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The optimization of channels for a proton exchange membrane fuel cell applying genetic algorithm

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ABSTRACT

A channel is a significant part of a proton exchange membrane fuel cell (PEMFC), and the configuration of the channel has a great effect on the mass transfer of the PEMFC, which directly influences the performance. In this study, a three-dimensional, single-phase, and non-isothermal model of a PEMFC with a single straight channel is developed. Based on the model, genetic algorithm (GA) is adopted to obtain an optimal design of the channel configuration. Power consumption of flow and output power of a PEMFC are considered into the objective function, and the width of bottom and top edges of the channel, in both the anode and cathode sides, are selected as variables. The optimal design obtained is a trapezoidal channel. At an operating potential of 0.4 V, the increment in current density in the optimal design is 10.92% compared to a basic design having a square channel. Moreover, the optimal design shows more uniform distributions of reactants and current density than the basic design.

1. Introduction

Proton exchange membrane fuel cell (PEMFC) technology is a type of green energy technology because it utilizes hydrogen, which is a renewable energy resource, as fuel. In a PEMFC, the chemical energy of reactants is converted directly into electricity [1], and the byproducts are water and heat. Therefore, a PEMFC is considered an ideal alternative to future power sources [2]. In addition, because of the advantages of high power density, low emissions, and fast startup, a PEMFC has wide application prospects in the automotive field and portable electronic devices. However, high manufacturing cost and low reliability make it difficult for widespread commercial use. Therefore, the performance of a PEMFC needs to be improved further.

Diffusion of hydrogen and oxygen through the gas diffusion layer (GDL) and the distributions of these species in the catalyst layer are important determinants of PEMFC performance [3]. The channel of a PEMFC plays an important role in the transportation and distribution of reactants. Therefore, changing the geometrical configuration of the channel to obtain an optimal channel configuration is an important aspect of improving PEMFC performance. During the past decades, many researchers have made great efforts to improve the PEMFC performance by optimizing the configuration of the channel.

Ahmed et al. [3] studied the influence of rectangular, trapezoidal, and parallelogram cross-sections of a channel on the performance of a PEMFC, and they observed higher cell voltage in the rectangular channel, but more uniform reactant and current density distributions in the trapezoidal channel. Manso et al. [4] developed three-dimensional models with different channel height/width ratio to investigate the influence of the channel cross-section aspect ratio on the performance of a PEMFC. Yoon et al. [5] adopted an experimental method to investigate the effects of channel and rib width on the performance of a PEMFC. Their results indicated that a narrow rib width could improve the performance of a PEMFC. Bilgili et al. [6] added obstacles near the outlet of a channel and compared the difference in performance between the channel with obstacles and a straight channel. In their study, they observed that the obstacles could improve the reactants distribution along the channels and facilitate the transport of reactants through the GDL, which could enhance the PEMFC performance. Shimpalee et al. [7] used a three-dimension model with a serpentine channel to study the effects of channel and rib width on PEMFC performance. They observed that a narrower channel with a wider rib spacing showed a higher performance. Liu et al. [8] conducted studies on a two-dimensional model of a PEMFC with a tapered flow field design. It was observed that the tapered flow channel could force more reactants into the GDL

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Nomenclature

A	effective catalyst area per unit volume ($m^2\ m^{-3}$)
C	molar concentration ($mol\ m^{-3}$)
D	mass diffusivity of species ($m^2\ s^{-1}$)
F	Faraday's number 96,487 ($C\ mol^{-1}$)
j	transfer current density ($A\ m^{-3}$)
R	universal gas constant 8.314 ($J\ mol^{-1}\ K^{-1}$)
S	source term
T	temperature (K)
$\mathbf{u}$	velocity ($m\ s^{-1}$)
k	thermal conductivity (W/m K)
K	permeability (m^2)
M	molecular weight
p	pressure (Pa)
C_p	constant-pressure heat capacity ($J\ kg^{-1}\ K^{-1}$)

