Short communication

Fractal geometry model for through-plane liquid water permeability of fibrous porous carbon cloth gas diffusion layers

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HIGHLIGHTS

- Fibrous porous structure effects on liquid flow in fiber bed are studied.
- A fractal model for through-plane permeability of GDL is proposed based on the fractal analysis method.
- The model is more accurate for the prediction of the through-plane permeability of GDL.

ARTICLE INFO

ABSTRACT

The short communication presents an improved fractal model to predict through-plane liquid water permeability of the gas diffusion layer (GDL) in proton exchange membrane fuel cells (PEMFCs). The porous structure of a GDL is modeled as a combination of parallel and perpendicular channels to the fluid flow direction. The through-plane permeability equation is derived by a hybrid of fractal longitudinal permeability and transverse permeability in parallel with the former. This model is validated by comparing with the referenced data. It is found that the proposed fractal model is preferred for through-plane permeability predictions of GDL.

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1. Introduction

The proton exchange membrane fuel cells (PEMFCs) have shown immense potential as one of the best alternative power source for automotive, stationary and portable applications because of their low emission and relatively high efficiency. The gas diffusion layer (GDL) which is sandwiched between the catalyst layer (CL) and the gas flow channels is a crucial component in the PEMFCs [1]. In general, carbon cloth consisting of randomly packed carbon fibers is commonly used as the GDL. As a transport property, the permeability of the GDL is a key parameter on the performance of the PEMFCs since GDL allows transport of reactant gas, removal of liquid water and conducting electrons. Therefore, numerous research papers aim at predicting the gas permeability of GDL in the past few years. Tamayol et al. [2] theoretically and experimentally investigated effects of mechanical compression and PTFE

content on the through-plane gas permeability of GDL of PEM fuel cells. Hao Liang and Cheng [3] used the multiple-relaxation-time (MRT) lattice Boltzmann method (LBM) with multi-reflection solid boundary conditions to study anisotropic permeabilities of a carbon paper gas diffusion layer (GDL). Didari et al. [4] used a geometric modeling scheme called periodic surface model to construct 3D models of GDL microstructure. The through-plane and in-plane permeability of the GDL were computed by solving the incompressible flow field in the reconstructed zone.

The previous experimental results have shown that the micro-structures and pore-size distribution of the GDL in PEMFCs have fractal characteristics [5,6]. This means that the fractal theory may be used to predict the gas or water permeability of GDL. Shi et al. [7] presented a fractal permeability model for the GDL. The actual microstructures of the GDL in terms of pore area dimension and tortuosity dimension are accounted in the model. He et al. [8] developed a fractal to predict the permeability and liquid water relative permeability of the GDL (Tornay TGP H-120 carbon paper) in PEMFCs for the hydrophilicity case and the hydrophobicity case. Their research results indicated that a hydrophobic carbon paper is

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preferred for efficient removal of liquid water from the cathode of PEMFCs. Lo et al. [9] investigated the gas permeability for the microporous layer (MPL) and GDL of PEMFCs using fractal method respectively. The gas molecule effect is also considered by using the Adzumi equation. All the above-mentioned fractal models were based on the assumption that the pores within GDL were only considered as a bundle of tortuous capillary tubes with variable cross-sectional area in the through-plane direction. However, randomly oriented, straight, cylindrical fibers of constant diameter are randomly distributed in a unit cell with free overlapping in the carbon paper. The complex structure of pore-level geometry yields numerous capillary/channels not only parallel to fluid flow but also normal to fluid flow in the media. So, the geometrical structure shown in Fig. 1 can be assumed as an idealized representation of the GDL. All gas channels consist of ones which are parallel to the direction of fluid flow (Part A) and ones which are perpendicular to the direction of fluid flow (Part B) (Fig. 2).

In this short communication, we propose a suitable fractal longitudinal and transverse model for predicting the through-plane permeability of fibrous GDL based on the dual-scale porous microstructural characteristics of such fibrous material. Both the parallel and perpendicular channels are included in the fractal model. Some conclusions are to be drawn from the comparisons among proposed fractal model, other existing analytical models and experimental value.

