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A numerical investigation of reactant transport in a PEM fuel cell with partially blocked gas channels

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ABSTRACT

In this study, a numerical model was presented to investigate the mass transport in a PEM fuel cell with partial blocks inserted in the gas channel designed to progress reactant gas distribution in the gas diffusion layer. The effect of the partial blocks design, the gas diffusion layer porosity on the reactant gas transport and distribution were examined. In particular, the desirable gas channel design for enhancing the performance of the PEM fuel cell is determined by examining the tilt angle of partial blocks. The results attained show that partial blocks introduced in the gas channel improve the PEM fuel cell performance. To validate the numerical model, an experimental test bench has been used to examine the cell performance. The simulation results specify that the effect of tilt angle is critical to the PEM fuel cell performance especially to minimize concentration over-potential.

1. Introduction

Fuel cells are electrochemical devices that convert fuel directly into electrical energy at relatively high efficiency [1]. A uniform flow distribution is critical to obtaining high performance in many heat and mass transfer devices. The geometry of a fuel cell flow construction requires several parameters, e.g., flow channel pattern, and diffusion layer width. In effect, it is extremely difficult to consider the effects from all arrangements of these factors concurrently [2]. A poorer reactant transport leads to a lower gas concentration at the catalyst sites and may give rise to a maximum concentration over potential. The effect of gas distribution becomes more significant when the current density increases, leading to a limitation of the maximum power density supplied by the cell. However, optimizing the flow field is a very difficult task and very complicated to treat [3]. The aim of the flow field optimization is to enhance the reactant transport inside the porous diffusion and catalytic layers for contributing in the electrochemical reactions.

Therefore previous work has focused on modeling the gas transfer process on the PEM fuel cells. The effect of gas channel flow field design is significant to avoid reactant maldistribution in the gas diffusion layer and catalyst sites. Wang et al. [4] investigated the effect of the channel size on the PEM fuel cell performance with serpentine flow fields using a three dimensional, two-phase model. Various interpolation schemes were used so that the model can be used in a variety of Knudsen number. Then the model was comprehensive to include porous media by counting some correction factors into the governing equations. Boddu et al. [5] have evaluated the gas channel with dissimilar serpentine configurations using CFD modeling. Results demonstrated that serpentine channels lead to additional pressure losses due to the presence of flow separations, thus resulting to an improvement in the heat and mass transfer. Sadiq Al-Baghdadi and Shahad Al-Janabi [6] showed a three dimensional model for a PEM fuel cell and demonstrated the effect of operating conditions and material factors on the cell performance. Han et al. [7] presented the optimized design of the channel by studying the flooding phenomenon in the gas diffusion layer, which is very important because it is involved in the reactants transport. Their result demonstrates that when the channel satisfies the Concus Finn condition, it shows higher performance and increased efficiency of about 5%, but they did not consider the effects of pressure drop caused by the non homogeneous reactant distribution in the gas diffusion layer. Nguyen and Knobbe [8] presented a numerical model to investigate the effect of rib width and depth in the PEM fuel cell performance by using commercial software for several channels. Several studies were very recently carried out to investigate the effect of flow channel on the PEM fuel cell performance and durability [9,10].

Jung et al. [11] used several flow fields, such as spiral, serpentine, discontinuous, and Z-type channels in a PEM fuel cell model, which was solved with a computational fluid dynamic code. Tseng and Lo [12] discussed the effects of the microstructure characteristics of the gas diffusion layer (GDL) and micro porous layer (MPL), including pore size distribution, hydrophobic treatment, and gas permeability on the water management and fuel cell performance. They concluded that under light and intermediate load conditions, fuel cells with and without MPL show similar performances.

