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Multi-objective optimization of operating conditions and channel structure for a proton exchange membrane fuel cell

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ABSTRACT

In this study, the operating condition (operating temperature, anode pressure, cathode pressure and current density) and channel structure (heights of channel inlet and outlet) of a proton exchange membrane fuel cell (PEMFC) are optimized using multi-objective genetic algorithm. The optimizations of the operating condition and channel structure are based on a PEMFC stack model and a three-dimensional, steady-state, non-isothermal PEMFC model, respectively. The optimal operating condition and channel structure are selected by TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) from the optimal solution set called Pareto front. After the optimized operating condition is obtained, it is applied to the optimization of the channel structure. The results present that the optimal channel structure under the optimal operating condition is a type of tapered channel. Compared to the conventional straight channel, the tapered channel can enhance gas reactant transport in the PEMFC and a greater amount of reactant can participate in the electrochemical reaction, thus, more output power can be obtained.

1. Introduction

The proton exchange membrane fuel cell (PEMFC) is considered as a promising energy conversion device due to their high energy efficiency and low emission [1]. The PEMFC has application prospect in the field of automobile and electronics. However, there exists challenging problems such as high cost of catalyst and low durability that cause difficulties in the wide spread application of the PEMFC [2,3]. Therefore the performance of PEMFC should be improved. During the past decades, many researchers have made efforts to optimize the performance of PEMFC. The optimization of PEMFC can be carried out from two aspects: operating condition and geometric structure.

For optimization of the operating condition, many research efforts have been conducted. Na and Gou [4] set the operating condition as variable to optimize the efficiency and cost of the fuel cell stack by using a multi-objective optimization technique called, the sequential quadratic programming (SQP) method. They discussed the effects of the initial operating condition on the efficiency and cost of the fuel cell stack. Ang et al. [5] developed the PEMFC stack model and optimized the efficiency and the size of the PEMFC stack by using a multi-objective method. The results indicated that when the PEMFC stack operated at an efficiency between 40% and 47% and the membrane electrode assembly (MEA) area was at least 3 cm^2/W, the efficiency and size of PEMFC stack could be balanced and the comprehensive performance of PEMFC stack achieved optimum. In their paper, the results of optimization were selected artificially from the optimal solution set called Pareto front obtained by multi-objective genetic algorithm. Therefore their results were approximate, not exact.

Mert et al. [6] analyzed the energy and exergy efficiencies and power output of the stack at different operating conditions. The operating condition that they took into account included temperature, pressure, anode stoichiometry, and cathode stoichiometry. They found that the temperature and pressure were the positive parameters for the stack efficiency, while the anode and cathode stoichiometry were the negative parameters. Wishart et al. [7] optimized the performance of PEMFC based on a semi-empirical fuel cell stack model from two aspects: net system power and system exergetic efficiency. They used global and local optimization algorithm to optimize the operating condition of PEMFC, respectively and compared the results of these two optimization algorithm. The results showed the optimal operating conditions obtained by global and local optimization algorithm were similar. Mert et al. [8] investigated the effects of operating condition on the PEMFC stack performance by using parametric studies. The results they obtained were identical to the study of Ref. [6].

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Nomenclature

A	active area (cm^2)
C	molar concentration (mol/m^3)
D	mass diffusivity of species (m^2/s)
F	Faraday's number 96,487 (C/mol)
i	current (A)
I	current density (A/cm^2)
P	pressure (Pa)
PEMFC	proton exchange membrane fuel cell
R	resistance (Ω) or universal gas constant 8.314 (J/mol K)
T	temperature (K)
T_e	entry air temperature (K)
n_{cell}	number of fuel cells in stack
t	thickness (cm)
$\mathbf{u}$	velocity (m/s)
k	thermal conductivity (W/m K)
K	permeability (m^2)
GA	genetic algorithm
M	molecular weight (g/mol)
MEA	membrane electrode assembly
RH	relative humidity
LHV	lower heating value of hydrogen (2.4 × 105 J/mol)

Greek letters

α	transfer coefficient
ε	porosity
μ	viscosity (Pa/s)
ρ	density (kg/m^3)
σ	conductivity (S/m)
ϕ	phase potential (V)
ω	species mass fraction
λ	stoichiometric ratio or water content

