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Performance improvement of proton exchange membrane fuel cell by using annular shaped geometry

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ABSTRACT

A complete three-dimensional and single phase CFD model for a different geometry of proton exchange membrane (PEM) fuel cell is used to investigate the effect of using different connections between bipolar plate and gas diffusion layer on the performances, current density and gas concentration. The proposed model is a full cell model, which includes all the parts of the PEM fuel cell, flow channels, gas diffusion electrodes, catalyst layers and the membrane. Coupled transport and electrochemical kinetics equations are solved in a single domain; therefore no interfacial boundary condition is required at the internal boundaries between cell components.

This computational fluid dynamics code is used as the direct problem solver, which is used to simulate the three-dimensional mass, momentum and species transport phenomena as well as the electron- and proton-transfer process taking place in a PEMFC that cannot be investigated experimentally. The results show that the predicted polarization curves by using this model are in good agreement with the experimental results. Also the results show that by increasing the number of connection between GDL and bipolar plate the performance of the fuel cell enhances.

1. Introduction

The polymer exchange membrane fuel cell (PEMFC) is considered to be the most promising candidate for electric vehicles by virtue of its high power density, zero pollution, low operating temperature, quick start-up capability and long lifetime. PEMFC can also be used in distributed power systems, submarines, and aerospace applications [1].

The single-cell PEMFC consists of a carbon plate, a gas diffusion layer (GDL), a catalyst layer, for each of the anode and the cathode sides, as well as a PEM membrane at the center.

Flow channel geometry is of critical importance for the performance of fuel cells containing proton exchange membranes (PEM) but is of less concern for solid oxide fuel cells (SOFC). The reactants, as well as the products, are transported to and from the cell through flow channels. Flow field configurations, including parallel, serpentine, interdigitated, and other combined versions, have been developed.

The losses of voltage in the fuel cell dominate over different current density ranges. For low current densities; the activation over-potential is dominant. For high current densities, which are of particular interest for vehicle applications because of higher power density; the mass transfer limitations dominates the losses. For moderate current densities, the ohmic drop across the polymer membrane dominates. Moreover, for high current densities, water starts to exist in liquid form leading to a two-phase transport of reactants to reaction site, which is an additional transport phenomenon of PEM Fuel Cell operation.

Berning and Djilali [2] examined the effect of the porosity and thickness of gas diffusion layer in straight channel with three-dimensional model. These PEMFC numerical analysis models contributed to the optimization of component design and operation condition, and to the examination of issues included in present cell. However, these studies calculated internal phenomena in short straight gas channel and one serpentine channel or in small cell, and there are very few researches that evaluated various component shapes of actual size cell under considering realistic calculation time and calculation resource.

Chiang and Chu [3] investigated the effects of transport components on the transport phenomena and performance of PEM fuel cells by using a three-dimensional model. The impacts of channel aspect ratio (AR) and GDL thickness were examined. It was found that a flat channel with a small AR or a thin GDL generates more current at low cell voltage due to the merits of better reactant gas transport and liquid water delivery.

Wang et al. [4] developed a two-dimensional numerical model to study the two-phase flow transport in the air cathode of a PEMFC. In this paper, the model encompassed both single and two-phase regimes corresponding to low and high current

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Nomenclature

A	superficial electrode area (m^2)
C	molar concentration ($mol\ m^{-3}$)
D	species diffusivity ($m^2\ s^{-1}$)
I	current density ($A\ m^{-2}$)
i_0	reference current density ($A\ cm^{-2}$)
U	inlet velocity ($m\ s^{-1}$)
j	transfer current density ($A\ m^{-3}$)
$\vec{u}$	velocity vector ($m\ s^{-1}$)
p	pressure (Pa)
S	stoichiometric ratio
T	temperature (K)

Greek letters

η	overpotential (V)
ρ	density ($kg\ m^{-3}$)
ε	porosity
σ	ionic conductivity ($S\ m^{-1}$)
ϕ	phase potential (V)
ν	volumetric flow rate ($m^3\ s^{-1}$)
ξ	water content of the membrane
μ	viscosity ($kg\ m\ s^{-1}$)
α	transfer coefficient for the reaction

densities and was capable of predicting the transition between the two regimes.

Kuo et al. [5] performed numerical simulations to evaluate the convective heat transfer performance and velocity flow characteristics of the gas flow channel design to enhance the performance of proton exchange membrane fuel cells (PEMFCs). Their study has simulated low Reynolds number laminar flow in the gas flow channel of a PEMFC. The heat transfer performance and enhanced gas flow velocity characteristics of four different channel geometries have been considered, namely a conventional straight gas flow channel and a gas flow channel with the three novel periodic patterns geometries. The results indicated that, compared to the conventional gas flow channel, the novel gas flow channels proposed in this study provide a significantly improved convective heat transfer performance and a higher gas flow velocity and, hence, an improved catalysis reaction performance in the catalyst layer.

