International Journal of Heat and Mass Transfer 53 (2010) 1750–1758

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Modeling fluid spread in thin fibrous sheets: Effects of fiber orientation

A. Ashari, T.M. Bucher, H. Vahedi Tafreshi *, M.A. Tahir, M.S.A. Rahman

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

A R T I C L E   I N F O

Article history:
Received 24 August 2009
Available online 26 January 2010

Keywords:
Fibrous porous media
Two-phase flows
Anisotropic permeability
Fiber orientation
Absorbency
CFD simulation

A B S T R A C T

In this paper, a dual-scale model is developed to simulate the radial spreading of liquids in thin fibrous sheets. Using 3-D microscale simulations, the required constitutive equations, capillary pressure and relative permeability, have been determined at each saturation level and used in a macroscale model developed based on the Richards' equation of two-phase flow in porous media. The dual-scale approach allowed us to include the partially-saturated region of a porous medium in calculations. Simulating different fibrous sheets with identical parameters but different in-plane fiber orientations, it is revealed that the rate of fluid spread increases with increasing the in-plane alignment of the fibers. Our simulations are discussed with respect to existing studies in the literature.

1. Introduction

The literature regarding fluid flow modeling in partially-saturated fibrous media is very scarce. Most of the published studies to date are empirical in nature, and were conducted for specific purposes/applications [1]. Because of this, the results of one study are often of no use to another. There are a few theoretical studies conducted for predicting fluid spread in fibrous media. The well-known work of Lucas [2] and Washburn [3] was the first mathematical model developed to predict fluid infiltration in a porous medium made up of series of capillary tubes. This approach of modeling the complex pore space of a fibrous medium with a series of capillary tubes has been often criticized [4,5]. This is mainly because there is no direct method of finding the Lucas–Washburn's required equivalent capillary diameter, and it is hard to establish a fundamental relationship between the predictions of Lucas–Washburn's model and the microstructural parameters of the media (e.g., porosity, fiber diameter, etc.). Another over-simplification in the Lucas–Washburn model is the assumption that the medium is either fully-saturated or fully dry, ignoring the partially-saturated region between the two. Mao and Russell [6,7] proposed capillary pressure and relative permeability expressions for anisotropic homogenous fibrous media. The work of Mao and Russell [6,7] is based on series of assumptions similar to those of Lucas–Washburn's model, and therefore is inaccurate when the partially-saturated region in the medium is not negligible, as the capillary pressure and relative permeability expressions derived by Mao and Russell exhibit no dependence on saturation. Hyvaluoma et al. [8] developed a Lattice–Boltzmann simulation scheme to study liquid penetration inside paper sheets and reported excellent agreement between their work and the expression developed by Marmur [9]. The work of Hyvaluoma et al. [8] also ignores the partially saturated part of the domain.

It is worth mentioning that Adams et al. [10] also simulated the radial penetration of liquids in planar anisotropic porous media. Their work, however, was mostly formulated for pressure-driven fluid spread (such as the case of resin impregnation in fiber-reinforced composite manufacturing), and so the dependency of capillary pressure on saturation was ignored.

There are also a few statistical/semi-statistical simulations developed for studying fluid spread in fibrous media (e.g., [11–14]). The major difficulty with such simulations is that it is often hard to directly relate measurable microstructural parameters of a real fibrous material (e.g., fiber diameter, fiber orientation distribution, etc.) to the irregularity and randomness parameters used in statistical models. For a more complete review of the previous theoretical and experimental studies, readers are referred to the book of Pan and Gibson [1].

In a recent work, Landeryou et al. [15] presented a comprehensive study on the problem of fluid imbibition in isotropic partially-saturated fibrous sheets under different inclinations, both experimentally and theoretically. Simulations of Landeryou et al. [15] were based on the work of Richards [16] who developed a diffusive absorption model for two-phase flow in partially-saturated granular porous media. Our work in this paper follows the work of Landeryou et al. [15] in using Richards' equation for predicting the rate of fluid spread in fibrous sheets. Our emphasis, however, is on the effect of fiber in-plane orientation on fluid imbibition and spread. Moreover, we use a dual-scale simulation method, where the constitutive equations of capillary pressure and relative permeability are obtained via microscale 3-D simulations and utilized in a 2-D

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

0017-9310/$ - see front matter
doi:10.1016/j.ijheatmasstransfer.2010.01.015