Journal of Power Sources 385 (2018) 100–113

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

An optimized microstructure to minimizing in-plane and through-plane pressure drops of fibrous materials: Counter-intuitive reduction of gas diffusion layer permeability with porosity

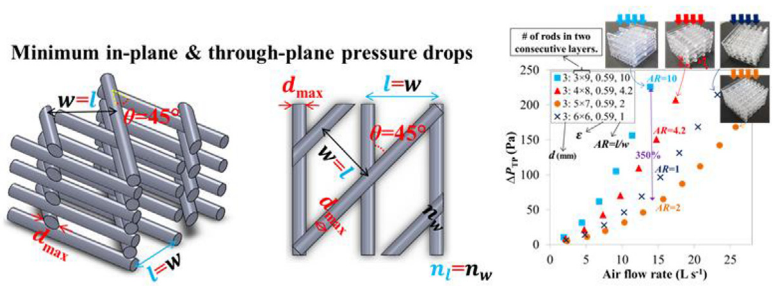
Hamidreza Sadeghifar[a,b,c,d,e,*]

[a] Laboratory for Alternative Energy Conversion (LAEC), School of Mechatronic Systems Engineering, Simon Fraser University, Surrey, BC V3T 0A3, Canada
[b] Institute for Integrated Energy Systems (IESVic) & Energy Systems and Transport Phenomena Lab (ESTP), Department of Mechanical Engineering, University of Victoria, Victoria, BC V8W 3P6, Canada
[c] Department of Chemical and Biological Engineering, University of British Columbia, 2360 East Mall, Vancouver, BC V6T 1Z3, Canada
[d] Vancouver International CleanTech Research Institute Inc., 4475 Wayburne Dr. Suite 310, Burnaby, BC V5G 4X4, Canada
[e] Department of Material Science and Engineering, Southern University of Science and Technology of China (SUSTech), 1088 Xueyuan Ave, Nanshan Qu, Shenzhen Shi, Guangdong Sheng 518055, China

HIGHLIGHTS

- Permeability does not necessarily increase with porosity or fiber diameter.
- Widely-used permeability-porosity models may provide inaccurate results.
- In-plane pressure drop highly depends on the number of fibers parallel to the flow.
- Fiber spacing and not the fiber angles impacts through-plane pressure drop largely.
- Large diameter, equal spacing and 45° angle of fibers lead to low pressure drops.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Fibrous porous media
In-plane and through-plane pressure drops
Permeability
Fiber diameter
Fiber spacing
Fiber angle

ABSTRACT

The present study experimentally investigates the realistic functionality of in-plane and through-plane pressure drops of layered fibrous media with porosity, fiber diameter, fiber spacing, fiber-fiber angles and fiber-flow angles. The study also reveals that pressure drop may increase with porosity and fiber diameter under specific circumstances. This counter-intuitive point narrows down the validity range of widely-used permeability-porosity-diameter models or correlations.

It is found that, for fibrous materials, the most important parameter that impacts the in-plane pressure drop is not their porosities but the number of fibers extended in the flow direction. It is also concluded that in-plane pressure drop is highly dependent upon the flow direction (fiber-flow angles), especially at lower porosities. Contrary to in-plane pressure drop, through-plane pressure drop is a weak function of fiber-fiber angles but is strongly impacted by fiber spacing, especially at lower porosities. At a given porosity, low through-plane pressure drops occur if fiber spacing does not change practically from one layer to another. Through-plane

* Department of Chemical and Biological Engineering, University of British Columbia, 2360 East Mall, Vancouver, BC V6T 1Z3, Canada.
E-mail addresses: hsf@mail.ubc.ca, hamidreza.sadeghifar@mail.ubc.ca, sadeghif@sfu.ca, h_sadeghifar@alum.sharif.edu, hr@sustc.edu.cn.

https://doi.org/10.1016/j.jpowsour.2018.03.028
Received 7 November 2017; Received in revised form 7 February 2018; Accepted 12 March 2018
Available online 22 March 2018
0378-7753/

pressure drop also, insignificantly, increases with the intersecting angles between fibers. An optimized microstructure of fibrous media resulting in minimal in-plane and through-plane pressure drops is also offered for the first time in this work.

1. Introduction

Multi-layered or two dimensional (2D) fibrous materials are extensively used in a variety of applications [1,2,3]. This bolds the importance of characterizing the microstructure of these materials [4,5] and its impact on their transport properties [6,7,8]. Among the key properties of fibrous materials, in-plane and through-plane pressure drops or permeabilities are crucial for transport phenomena applications [9,10,11]. The functionality of permeabilities of fibrous materials with their microstructure has to be still fully characterized and elucidated, in spite of having numerous studies already available on porous media in the literature. Specifically, the majority of the works conducted on pressure drops or permeability of fibrous media are solely based upon two parameters: porosity (ε) and fiber diameter (d). These modeling [12,13], simulation [1,14,15,16] and experimental [17,18,19,20] studies did not consider the other important geometrical parameters such as the angle and the distance between fibers as well as the number of fibers in in-plane directions. The main idea in these works was to first reconstruct or consider a porous structure having the same porosity and fiber diameter as the fibrous medium does, and then to use or develop correlations, empirical relations or mathematical models to determine the permeability (K) as a function of these two parameters:

$$K = K(\varepsilon, d) \tag{1}$$

It is worth mentioning here that throughout this study, both terms "permeability (K)" and "pressure drop (ΔP)" are used since pressure drops are convertible to permeability data through the governing laws such as Darcy's law or Brinkman's equation for low-velocity laminar (creeping or weak inertial) flows [21,22] or the family formulas of Forchheimer law [23,24] or Izbash's law [25] for high-velocity (non-Darcy or turbulent) flows:

$$\Delta P = f\left(\frac{1}{K}\right) \tag{2}$$

1.1. Filling the gaps in the literature

K-ε-d (permeability-porosity-diameter) correlations or formulas have been used for decades in estimating the permeability or pressure drops of fibrous porous materials in various applications. These correlations provide permeability or pressure drop as a function of only two parameters: porosity and fiber diameter. Recently, a few *theoretical* attempts [26,27,28,29,30], summarized in Table 1, have been made to investigate the functionality of permeability with other geometrical parameters than porosity and fiber diameter. However, these works are mostly limited to numerical or modeling studies of either in-plane or through-plane Darcy (low-velocity) flows through a specific fibrous medium.

A thorough review of the literature shows that less attention has been to date devoted to the other structural parameters such as the intersecting angles and the characteristic distances between fibers in different layers. Specifically, the literature severely lacks a rigorous, experimental study revealing the realistic relationship between in-plane/through-plane pressure drops (or permeabilities) and all the geometrical parameters of a 2D fibrous medium, especially for medium- to high-velocity (non-Darcy) flows, as below:

$$K \text{ or } \Delta P = f(\varepsilon, d, \theta, l, w) \tag{3}$$

where θ ($0 \le \theta \le 90°$) is the intersecting angle between two touching fibers in two consecutive layers and l and w ($l \ge w$) are the spacing between fibers in two successive layers as shown in Fig. 1.

Equation (3) can be rewritten based on the number of fibers in touching layers instead of the fiber spacing (l and w):

$$K \text{ or } \Delta P = f(\varepsilon, d, \theta, n_l, n_w) \tag{4}$$

where n_l and n_w are the number of fibers in two consecutive (or touching) layers, see Fig. 1. It should be noted that since we assume $l \ge w$ (for consistency throughout this study), n_w is always greater than or equal to n_l ($n_l \le n_w$) per square unit.

In addition to determining the pressure drop-geometry relationships, the optimized microstructure of a fibrous medium that results in its minimum in-plane and through-plane pressure drops has not yet been identified in the literature. The objective of the present study is to (*i*) offer the optimized geometric parameters of fibrous media that corresponds to their minimal in-plane and through-plane pressure drops at a given porosity, and (*ii*) to identify the key geometric parameters having the most profound effects on the in-plane and through-plane pressure drops or permeabilities. This objective can be met by picturing the realistic impacts of porosity, fiber diameter, the intersecting angles and the characteristic distances between fibers on either of in-plane and through-plane pressure drops.

2. Experimental apparatus and methodology

Several stacks of cylindrical rods with different porosities, rod

Table 1
Recent studies on permeability or pressure drops of fibrous media and gas diffusion layers considering fiber orientations.

Authors (year)	Fibrous medium	Flow	Work (method)	Remarks
Soltani et al. (2014) [28]	1D-3D nonwoven fabrics	Darcy (IP &TP)[a]	CFD[b] simulation	3D orientation of fibers in fibrous networks affects the permeability.
Pradhan et al. (2012) [30]	3D	Darcy (TP)	Numerical Simulation	Transverse permeability was increased with the increase in degree of anisotropy of 3D fiber orientation.
Ashari et al. (2010) [27]	2D	Darcy (IP)	Simulation by PlexPDE	The rate of fluid spread increases with increasing the in-plane alignment of the fibers.
Tahir and Tafreshi (2009) [29]	2D & 3D	Darcy (IP &TP)	CFD simulation by Fluent	Transverse permeability is independent of in-plane fiber orientation but increases with increasing deviation of the fibers' TP angle from zero.
Doormaal and Pharoah (2009) [26]	2D GDLs	Darcy (IP &TP)	Simulation (lattice Boltzmann)	Fiber arrangement strongly impacts GDL permeability. The TP permeability is not affected much by the fiber angle contrary to the IP permeability.

[a] IP: In-plane & TP: Through-plane.
[b] CFD: Computation fluid dynamics fluid dynamic