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Modeling motion-induced fluid release from partially saturated fibrous media onto surfaces with different hydrophilicity

A. Ashari, T.M. Bucher, H. Vahedi Tafreshi *

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

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ABSTRACT

Modeling the rate of fluid release from moving partially saturated nonwoven sheets in contact with a solid surface is a challenge, as the release rate depends on many parameters, some of which are difficult to quantify. In this paper, we report on a diffusion-controlled boundary treatment which we have developed to simulate fluid release from partially saturated porous materials onto surfaces with different hydrophilicy. The new boundary treatment considers the solid impermeable surface as a fictitious porous layer with a known fluid diffusive coefficient. Motion of the porous sheet on the surface is incorporated in the simulations by periodically resetting the saturation of the fictitious layer equal to zero, with a period obtained from the sheet's speed of motion. Fluid transport inside the fibrous sheets is calculated by solving Richards' equation of two-phase flows in porous media. Our numerical simulations are accompanied with experimental data obtained using a custom-made test rig for the release of liquid from partially saturated media at different speeds. It is demonstrated that the novel mathematical formulations presented here can correctly predict the rate of fluid release from moving fibrous sheets onto solid surfaces with different hydrophilicity as a function of time.

1. Introduction

Engineered nonwoven materials are becoming more sophisticated in design every day, and have entered many new and critical applications in the field of medicine and personal health/hygiene. The problem of controlled fluid release from fibrous media, unlike its traditional counterpart, i.e., fluid absorption, is very recent. This paper introduces a novel modeling approach for the release of wetting fluid from a thin fibrous sheet in motion across surfaces with different hydrophilicity. The most practical application of the study presented here is predicting, and therefore optimizing, performance of fibrous materials used in delivering medicine or sanitizing/sterilizing lotions for wound cleaning or personal/cosmetic hygiene, among countless other applications (see Fader et al. (2010) and Cottenden et al. (2008) for reviews on incontinence products and skin–fabric interactions). Developing in-depth understanding of the problem of fluid release from partially saturated fibrous media is of crucial importance for engineering new products with optimized performance.

Being fairly new, the problem of fluid release from fibrous media has not yet been systematically studied in the literature. Most of the published studies dealing with fluid transport in fibrous media are only concerned with fluid absorption (e.g., Marmur, 1988; Lucas et al., 1997; Tompson, 2002; Eames et al., 2003; Mao and Russell, 2003, 2008; Hyvaluoma et al., 2006; Pan and Gibson, 2006; Mullins et al., 2007).

We previously developed a dual-scale numerical simulation framework for modeling the rate of fluid transport in multi-layered fibrous materials (Jaganathan et al., 2009; Ashari and Tafreshi, 2009a; Ashari et al., 2010a,b). In this paper, we use the above-mentioned dual-scale simulation technique to model fluid release from fibrous sheets when moved on solid surfaces with different hydrophilicity. To do so, a novel diffusion-controlled boundary treatment has been developed and used along with experimental data obtained using a test rig that we have designed and built for model validation and adjustment.

Our simulation methodology is based on solving Richards' equation of two-phase flows in porous media at the macroscale (Richards, 1931), coupled with capillary pressure and relative permeability information obtained via 3-D simulations at microscales. Our microscale simulations are fully described in our previous publications and will not be repeated here (see Jaganathan et al., 2009; Ashari and Tafreshi, 2009b).

For demonstration purposes, we have arbitrarily chosen two different nonwoven fibrous sheets, one consisting of porous Rayon fibers, and the other made of solid (non-swelling) PET fibers. Both sheets have anisotropic in-plane fiber orientations common in hydroentangled nonwoven fabrics (Tafreshi et al., 2003; Anantharamaiah et al., 2007). We have also arbitrarily chosen a commer-

* Corresponding author. Tel.: +1 804 828 9936; fax: +1 804 827 7030.
E-mail address: htafreshi@vcv.edu (H.V. Tafreshi).

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