Yi and Nguyen [6] proposed an along the channel model for evaluating the effects of various design and parameters on the performance of a PEMFC. The results show that the humidification of the anode gas is required to enhance the conductivity of the membrane, and the liquid injection and higher humidification temperature can improve the cell performance by introducing more water into the anode. It is noted that the mass transport processes in the presence of liquid water are not considered in these two-dimensional models.

Um and Wang [7] used a three-dimensional model to study the effects an interdigitated flow field. The model accounted for mass transport, electrochemical kinetics, species profiles and current density distribution within the cell. Interdigitated flow fields result in forced convection of gases, which aids in liquid water removal at the cathode. This would help improve performance at high current densities when transport limitations due to excessive water production are expected. The model shows that there is little to no difference at low to medium current densities between an interdigitated flow field and a conventional flow field.

In this work a three-dimensional and single phase CFD model for annular-shaped geometry of proton exchange membrane (PEM) fuel cell is presented to investigate the effect of using different connections between bipolar plate and gas diffusion layer on the performances, current density and gas concentration. The objective of the current work is to show using a different geometry of the fuel cell and the effect of increasing the connections between bipolar plate and gas diffusion layer that it may be of interest to engineers attempting to develop the optimization of a PEMFC and to researchers interested in the flow modification aspects of the PEMFC performance enhancement.

2. Numerical model

The cathode electrochemical reactions produce a large amount of liquid water at low operating voltages. If the liquid water is not properly removed and accumulates in the pores of the porous layers, it restricts the oxygen transport to the gas diffusion layer and the catalyst layer, thereby reducing the electrochemical reaction rate.

The numerical model for the fuel cell used here includes the anode flow channels, anode gas diffusion layer, anode catalyst layer, proton exchange membrane, cathode catalyst layer, cathode gas diffusion layer, and cathode flow channels. Miniature annular fuel cells with dimensions of $D = 4.8$ mm and $L = 12$ mm are considered in this investigation. The gas diffusion layer is 0.3 mm thick, the catalyst layer is 0.01 mm thick, and the proton exchange membrane is 0.05 mm thick.

The geometrical relations in this study are for six different connections between GDL and bipolar plate.

The physical problem considered in this paper is the three-dimensional cell model of the PEMFC system as shown in Fig. 1.

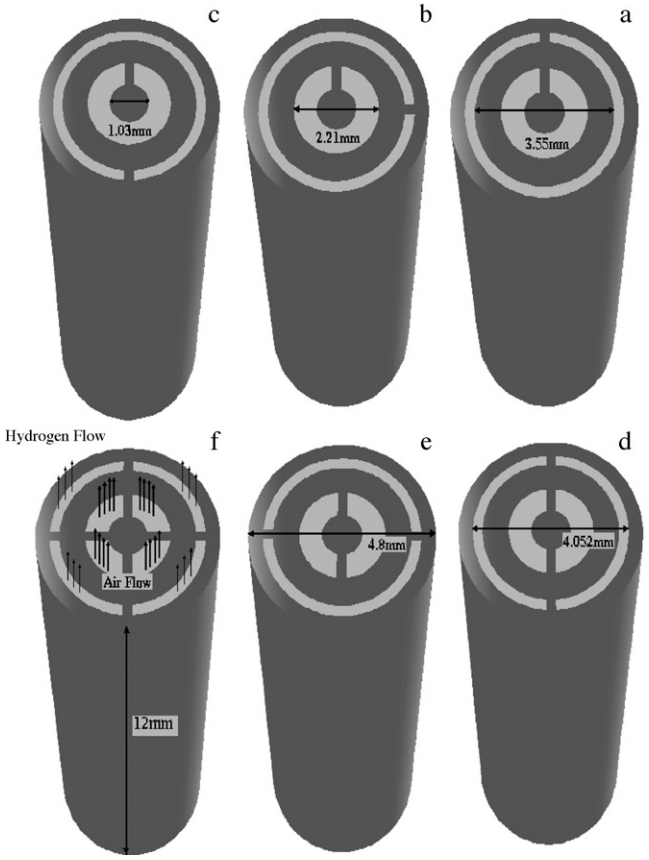

Fig. 1. Computational domain and schematic of annular PEMFC with (a) one connection (1), (b) one connection (2), (c) one connection (3), (d) two connection (1), (e) two connection (2) and (f) four connection.