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Effect of 3D fiber orientation on permeability of realistic fibrous porous networks

Parham Soltani [a,*], Majid Safar Johari [a], Mohammad Zarrebini [b]

[a] Department of Textile Engineering, Amirkabir University of Technology, Tehran, Iran
[b] Department of Textile Engineering, Isfahan University of Technology, Isfahan, Iran

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The development of scientifically based fibrous porous networks has been gaining momentum due to their potential advantages in a wide spectrum of end-uses. Flow of fluid through fibrous networks is the determining factor in the engineering of these materials for applications in various manufacturing and process industries. Precise definition of transport properties of fibrous porous networks necessitates greater understanding of their internal structure at the micro-scale. To this end, in this work an X-ray micro-computed tomography-based CFD simulation methodology was developed. Realistic 3D images of fibrous networks were prepared using sets with various degrees of alignment including nearly isotropic, nearly layered and moderately aligned networks. The in-plane and transverse permeability of such structures were obtained by solving the Stokes equations. The presentation of the results for each type of fibrous network structure and flow configuration is preceded by brief outlines of the pertinent literature works, and followed by a discussion on the performance of the micro-computed tomography-based method and the literature models. It was established that simultaneous application of X-ray micro-computed tomography and CFD techniques merits the in depth understanding of the microscopic fluid flow phenomenon in respected models of fibrous porous structures and its subsequent role on the performance of a fibrous porous network. Results indicated that not only the solid volume fraction, but also the 3D orientation of fibers in fibrous networks affects the permeability.

1. Introduction

Fibrous porous networks stand out as a unique class of porous materials. These materials simultaneously are soft, porous, and voluminous, with relatively high resistance to mechanical deformation. A feature that distinguishes fibrous porous networks from granular materials is their much lower solid volume fraction. The granular materials are inherently compact with grain occupancy in excess of 0.6 of material volume. However, with fibers, much less material is needed to form a comparable stable structure, thus the fraction of solid material can be reduced to as low as 0.01 [1–4]. Such an interesting behavior of fibrous porous networks is ascribed primarily to the relatively complex manner that fibers can be positioned within the network and the exceptional characteristics of the constituent fibers. This internal structure of the fibrous porous networks is generally characterized by the directional and packing arrangement of the fibers within the media. While the directional arrangement of fibers is simply known as fiber orientation, the packing arrangement of fibers is represented by fiber solid volume fraction (SVF) [4].

The study of fluid behavior in fibrous porous networks is of considerable interest to a wide variety of applications such as production of paper [5–7], filtration [8,9], compact heat exchangers [10,11], fibrous beds for manufacturing processes [12–14], fuel cell technology [15–17], acoustic properties [18,19] and transport in biological systems [20,21]. Engineering of fibrous porous networks to meet full or partial requirements of the above mentioned processes has become a challenge to material designers in recent years. Therefore, the ability to predict the transport properties of fibrous porous networks is a valuable asset in the engineering design of these materials. The most important criterion for characterization of such flows is permeability, which for a porous medium is defined by Darcy's law as:

$$V = \mu^{-1} k \frac{\Delta P}{\Delta x} \tag{1}$$

where k denotes material permeability and has units of (length)^2, V, μ and ΔP represent superficial fluid velocity (m/s), fluid viscosity (Pa.s) and pressure difference (Pa), respectively and Δx corresponds to the distance over which the pressure difference acts [22].

Earlier studies of flow behavior in fibrous porous networks were conducted experimentally and a number of well-established models for the permeability of porous media are based on experimental data [23–27]. In these studies, primarily due to the macroscopic nature of the experimental approach, the details of the micro-scale flow-pattern in the porous medium cannot be captured. In general, studying the

* Corresponding author. Tel.: +98 2164542635; fax: +98 2164542636.
E-mail addresses: Parham-aut@aut.ac.ir (P. Soltani), mjohari@aut.ac.ir (M.S. Johari).

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effect of micro-structure on bulk properties entails a large experimental dataset, which is both time-consuming and expensive to generate. As an alternative approach, the use of analytical and numerical methods with the aim of predicting the permeability by solving the fluid flow inside the porous medium has also been established.

The characterization of fluid behavior through fibrous porous networks encompasses a number of parameters. Volumetric solid volume fraction (SVF) defined as the ratio of total volume of fibers to bulk volume of a fabric is the first and foremost property which affects flow fluid through porous media. Numerous research articles are published on the effect of SVF on the permeability of fibrous porous media [28–33]. These studies are thoroughly reviewed by Jackson and James [1] and Tomadakis and Robertson [32].

Fiber orientation is another structurally related parameter that affects fluid flow through a fibrous structure. The orientation of fibers in a fibrous structure influence the drag offered to fluid flow, thus the ability to control fiber orientation is vitally important. Generally, disordered micro-structurally fibrous materials can be categorized into:

(i) Unidirectional structures (1D) in which all cylindrical fibers axes are parallel to each other [34–38].
(ii) Layered structures (2D) in which cylindrical fibers axes lie randomly in parallel planes often perpendicular to the fluid flow [32,39].
(iii) Three-dimensionally isotropic structures (3D) in which fiber axes can be randomly oriented in any direction in space [32,39–41].

