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Modeling liquid porosimetry in modeled and imaged 3-D fibrous microstructures

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ABSTRACT

In this paper, an analysis to distinguish the geometric and porosimetric pore size distributions of a fibrous material is presented. The work is based on simulating the intrusion of nonwetting fluid in a series of 3-D fibrous microstructures obtained from 3-D image reconstruction or virtual geometries mathematically generated according to the properties of the media. We start our study by computing the pore size distribution of two typical hydroentangled nonwoven materials and present a theoretical model for their geometric pore size distributions based on Poisson line network model of the fibrous media. It is shown that the probability density function of the geometric pore size distribution can be approximated by a two-parametric Gamma distribution. We also study connectivity of the pore space in fibrous media by computing and comparing the accessible and allowed pore volumes in the form access function graphs. It is shown that the so-called ink-bottle effect can significantly influence the fluid intrusion in a porous material. The pore space connectivity of a homogeneous fibrous media is observed to be a function of thickness, solid volume fraction (SVF), and fiber diameter. It is shown that increasing the materials' thickness or SVF, while other properties are kept constant, reduces the pore space connectivity. On the other hand, increasing the fiber diameter enhances the connectivity of the pores if all other parameters are fixed. Moreover, modeling layered fibrous microstructures; it is shown that the access function graphs can be used to detect the location of the bottle neck pores in a layered/composite porous material.
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1. Introduction

Nonwoven fibrous materials have enormous applications in filtration, insulation, acoustics, and clothing as well as in fluid absorbent and/or barrier materials. This is mainly because of the wide range of pore sizes that nonwovens can provide for fluid and particle flow, heat transfer, and acoustical waves, to name a few. Characterizing pore space of a fibrous medium is, therefore, of fundamental importance to optimize and develop new products. Pore space of a fibrous material can be characterized by different measures including, but not limited to, porosity ε, permeability, pore size distribution, and topological parameters such as connectivity [1].

In this paper we study pore size distribution of nonwoven fibrous materials. Note, however, that pore space in almost all fibrous media is a continuous domain. Dividing such a continuous domain into a number of discrete cylindrical volumes, i.e., cylindrical pores, is only a widespread approximation that has been used often in the context of solid–liquid separation or barrier materials. Defining pore size distribution for a given material makes it easy, in many cases, to characterize and compare different porous materials. Techniques such as porosimetry are, therefore, developed to obtain a pore size distribution for a given porous material. Porosimetry is developed based on the so-called "bundle of capillaries" assumption in which pores are regarded as straight capillary tubes with no interconnectivity. By incrementally forcing a nonwetting fluid into a porous material and monitoring the volume of intruded fluid, one can obtain a pore size distribution using the well-known Young–Laplace equation,

$$r = \frac{2\sigma \cos\theta}{\Delta p}, \tag{1}$$

where r is the pore radius, σ is the fluid's surface tension, θ is the solid–fluid contact angle, and Δp is the applied pressure.

Thanks to the recent progress in imaging techniques, it is now possible to obtain 3-D images of the microstructure of a porous material with relatively good resolutions. Such images can be used to characterize the pore size and the pore-related properties of porous materials. There are basically three different techniques for obtaining 3-D images of porous materials: serial sectioning-imaging the resin-impregnated samples, magnetic resonance imaging (MRI), and X-ray computed tomography [2–5]. In a recent paper [6,7] we used an automated serial sectioning-imaging technique to obtain 3-D images of the microstructure of a hydroen-

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