare their permeability values with those of the aforementioned microstructures.

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In Sec. II, we briefly describe our modeling procedure developed to produce 3D fibrous microstructures and solve the Stokes flow equation in the void space between the fibers. A comparison between our work and the studies reported in literature is presented in Sec. III followed by our conclusions in Sec. IV.

II. MODELING THROUGH-PLANE PERMEABILITY OF VIRTUAL FIBROUS STRUCTURES

To generate 3D virtual models resembling the microstructure of a fibrous medium, we developed a computer program capable of producing random fibrous structures of different fiber diameters, porosities, thicknesses, and orientations. These media can be 3D isotropic or layered, with differing levels of in-plane and through-plane fiber orientations. The program can also generate disordered layered microstructures with orthogonal fibers. Figure 1 shows examples of these fibrous microstructures.

The media generation process is based on the μ-randomness algorithm[19] and has also been fully described in our previous studies.[8,13–15] For the unidirectional media, fibers with a length equal to the domain size are placed in the given direction. A similar routine is used for generating disordered orthogonal media, except that the alignment of the fibers alternates between layers orthogonally. Here, unlike our previous work, we allowed the fibers to interpenetrate as this does not affect the permeability of the media as long as the true porosity is calculated correctly. For the case of unidirectional, however, we enforced a minimum gap (40% of the fiber diameter) between the fibers to avoid generating fibers that significantly overlap and also to ease the meshing process.

In order to find an appropriate size for the simulation domain, we used the Brinkman screening length criterion. Following the work of Clague and Phillips,[17] a minimum domain size of $14\sqrt{k}$, where k is the medium's permeability,