Greek letters

α	transfer coefficient or water transport coefficient
ε	porosity
μ	viscosity ($Pa\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
σ	conductivity ($S\ m^{-1}$)
ϕ	phase potential
ω	species mass fraction
η	overpotential (V)

Subscripts

a	anode
c	cathode
eff	effective
ref	reference
k	H_2 or O_2
e	electrolyte
s	electron
aggl	agglomerate

and catalyst layer, which in turn increased the output power. Tiss et al. [9] added partial blocks in a channel and analyzed three different designs whose the tilt angles of partial blocks were 4.9°, 6.6° and 8.2°, respectively. Their results indicated that the performance of a PEMFC was best when the tilt angle was 4.9°. Liu et al. [10] applied a baffle-blocked flow channel in the cathode of a two-dimensional fuel cell model. They observed that the reactant transport and the performance of the PEMFC were enhanced by the baffles. Kuo et al. [11] developed a three-dimensional, single-phase, multi-species, steady-state model of a PEMFC with wave-like flow channels and compared its performance with that of a conventional straight channel at temperatures of 323 K, 333 K and 343 K. The results indicated that the PEMFC with wave-like channels obtained a higher power density. Hu et al. [12,13] compared the interdigitated flow field with the conventional flow field. They found the interdigitated flow filed made the fuel cell had better mass transfer performance. Wang et al. [14] changed the flow channel size to find the effect of the flow channel size on the cell performance for single serpentine flow field designs. The results shown that decreases of the flow channel and rib size led to more uniform current density distributions and more pressure drop. Wang et al. [15] proposed a novel serpentine-baffle flow field design for enhancing the performance of fuel cell. Roshandel et al. [16] established three fuel cell models with parallel flow channels, serpentine flow channels and bio inspired flow channel respectively. The bio inspired flow channel shown higher performance. Some other researchers [17–20] also proposed new channel designs for improving the performance of fuel cell.

In the studies mentioned above, a PEMFC was optimized using several specific configurations of the channel. However, few researchers adopted optimization algorithms to optimize the configuration of a PEMFC.

Perng et al. [21] investigated the effect of a tapered flow channel with a baffle plate on the performance of a PEMFC by developing a two-dimensional non-isothermal cathode model and used the element-by-element preconditioned conjugate gradient method to optimize the tapered ratio and gap ratio. Wang et al. [22] optimized the height and width of a serpentine channel PEMFC by adopting a simplified conjugate-gradient method. Yang et al. [23] conducted studies on a two-dimensional PEMFC model to optimize its configuration by using genetic algorithm. The widths of channel and rib and the channel height were chosen as geometric variables. They observed that the performance of a wider channel was better than a narrower channel, and a channel height of 0.515 mm showed the best performance. However, in their study, the evaluation criteria of PEMFC performance did not include pressure drop due to the flow of reactants in the PEMFC that could lead to extra power consumption.

In this study, a three-dimensional PEMFC model with a straight single channel is developed, and the results are verified with experimental data. Based on the model, genetic algorithm is used to obtain the best cross-section of the channel, and both output power and pressure drop are considered in the objective function.

2. Model development

The model developed in this study is a three-dimensional, steady-state, single-phase, and non-isothermal PEMFC model.

2.1. Model assumptions

To make the model manageable, the present model is developed under the following assumptions:

1. The flow in the fuel cell is laminar.
2. The gas mixtures are considered ideal, and ideal gas law was employed for gas mixtures.
3. Water in the fuel cell is assumed to be in the gaseous phase.
4. The membrane is assumed to be fully humidified because of 100% humidity in the anode and cathode, and its protonic conductivity is simplified to be a constant [24].

2.2. Governing equations

As shown in Fig. 1, the fuel cell geometry used in this model consists of nine components (anode and cathode bipolar plates, flow channels, GDLs, catalyst layers, and membrane). The geometric parameters of the model, which correspond to the experiment test case of [25], are listed in Table 1. Each component has different governing equations. In this study, the governing equations mainly involve the continuity, momentum, energy, electrochemical, and Maxwell–Stafen equations. The corresponding governing equations are written as follows: