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General capillary pressure and relative permeability expressions for through-plane fluid transport in thin fibrous sheets

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ABSTRACT

The rate of fluid transport in partially saturated porous media depends on the media's instantaneous (function of saturation) relative permeability, $k_r(S)$, and capillary pressure, $P_c(S)$. Obtaining functional relationships for relative permeability and capillary pressure is only possible via experimentation or expensive microscale simulations, and needs to be repeated for different media having different fiber diameters, thicknesses, or porosities. In this concern, we conducted series of 3-D microscale simulations to investigate the effect of the above parameters on the relative permeability and capillary pressure of fibrous porous sheets. The results of our parameter study are utilized to develop general expressions for $k_r(S)$ and $P_c(S)$. Our general expressions are based on the existing empirical correlations of two-phase flow in granular media, and can easily be included in macroscale fluid transport equations to predict the rate of fluid release from partially saturated fibrous sheets in a time and cost-effective manner.

1. Introduction

Fibrous materials have been used for fluid absorption and release for many years. However, only in recent years has optimizing their microstructure become important. This is, in part, due to the inception of many new applications demanding controlled fluid absorption, storage, and release. Drug delivery patches, sanitizing wipes, wound dressings, and very many other hygiene and industrial products are among the applications taking advantage of the unique properties of fibrous materials in absorbing, storing, and releasing a fluid. For a complete review of the previous works on fibrous media readers are referred to the recent book of Pan and Gibson [1].

Quantitative relations for capillary pressure, P_c, and relative permeability in terms of the media's saturation, S, are required for predicting the rate of fluid transport in porous materials. Such relationships have been empirically obtained for granular porous media over the last few decades for applications in the oil and gas industries or soil sciences. Unfortunately, there are no such relationships available for fibrous materials except for the work of Landeryou et al. [2], who used an auto-porosimeter to study liquid rise in needle-felt fabrics. The correlation of Landeryou et al. [2] was obtained for in-plane (as opposed to through-plane) fluid infiltration in fibrous media. The only available study reporting on a capillary pressure–saturation, $P_c(S)$, and relative permeability–saturation, $k_r(S)$, relationship for through-plane fluid transport in a fibrous medium is that of our group [3]. In that work, we simulated fluid release from a partially saturated fibrous sheet using a combined micro- and macro-scale modeling approach. Results of our previous work, however, were obtained for a specific fibrous material. Our objective in this work, on the other hand, is to develop, for the first time, general $P_c(S)$ and $k_r(S)$ expressions valid for a whole family of fibrous sheets with a practical range of fiber diameter, thickness, and porosity. These expressions are required, for instance, in solving the Richards' equation [4], among many others. The Richards' equation is a partial differential equation relating the fluid's continuity equation to Darcy's law, and is often used in literature to predict the percentage of fluid saturation in a porous medium as a function time and space, $S(x,y,z,t)$ (e.g., see [2,5] or [3]).

It is worth mentioning that $P_c(S)$ and $k_r(S)$ expressions can only be obtained via experimentation [2] or computationally expensive microscale simulations [3,5], and they are only valid for the material used in the experiment or simulation. Developing generalized $P_c(S)$ and $k_r(S)$ expressions is very important as they enable us to circumvent the need for conducting expensive microscale simulations (or laborious experiments), and help in performing fast and affordable macroscale calculations for fluid transport in partially saturated porous media.

In this work, we generate a large series of 3-D microstructures resembling the internal geometry of fibrous sheets. These virtual

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