2. Fractal longitudinal permeability K_L

The GDL is usually made of carbon paper which is composed of randomly packed carbon fiber. Porous Part A can be considered as a bundle of tortuous capillary tubes with variable radius for the two-dimensional case. Let the diameter of a capillary in the Part A be λ, and its tortuous length along the flow direction be $L(\lambda)$. Then, these tortuous capillaries can be described by fractal scale equation [10]

$$L(\lambda) = L_0 \left(\frac{L_0}{\lambda}\right)^{d_t - 1} \qquad (1)$$

where L_0 is the characteristic length of a straight channel and d_t the tortuosity fractal dimension with the value of $1 < d_t < 2$. A lower value of d_t corresponds to a lowly tortuous capillary, thus $d_t = 1$ represents a straight capillary and $d_t = 2$ corresponds to a highly tortuous line that fills whole space. Another characteristic of the fractal object is that the cumulative size distribution of passages/channels follows the power law relation [10]

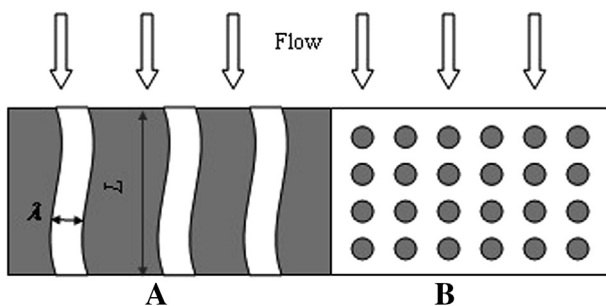$$N(L \geq \lambda) = \left(\frac{\lambda_{max}}{\lambda}\right)^{d_f} \qquad (2)$$

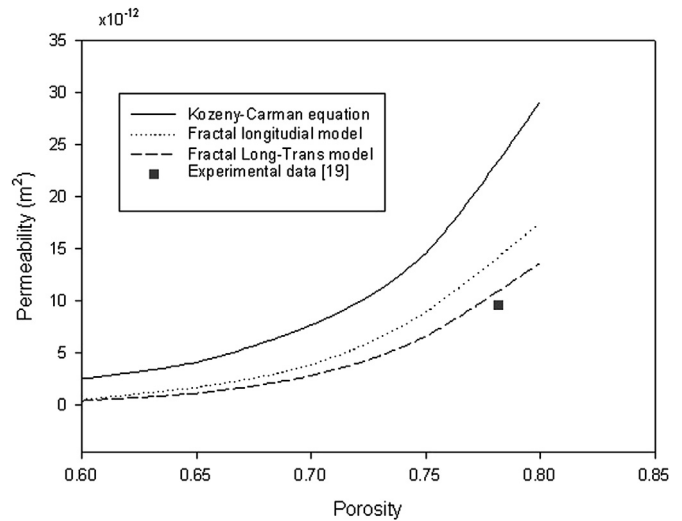**Fig. 1.** Porous geometrical structures for GDL.

Fig. 2. Comparison between proposed model, referenced data, and other existing models (Long-Trans — longitudinal and transverse).

and

$$-dN = d_f \lambda_{max}^{d_f} \lambda^{-(1+d_f)} d\lambda \qquad (3)$$

where d_f is the pore area fractal dimension, λ and λ_{max} are the pore/channel diameter and the maximum pore/channel diameter, respectively.

According to the well-known Hagen–Poiseulle law, one can obtain the flow rate $q(\lambda)$ through a single tortuous capillary. It should be noted that only liquid water permeation is considered, so the Knudsen gas permeability diffusion will not included in the short communication. The $q(\lambda)$ can be given by Ref. [11]

$$q(\lambda) = \frac{\pi}{128} \frac{\Delta p}{L(\lambda)} \frac{\lambda^4}{\mu} \qquad (4)$$

where Δp is the pressure gradient, μ is the viscosity of permeation fluid. Then, the total flow rate Q can be calculated by integrating the individual flow rate, $q(\lambda)$ over the entire range of pore sizes from the maximum pore λ_{min} to the maximum pore λ_{max} in a unit cell.

$$Q = - \int_{\lambda_{min}}^{\lambda_{max}} q(\lambda) dN(\lambda) \qquad (5)$$

Therefore, the longitudinal permeability K_L of Part A can be written following the Darcy's law [11,21]

$$K_L = \frac{\mu L_0 Q}{\Delta p \cdot A} = \frac{\pi}{128} \lambda_{max}^{3+d_t} \frac{L_0^{1-d_t}}{A} \frac{d_f}{3 + d_t - d_f} \qquad (6)$$

where A is the total area of the unit cell and is related to the total pore area A_p by the definition

$$A = \frac{A_p}{\varphi} = \frac{\pi d_f}{4\varphi(2 - d_f)} \lambda_{max}^2 [1 - \varphi] \qquad (7)$$

Substituting Eq. (7) into Eq. (6) leads to

$$K_L = \frac{1}{32} \lambda_{max}^{1+d_t} \frac{\varphi}{1-\varphi} L_0^{1-d_t} \frac{2 - d_f}{3 + d_t - d_f} \qquad (8)$$