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A semi-analytical model for simulating fluid transport in multi-layered fibrous sheets made up of solid and porous fibers

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ABSTRACT

Direct simulation of fluid transport in fibrous media consisting of swelling (i.e., fluid-absorbing) and non-swelling (i.e., solid) fibers is a challenge. In this work, we have developed a semi-analytical modeling approach that can be used to predict the fluid absorption and release characteristics of multi-layered composite fabrics made up of swelling and non-swelling fibrous sheets. The simulations presented here are based on a numerical solution of Richards' equation. Two different fibrous sheets composed of non-swelling (PET) and swelling (Rayon) fibers with different Solid Volume Fractions (SVFs) and thicknesses were arbitrarily chosen in this study for demonstration purposes. The sheets' capillary pressure and relative permeability are obtained via a combination of numerical simulations and experiment. In particular, the capillary pressure expression for non-swelling media is obtained from the analytical expressions that we previously developed via 3-D microscale simulations, while the capillary pressure for swelling media is obtained via height rise experiments. The relative permeability expressions for both swelling and non-swelling media are obtained from the analytical expressions previously developed via 3-D microscale simulations, which are also in agreement with experimental correlations from the literature. On the macroscale, simulation results are reported for fluid transport in bi-layered composite fabrics, and comparison is made between the performances of these fabrics in terms of the order in which the layers are stacked on top of one another. A higher rate of absorption was observed when the layer in contact with the fluid is that comprised of swelling fibers. A similar study was conducted for motion-induced fluid release from the composite fabrics when partially-saturated with a fluid. It was shown that less fluid release is expected when the swelling sheet is placed in contact with the surface.

1. Introduction

Products designed for fluid absorption or release, such as wound dressings, absorbent dry wipes, sanitary wet wipes, among many others, are ubiquitous and of crucial importance in industry and everyday life. Engineered composite nonwoven fabrics (often multi-layered) continue to rise in sophistication day by day, and thoughtful and methodical approaches to their design and development require in-depth understanding of two-phase diffusive fluid transport in fibrous media.

The majority of published studies discussing fluid transport in fibrous media are purely empirical, and consequently, their applications are limited to the products or conditions for which the experiments were conducted (see [1] for a review). While there have been a few analytical, statistical, or numerical studies in which fluid absorption in dry fibrous media has been investigated (see for instance, [2–7]), no modeling works were reported to account for a given medium's anisotropy and partial saturation at the same time. Inspired by the seminal work of Landeryou et al. [8], we recently developed a dual-scale (microscale-macroscale) modeling methodology suitable for simulating fluid transport in partially-saturated anisotropic fibrous media [9,10]. Unlike the work of Landeryou et al. [8], the capillary pressure and relative permeability expressions in our work were obtained from 3-D microscale simulations. Note that the interrelationship of parameters in a partially-saturated fibrous medium is such that fluid transport depends on capillary pressure and relative permeability, both of which in turn depend on the medium's microstructure, material of the fibers, fluid properties, and of course, instantaneous fluid saturation. Quantitative knowledge of capillary pressure and relative permeability allows one to solve the so-called Richards equation for diffusive flow in partially-saturated porous media (the macroscale model) to obtain the rate of fluid absorption [9,10] or release [11] as a function of time and space throughout the material.

In almost all modeling studies published previously, including those of our group, fibers were treated as impermeable solid cylinders, incapable of absorbing and/or storing the fluid in their

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