There are a few research work published on the influence of fiber orientation on the permeability of the fibrous porous networks [4,32,40–43]. To estimate the permeability of the fibrous structures, several researchers have analytically modeled the complex microstructure of the porous media with simplified 1D “unit cells” [34–38,44,45]. In these models, the cylindrical fibers are parallel and arranged in a periodic pattern like a square or triangular array. Most of these models have a limited range of application as reported by others [40,42].

Analytical studies of permeability of 2D and 3D materials are not as frequent as that of 1D arrangement, which is, in part, due to the geometrical complexity of these media [17,32,46,47]. Rigorous solution of flow past a fibrous system is a demanding task in these scenarios. Tsay and Weinbaum [48] investigated the effect of through-plane fiber orientation on the transverse permeability of fibrous media. For spatially periodic networks, the Stokes equations were solved for flow past a square array of fibers confined between two parallel walls. Higdon and Ford [41] used a spectral boundary element method to calculate the permeability in simple cubic, body-centered cubic, and face-centered cubic structures. The dimensionless permeability over the entire range of viable SVF was reported for idealized fiber structures. These results provided valuable insight into the variation of permeability versus porosity and formed the cornerstone for subsequent models.

Most of analytical works generally idealize the fibrous porous medium as a simple periodic array of rods where established equations such as Stokes for a particular configuration can be solved. These models usually ignore factors such as fiber crimps and inherent inhomogeneity of solid volume fraction and fiber orientation distribution.

The general treatment of fibrous porous networks at the microscopic level relies on the numerical simulations for prediction of permeability. There have been a large number of computational approaches in modeling of flows in fibrous micro-structures [49]. Many authors have used virtual geometries of fibrous structure to study fluid flow phenomenon. Virtual geometries are generated as interpenetrating structures [4,42,50] where fibers penetrate into or are separated from each other either just touching [17,32] or with certain inter-fiber spacing [46]. These virtual 3D geometries are usually constructed digitally using data obtained by inspection. This process involves the positioning of virtual cylindrical objects with diameters that correspond to the average of fiber diameter on top of each other at varying angles to fill the desired domain. Wang and his co-workers [51] used the above technique to investigate fluid flow behavior through the virtual geometry of a filter media having bimodal fiber diameter distribution. To be more realistic some authors have introduced crimp and bending of fibers at crossovers [52–54].

The virtual geometry technique was used by Van Doormal and Pharoah [17] in the investigation of through-plane and in-plane permeability of virtual proton exchange membrane fuel cell (PEMFC) in which porous transport layers with fibers arranged in defined angles and random orientation were used. It was shown that the through-plane and in-plane permeability depends strongly on the porosity of the sample. It was also established that in contrast to the in-plane permeability, the through-plane permeability was marginally affected by fiber angle. Maximum and minimum values of permeability were achieved when fibers were aligned parallel or perpendicular to the flow direction, respectively.

There are relatively few studies for the determination of permeability in random fibrous networks [4,40,43,55]. Clague and Phillips [55] managed to determine permeability, using slender body theory together with Ewald summation technique. Recently, Stylianopoulos and his co-workers [43] developed 3D fibrous networks with three different levels of fiber orientations and compared the permeability of their 3D isotropic structures with those of their moderately and highly oriented media. It was observed that the highly aligned networks were more permeable than the moderately aligned networks, the latter in turn, was more permeable than the isotropic fibrous networks. Pradhan and his co-workers [4] by varying the degree of fiber orientation of a series of virtually generated fibrous structures analyzed their transverse permeability by solving the Stoke equations. It was established that fibrous structures with higher preferential orientation of fibers along z-axis (fluid flow direction) exhibited higher transverse permeability and this behavior was found to be non-linear. This was found to be in line with the findings of Stylianopoulos et al. [43], and in contradiction with findings of Tahir and Tafreshi [42]. Tahir and Tafreshi [42] demonstrated that the transverse permeability of a fibrous medium while is independent of in-plane fiber orientation, raises with an increase in deviation of the fibers' through-plane angle from zero.

Studies relevant to fluid flow through fibrous structure with virtual geometries face limitations in prediction of permeability of realistic complex fabric geometries and structural shapes [4,17,42,43]. More recently, a 3D structure of fibrous porous networks was obtained via digital volumetric imaging (DVI) [29], magnetic resonance imaging (MRI) [56] and X-ray micro-computed tomography (XMT) [28,57] and flow simulations were performed using a commercial computational fluid dynamics code. These have resulted in the prediction of permeability in relation to porosity of the media. Using real geometries and applying realistic boundary conditions leads to higher level of confidence as well as elimination of inevitable guess work that is necessary in the creation of virtual geometries.

The above review is by no means exhaustive; however it highlights the effect of fiber orientation on anisotropic permeability of fibrous materials. The reported results on the effect of 3D fiber orientation on the permeability of fibrous porous networks appeared to be contradictory [42,43]. These contradictions call for re-examination of the effect of 3D fiber orientation on the in-plane and transverse permeability of the fibrous porous networks. The reviewed models and other studies in this field fundamentally suffer from the limitation that is imposed due to the employment of stochastic techniques used for reconstruction of digital 3D models of fibrous networks [4,17,42]. Application of analytical methods has always been based on the general assumption that the fibrous porous network is essentially composed of a number of simplified assumptions. Review of the literature also shows that as the complexity of flow problem increases, analytical solutions to fluid flow equation become scarce and numerical solutions become more prevalent. For the simulations to become more realistic, generated 3D models must be based on the actual micro-structure of manufactured fibrous porous materials. In a recent study, the authors