ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2018) 1–9

Available online at www.sciencedirect.com

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An analytical model for the transverse permeability of gas diffusion layer with electrical double layer effects in proton exchange membrane fuel cells

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ARTICLE INFO

Article history:
Received 5 June 2018
Received in revised form
19 July 2018
Accepted 30 July 2018
Available online xxx

Keywords:
Gas diffusion layer
Proton exchange membrane fuel cell
Permeability
Electrical double layer
Zeta potential

ABSTRACT

An analytical model is presented for the transverse permeability of gas diffusion layer (GDL) based on an ordered array of parallel charged circular cylinders at the steady state. The formula of calculating the permeability of the transverse direction is given by solving the fluid momentum equation in a unit cell. In the present approach, the proposed model is explicitly related to the porosity and fiber radius of fibrous porous media, the zeta potential, and the physical properties of the electrolyte solution. Besides, the effects of these parameters (the porosity, unit cell aspect ratio, fiber radius, and molar concentration) on the transverse permeability are discussed detailedly. The model predictions are compared with the previous studies in the available literature, and good agreement is found.

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Introduction

Gas diffusion layer (GDL) in the proton exchange membrane fuel cells (PEMFCs) [1–4] is a fibrous porous medium. And the GDL plays the essential role in PEMFCs of permitting gas/liquid to be transported from the supply channel to the electrode/electrolyte interface. Generally, the slow fluid flow in the GDL satisfies Darcy's law [5], viz.

$$\overline{u} = -\frac{K}{\mu}\nabla P \tag{1}$$

where $\overline{u}$, K, μ and ∇P are the volume-averaged superficial fluid velocity, permeability of the porous medium, fluid viscosity and pressure gradient, respectively. It is well-known that the permeability is one of the most important transport properties [6–16] of porous media, and represents the ability of porous matrix to transport fluids.

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https://doi.org/10.1016/j.ijhydene.2018.07.186

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Please cite this article in press as: Liang M, et al., An analytical model for the transverse permeability of gas diffusion layer with electrical double layer effects in proton exchange membrane fuel cells, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.07.186

Nomenclature

K	permeability of the porous materials (m^2)
$\bar{u}$	volume-averaged superficial fluid velocity (m/s)
u	fluid velocity (m/s)
P, p	pressure (Pa)
r	fiber radius (m)
S	side length of a rectangular cell
h	half-height of a channel
C_0	molar concentration of an electrolyte solution (mol/L)
N_A	Avogadro constant (mol^{-1})
k_B	Boltzmann constant (J/K)
e	elementary charge (C)
Z	valence of an electrolyte solution
j	current density (A/m^2)
E	induced electric field (V/m)
T	absolute temperature (K)
Q	total flow rate through a unit cell (m^3/s)

Greek symbols

ϕ	porosity of the porous materials
∇	gradient
Δ	difference
μ	viscosity of an electrolyte solution ($Pa \cdot s$)
ρ_e	the net charge density per unit volume (C/m^3)
ε	permittivity of an electrolyte solution (F/m)
λ	electrical conductivity of an electrolyte solution (S/m)
ζ	zeta potential (V)
κ	Debye-Huckel parameter (m^{-1})
ψ	local electrical potential (V)
α	unit cell aspect ratio
β, χ, Θ	dimensionless parameter

Subscripts

+	dimensionless
x	x-direction
y	y-direction

Functions

cosh	hyperbolic cosine function
arctan	tangent function

So far, a number of experiments [17–24] for the permeability of fibrous porous media were reported. Some researchers studied the transverse permeability of various fibrous porous materials including square [17–21], staggered [21], and hexagonal [21] arrangements of unidirectionally aligned fibers. Recently, Aitomäki et al. [22] researched experimentally the influence of porosity on the permeability of cellulose nanofibre (CNF) network composites, and found that the permeability of CNF networks was much lower than that of the Kraft paper. Later, the gas permeability [24] of catalyzed electrodes was investigated experimentally in PEMFCs at various temperatures for air, oxygen and nitrogen gases. These experimental data indicated that the catalyst layer reduced considerably the gas permeability. Besides, the higher temperatures slightly enhanced the gas permeability. Generally, in view of the expensive and time-consuming natures of experiments, theoretical works [17,21,25–33] for the permeability have attracted scholars' considerable attention. In early studies, some theoretical models were developed to predict the transverse permeability of a variety of unit cells including square [21,25,26], staggered [21,25,26], and hexagonal [21,26] arrangements of fibers. However, these theoretical models contain some empirical constants. Furthermore, Shou et al. [34] utilized the square and hexagonal arrangements of circular yarns to develop the mathematical models for the transverse permeability in dual-scale fibrous media. But, these models are semi-analytical. With the development of computer technology, more and more numerical methods were used to predict the permeability, such as Lattice-Boltzmann method [35], Monte Carlo method [36,37], and Computational Fluid Dynamics method [38]. Nevertheless, the numerical results can not clearly explain transport mechanisms in porous media. In recent years, the permeability for GDL in PEMFCs was also studied by some scholars. For example, a fractal model [39] was reported for the through-plane permeability of the GDL in PEMFCs and validated by the available experimental data. Moreover, the model was better than other analytical models. Later, the effective permeability [40] of GDL in PEMFCs was investigated analytically based on a scaling estimate method. These model predictions agreed closely with experimental and numerical results over a wide porosity range. Recently, Xiao et al. [41] presented a dimensionless fractal model for permeability of fibrous gas diffusion layer in PEMFCs. In this model, the permeability was expressed as a function of the tortuosity, porosity, and pore area fractal dimensions of fibrous gas diffusion layer in PEMFCs.

Mattern and Deen [42], however, investigated the hydraulic permeability of fibrous porous media, and found that the electrolyte solution permeability was less than that of the neutral solution. This phenomenon is known as the electrokinetic effects [43–49] which can be explained as follows: on one hand, most solid surfaces of natural and artificial objects carry electrostatic charges. Furthermore, the interaction between the electrostatic charges on solid surfaces and these ions in liquids will produce the zeta potential [50] and the electrical double layer (EDL) [51] in the solid-liquid interface. On the other hand, the EDL has a significant influence on the flow when the thickness of the EDL is comparable with the channel/pore size in fibrous porous media. In addition, some researches for the permeability with electrokinetic effects in porous media have been reported in recent years. For examples, analytical permeability models [52,53] for the Newtonian and non-Newtonian fluids with EDL effects in fibrous porous media were presented based on the fractal theory for porous media. Recently, Cheng et al. [54] evaluated the permeability and streaming potential coupling coefficient together with the capillary bundle model, zeta potential model and specific surface conductance in porous transducers. Presently, however, the analytical permeability study related to the EDL effects in fibrous porous media with an ordered array of parallel circular cylinders has not reported.

In the present paper, we propose an analytical model for the transverse permeability of GDLs with rectangular

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