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Influences of operational factors on proton exchange membrane fuel cell performance with modified interdigitated flow field design

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HIGHLIGHTS

- ► Using 3D model and Taguchi method in interdigitated channel gets optimal performance.
- ► Adding rectangular parallelepipeds increases the electrochemical reaction.
- ► Novel design generates more uniform current density and concentration distribution.
- ► The rectangular parallelepiped number over 8 has little enhancement for net power.
- ► The net power of the novel design 26% more than that of the original one.

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ABSTRACT

This paper presents a novel design of the rectangular parallelepiped within the interdigitated flow field to augment the performance of a PEM fuel cell by simulation and experiment. The numerical results indicate that the performance is enhanced with increasing the rectangular parallelepiped number because of stronger obstructing reactant gases through the channel to enter catalyst layers. In addition, the novel design is numerically obtained for the interdigitated flow field. The operational parameters are then determined by the Taguchi method on the experiment according to the novel design. The net power obtained is 26% greater for the novel design at the optimum parameter combination of $A_2B_3C_2D_2E_2$ than for the smooth-walled channel at the $A_2B_2C_2D_3E_3$.

1. Introduction

A proton exchange membrane (PEM) fuel cell has most drawn attention through its simplicity, viability, quick start-up, and pollution-free from reaction to form H_2O. In addition, it is smaller in volume and lighter in weight compared with other fuel cell types and the electrolyte is a solid material, therefore making the technology attractive for any conceivable application from powering a cell phone to a locomotive [1]. That is why most major automobile and electronic companies are competing in fuel cell development and why approximately 90% of fuel cell research and development work involves PEM fuel cells [2–4].

In the components of a PEM fuel cell, the bipolar plate has a high position. Its most important function is to supply reactant gases to the catalyst layers via the flow channel, and also to assist water and heat management. For several decades, many researchers have studied the flow channel design for improving the PEM fuel cell performance [5–10]. Various configuration designs of flow channel in PEM fuel cell systems such as the serpentine, parallel, and interdigitated channels were used for bipolar plates. The results of Refs. [11–13] suggested an interdigitated flow channel design. This flow channel has been provided to shorten the diffusion path for better mass transfer and convection flow in GDL for enhancing water removal capability and bringing about better performance, particularly at higher current densities.

The authors conducted the Taguchi methodology of quality control in the experimental analysis. Taguchi method is an efficient tool for the design of high-quality manufacturing system adopted in various fields extensively [14–16]. The target of Taguchi method is to reduce the variation (increasing robust) of the system performance with sources from a single characteristic's variation and revealing optimal setting by conducting a limited number of experiments with factor combinations. In recent years, much attention has been focused on the application of Taguchi method to PEM fuel cell designs. The results of applications indicated that

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Nomenclature

Symbol Description Units

A	area, m^2
ANOVA	analysis of variance, –
C	mole concentration, kmol m^{-3}
C_p	mixture-averaged specific heat capacity, J kg^{-1} K^{-1}
CF	correction factor, –
CI	confidence level, –
D	diffusivity of species, m^2 s^{-1}
E	voltage, V
F	Faraday's constant, 96,478 C mol^{-1}
f_e	degree of freedom (DOF), –
I	current, A
i	current density, A m^{-2}
j	exchange current density, A m^{-3}
k	thermal conductivity, W K^{-1} m^{-1}
K	permeability, m^2
l	levels, –
M	molecular weight, kg mol^{-1}
N	number, –
P	pressure, Pa
R_u	gas constant, 8.314 J mol^{-1} K^{-1}
S	source term, –
SS	sum of squares, –
S/N	signal-to-noise ratio, dB
T	temperature, K
$\vec{u}$	velocity vectors, m s^{-1}
W	power, W
X	mole fraction, –
Y	mass fraction, –
α	transfer coefficients, –
ε	porosity, –
ρ	density of gas, kg m^{-3}
μ	viscosity, m s^{-2}
κ	conductivity, Ω^{-1} cm^{-1}
ζ	stoichiometric flow ratio, –
η	overpotential, –
Δs	entropy charge, kJ mol^{-1} K^{-1}
Φ	phase potential, V

Superscript

sat	saturation
eff	effective, –

Subscript

a	anode, –
c	cathode, –
e	electric, –
i, j	species, –
m	ionic, –
s	solid phase, –
w	water, –

this technique obtained the optimum operating parameters and improved the performance of PEM fuel cells [17–20]. However, as the single-response problem is discussed in the previous section, one factor is very important to one quality characteristic while it may be unimportant to the other quality characteristics in the process of flow field designs. In addition, the flow field designs in the bipolar plate have been considered more crucial factors for enhancing the cell performance and decreasing the pressure drop losses. If more than one characteristic is simultaneously considered for the same process, the one factor method may not give a unique optimal combination of parameters; in particular, these characteristics compete with each other. The quality characteristic of the electric power in the Taguchi method has therefore been applied to the cell performance enhancement in the PEM fuel cell systems.

In the heat exchangers and gas turbine, rib, fin, groove or baffle was often employed to enhance the convective heat transfer rate leading to the compact heat exchange and increasing the efficiency [21–23]. The cooling or heating air passed the channel with several ribs to increase the powerful degree of cooling or heating levels over the smooth wall channel. Presently, several researchers [24–27] have illustrated the PEM fuel cell performance for single baffle plate, single rectangular block, or a row of baffle plates using a two-dimensional cathodic half cell model. However, the investigation was few on a row of rectangular parallelepipeds and the row arrangements at the axis in the anode and cathode channels to deflect the fluid and the performance enhancement. Therefore, this study presents flow modification by rows of rectangular parallelepipeds in the interdigitated flow channel in PEM fuel cells to ensure uniform reactant gas distribution and effective heat removal.

The above presented modification needs to introduce a new concept of robust parameter design at each trial of orthogonal array for simultaneous maximization of output power and minimization of pressure drop losses. Moreover, the numerical results are verified by the experiments using an experimental model with rectangular parallelepipeds. The results of this paper may be supplying the information to the engineers and researchers on the transport phenomenon of the novel interdigitated flow field and the optimum operation condition in PEM fuel cells.

2. Mathematical description

2.1. Modeling geometry and assumption

The three-dimensional model of an entire cell with rectangular parallelepiped rows is displayed in Fig. 1. This model considered the smooth-walled channel and rows of rectangular parallelepipeds crossed through the axis in the interdigitated flow channel of PEM fuel cells. The shapes in this schematic are used as follows: $H/H_1 = 1.5$, $H_2/H_1 = 0.5$, $H_3/H_1 = 0.6$. Table 1 lists the relational geometry and physical properties as well as parameters of fuel cell's components. The smooth-walled channel with rectangular parallelepiped numbers and their positions, which are regarded as the design variables, are plotted in Fig. 2. Fig. 2(a) shows the rectangular parallelepiped number of $N = 1$–9 in the interdigitated channel. In case I of Fig. 2(b), the rectangular parallelepiped number of $N = 8$ is uniformly located at the CHout (covering CHo1–CHo8). The case II is at the CHin (covering CHi1–CHi9), and the case III at the central position of CHo4 and CHo5.

The conservation equations including mass, momentum, species, charges, and energy were converted to a finite-volume method. An orthogonal uniform grid for computational discretion was involved in this work. The equations are developed through the following set of assumptions:

(a) The flow in a PEM fuel cell is treated as steady-state and laminar flow.
(b) The gas mixtures behave like perfect gas and incompressible flow.
(c) The diffusion layer, catalyst layer and membrane are considered each homogeneous and isotropic porous media.