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Nomenclature

A	area (m^2)
a	effective catalyst area per unit volume (m^2/m^3)
act	water activation
C	concentration
D	mass diffusivity ($m^2\ s^{-1}$)
F	Faraday's number ($C\ mol^{-1}$)
I	current density ($A\ m^{-2}$)
J	transfer current ($A\ m^{-3}$)
H	channel height (m)
K	permeability (m^2)
l	thickness
R	universal gas constant ($J\ mol^{-1}\ K^{-1}$)
Re	Reynolds number
S	source term
T	temperature (K)
V	cell potential (V)
X	mole fraction of species
z	site charge number

Greek

α	transfer coefficient
λ	water content
σ	protonic conductivity ($\Omega^{-1}\ m^{-1}$)
ε	porosity
μ	dynamic viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)
η	over potential (V)
ξ	stoichiometric flow ratio
ϑ	volumetric flow rate ($m^3\ s^{-1}$)
ϕ	phase potential (V)

Subscripts

an	anode
ca	cathode
C	catalyst layer
GDL	gas diffusion layer
eff	effective
K	species (H_2, O_2, H_2O)
ref	reference

However, at the high current density region, the cell with a MPL has much better performance and does not show any sign of mass transfer limitation. Wang et al. [13] proposed a new serpentine-baffled flow field design to enhance the cell performance and evaluated with that for a conventional serpentine flow field. They established that the baffled design shows better performance than the ordinary design at low working voltages. However, only partial comparisons of these different flow field designs have been possible. A three dimensional half-cell model is investigated by Kumar and Reddy [14] to focus on the enhancement of PEM fuel cell performance through optimization of the channel dimensions and shape in the flow channels. Tiss et al. [15] explored the effect of water content in the membrane swelling phenomenon. Their model demonstrates that the membrane water content has to be optimized in order to increase the PEM fuel cell performance. Hu et al. [16] compared the liquid water allocation in triangular and rectangular channels and found that triangular channels keep less water and the droplet sizes were too smaller compared to rectangular. Su et al. [17] numerically studied the effects of channel geometry on water droplet dynamics in several channels, including triangle, trapezoid and rectangle with a curved bottom wall and upside-down trapezoid. They concluded that channel geometry certainly affects the detachment of water droplets. Bearing in mind the mass production of PEM fuel cell flow fields, the rectangular cross-section is not the right geometry despite being usually used for research purpose.

From the literatures mentioned above, it is suggested that the cell performance can be improved by a suitable flow channel design. However, there are only a limited number of studies that investigated the effects of geometry for diverse flow field designs on the PEM fuel cell performance. A considerable benefit of parallel channels is minimum pressure drop between the reactants inlet and outlet. On the other hand, when the width of the flow field is comparatively large, flow distribution in each channel might not be identical. This causes water swelling in some channel regions, which leads to performance drop.

The purpose of this work was therefore to create a two-dimensional computational fluid dynamic model of the PEM fuel cell to examine the effects of geometry on cell performance and transport reaction of the PEM fuel cell. The effect of gas channel tilt angle and the gas diffusion layer porosity on the PEM fuel cell performance was also systematically studied.

2. Model descriptions

In our paper, a two-dimensional model of a PEM fuel cell system is considered. Fig. 1 illustrates a schematic diagram of the two dimensional PEM fuel cell model with four partial blocks along the gas channel. The gases flowing are hydrogen in the anode and oxygen in the cathode at an inlet velocity U_0 and pressure P_0. The fin disruptive used in this work is a rectangular support glued at the bottom of the GDL having a height between 0.5 and 4 mm. The parameters H, G and θ (Fig. 1) describe the gas channel height, the GDL thickness and tilt angle, respectively. The property of the tilt angle, the porosity (ε) of the GDL on the reactant gas transport and the performance of the cell were critically investigated.

Processes occurring during PEM fuel cell operations include mass transport of different species (H_2, O_2, and H_2O) coupled with fluid flow, heat transfer and electrochemical reaction. In the present model, we consider the single-domain approach; the advantage of our CFD method is that zero internal boundary conditions require to be defined. The model consists of non-linear, coupled partial differential equations representing the conservation of

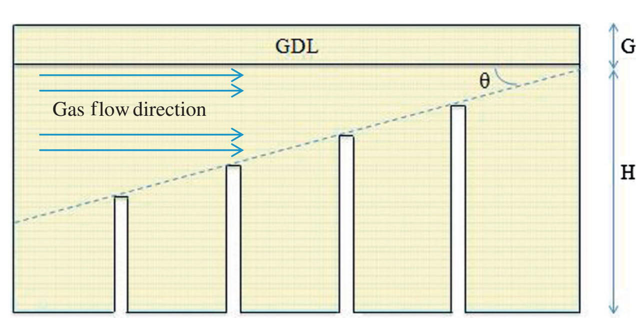

Fig. 1. Schematic illustration of GDL and gas channel with four partial blocks.