Subscript

a	anode
c	cathode
ch	channel
M	membrane
obj	objective
ref	reference
mom	momentum
eff	effective
agg	agglomerate
prs	parasitic

Jiao et al. [9] applied a different back pressure to each channel based on a PEM fuel cell with the novel parallel flow channel design. They found that the distributions of reactants were more uniform in the catalyst layer by increasing the pressure difference between the channels. Wan et al. [10] studied the temperature distribution of the PEMFC stack under the different operating conditions with in-situ measurement technology. Their results indicated that the temperature was more uniform as well as exhibiting better performance and generation of less waste heat when the operating pressure increased. Many other researchers [11–13] also studied the performance of the PEMFC under the different operating conditions through the experiment or calculation.

For the optimization of the geometric structure, the channel structure was optimized in many research efforts. Perng et al. [14] installed the transverse rectangular cylinder in the gas flow channel to enhance the performance of a PEMFC. They studied the effect of different gap sizes and the width of the cylinder on the PEMFC performance. Manso et al. [15] established a PEM fuel cell model with a serpentine flow field design and changed the channel cross-section aspect ratio which was defined as the ratio height/width of the channel to improve the cell performance. As a result, a higher channel cross-section aspect ratio provided better performance.

Bilgili et al. [16] installed obstacles in the gas channels to decrease the concentration losses. They found that the obstacles could improve the transport of reactants from channel to gas diffusion layer and made the PEM fuel cell perform better. Yang et al. [17] optimized the channel and rib widths and channel height by using a genetic algorithm to obtain the maximum output power of fuel cell. In their study, when the channel-to-rib width and the channel height were 1.84:1 and 0.515 mm, respectively, the output power of PEMFC would be maximum. Chiu et al. [18] aimed to make the PEMFC obtain higher output power by changing the widths, heights, and aspect ratios of the channel. Their results indicated that decreasing the channel cross-section could enhance gas velocity so that better performance was obtained.

Perng and Wu [19] proposed a tapered channel with a baffle plate to improve the performance of a fuel cell and optimized the structure of the baffle plate by applying an element-by-element preconditioned conjugate gradient method. The parameters of tapered ratio and gap ratio were the optimization variables while the cell performance was the objective function in their study. They found that a tapered flow channel with a baffle plate improved the fuel cell performance because of better gas transport performance. However, the high pressure loss caused by a tapered flow channel and baffle blockage was not considered in their work as that would have increased the balance of plant (BOP) power consumption.

Hasan et al. [20] simulated a PEMFC by using a three-dimensional, non-isothermal model with rectangular, trapezoidal and parallelogram channel cross-sections. The results showed that the rectangular channel cross-section showed better output performance. But the trapezoidal channel cross-section resulted in more even distributions of reactant and current density. Perng et al. [21] analyzed the fuel cell performance enhancement on changing the catalyst surface layer to a protuberance-like form. They found that the ribs opposite the protuberances enhanced gas reactant transport in the channel of the PEMFC, thereby improving cell performance. Kuo et al. [22] proposed a gas flow channel based on three novel periodic patterns geometries. These three kinds of channels improved the heat and mass transfer performance that led to better electrochemical reaction performance of a PEMFC. Jang et al. [23] designed baffles into flow channels of a fuel cell and optimized the baffles locations for obtaining maximum average current density by the method of combining the simplified conjugate-gradient method and commercial CFD code. Other researchers [24–26] also proposed some improved channel structure for enhancing the performance of PEMFC.

In summary, in the previous researches, combining the multi-objective optimization algorithm and TOPSIS selection for finding the optimal operating condition of fuel cell is rarely found. And introducing the multi-objective optimization algorithm into channel structure optimization to find a global optimal solution appeared unusually in the past studies. In this work, we combine the optimizations of operating condition and channel structure and optimize the operating condition and channel structure of fuel cell by multi-objective genetic algorithm. And TOPSIS is used for selecting optimal operating condition and channel structure from Pareto front obtained by multi-objective genetic algorithm.