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A study on compression-induced morphological changes of nonwoven fibrous materials

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ABSTRACT

Pore size is a characteristic parameter that is often defined for fibrous materials used in industrial applications. While there exist many available studies on the pore size distribution of different fibrous materials, the influence of compression load on pore size distribution has not been studied well. Studying the behavior of fibrous materials under compression is important especially because in many applications these materials are subjected to some degree of compression during use. In this work, we present a novel image-based modeling technique to study the changes in the pore size distribution of a fibrous material exposed to compressive load. This was made possible by building a miniature compression cell, and imaging the structure of a hydroentangled fabric under varying levels of compression. The 3D images obtained with Digital Volumetric Imaging were utilized to study the pore size distribution of the material and develop an empirical correlation as a function of compressive stress for these structures. This new correlation indicates that the mean pore diameter of a nonwoven material decreases exponentially with increasing the compressive stress.

1. Introduction

Fibrous porous media have enormous applications in filtration, insulation, acoustics, wipes, and many other industrial and consumer products. Due to their high degree of flexibility and compressibility, fibrous assemblies readily undergo structural deformation when exposed to a compressive stress. In many cases, a product is designed, manufactured, and even tested and rated, in the absence of any compressive stress. However, in practice, and often, the material is subjected to compression. For example, a cleaning wipe's behavior in use is often different from what has been measured in a lab because of the compression involved. For these reasons, understanding the morphological changes of a fibrous material under compression is critically important for better product design and development.

Many investigators have used analytical (e.g., [1–4]), numerical (e.g., [5,6]), and experimental [7] techniques to characterize the properties of fibrous structures under compression. Most of these works, however, have been based on over-simplified and/or unrealistic assumptions. Furthermore, in most of the above studies, nonwovens were assumed to be homogeneous and isotropic materials. Fibrous materials are known to have different degrees of in-plane and/or through-plane non-homogeneity. Additionally, micro-scale information of the structure, to the extent used in the present work, was not utilized by previous studies for characterizing morphological changes under compression.

Below, we demonstrate the utility of 3D imaging in visualizing and analyzing the internal micro-structure of a fibrous material. This makes it possible to track the relevant morphological changes under compression. Our objective in the present work is to develop an image-based characterization method to evaluate pore size distribution of fibrous materials and establish "easy-to-use" correlations. It is important here to clarify that the definition of pore and pore size depends on the material's application. In liquid porosimetry, for instance, a pore is assumed to be a cylindrical capillary with its diameter calculated via capillary-pressure measurements (the capillary-pressure is the pressure required to intrude (or extract) a non-wetting (or wetting) fluid into (from) the material and is related to the capillary diameter via the Young–Laplace equation). Such a pore size (and its distribution) is often used for characterization of fibrous materials in applications where two immiscible fluids (e.g., air and water) simultaneously occupy the void spaces between the fibers in the media (i.e., unsaturated media). On the other hand, in filters used for removing solid particles from a liquid stream, for instance, the pore size is defined based on the size of the particles that can penetrate through the medium without getting trapped, like in the case a micro-sieves. In the case of saturated media, the pore size depends only on the internal morphology of the

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