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Technical Note

On the effects of fiber orientation in permeability of fibrous media to power-law fluids

B. Emami, S. Fotovati, M.M. Amrei, H. Vahedi Tafreshi *

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

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ABSTRACT

In this note, for the first time, the flow of power-law fluids is numerically simulated in 3-D fibrous structures resembling the internal microstructure of fibrous hygiene products to study the effects of fibers' in-plane and through-plane orientations on the media's permeability. It was found that while the permeability of a fibrous material to a power-law fluid hardly depends on the in-plane orientation of the fibers, it increases with increasing the fibers' through-plane orientation. Moreover, we developed a simple analytical expression that can be used together with the empirical correlation of Davies (1973) [16], modified with an equation derived by Banks (1987) [17], to predict the permeability of anisotropic fibrous media to power-law non-Newtonian fluids. The predictions of our formulation are compared with our numerical simulations and good agreement is observed.

1. Introduction

Fibrous materials are mechanically strong, structurally flexible, and yet highly permeable. Such a peculiar combination of diverse properties has expanded applications of fibrous materials from polymer flows (e.g., polymer filtration and resin transfer molding) to medical and hygiene applications (e.g., wound dressing, surgical gowns, sanitizing or lotion-saturated scented wipes) among many others [1–10]. Understanding the interactions between non-Newtonian fluids (e.g., blood or scenting lotions) and fibrous media is of significant importance for efficient fluid transport in such materials and for successful product design/development.

For a Newtonian fluid flowing through a porous medium, the well-established empirical Darcy's law there exists a linear relationship between the flow velocity and the pressure drop, such that [11]

$$u_0 = \frac{k_D}{\mu}\frac{\Delta P}{L} \tag{1}$$

where u_0 is the superficial velocity, defined as the ratio of volumetric flow rate through the medium to the total cross-sectional area, k_D is the Newtonian permeability constant, μ is the dynamic viscosity, ΔP is the pressure drop across the medium, and L is the thickness of the medium. Note that Darcy's law as written in Eq. (1) holds only at low Reynolds numbers, i.e., creeping flows. Over the past few decades, several empirical and/or analytical expressions have been proposed for calculating Newtonian permeability constants for fibrous media as a function of their microstructural parameters (see [12–15] for more information). For example, Davies suggested an empirical expression for the through-plane permeability constant of Newtonian fluids through fibrous media with layered microstructures (flow perpendicular to the fibers) [16]

$$k_{Dav} = \frac{d_f^2}{64(1-\epsilon)^{\frac{3}{2}}[1+56(1-\epsilon)^3]} \tag{2}$$

Here d_f is the fiber diameter and ε is the porosity. Using the drag force exerted on a single fiber placed with an angle with respect to the flow, Banks [17] developed an analytical expression that can be used to modify the above equation for predicting the permeability of fibrous media with different average through-plane fiber orientations (see [18] for more information):

$$k^{\angle}_{Dav}(\beta) = \frac{d_f^2}{64(1-\epsilon)^{\frac{3}{2}}[1+56(1-\epsilon)^3](\cos^2\beta + \frac{1}{2}\sin^2\beta)} \tag{3}$$

where β is the fibers' average through-plane orientation. Unlike a Newtonian fluid, the effective viscosity of a non-Newtonian fluid depends on the strain rate and/or time. The focus of the current work is on time-independent non-Newtonian fluids, where the effective viscosity only depends on the strain rate. Several models

* Corresponding author. Tel.: +1 804 828 9936.
E-mail address: htafreshi@vcu.edu (H.V. Tafreshi).
URL: http://www.people.vcu.edu/~tafreshi/ (H.V. Tafreshi).

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