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Analysis of the system efficiency of an intermediate temperature proton exchange membrane fuel cell at elevated temperature and relative humidity conditions

Seung Won Jeon, Dowon Cha, Hyung Soon Kim, Yongchan Kim *

Department of Mechanical Engineering, Korea University, Anam-Dong, Sungbuk-Ku, Seoul 136-713, Republic of Korea

HIGHLIGHTS

- System efficiency of PEMFC is evaluated at elevated temperature and humidity.
- Operating parameters are optimized using response surface methodology.
- The optimal operating parameters are $T = 90.6\ ^\circ C$, RH = 100.0%, and $\zeta = 2.07$.
- The power output and system efficiency are 1.28 W and 15.8% at the optimum.
- The system efficiency can be effectively improved by increasing relative humidity.

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ABSTRACT

Humidification of the membrane is very important in a proton exchange membrane fuel cell (PEMFC), to maintain high ionic conductivity. At an elevated temperature, a large amount of thermal energy is required for humidification because of the exponentially increased saturation vapor pressure. In this study, the system efficiency of a PEMFC was evaluated by considering the heat required for preheating/humidification and compression work. Three-dimensional steady-state simulations were conducted using Fluent 14 to simulate the electrochemical reactions. The operating conditions were optimized using response surface methodology by considering both the fuel cell output and system efficiency. In addition, the effects of operating parameters such as the temperature, relative humidity, and stoichiometric ratio were investigated. The system efficiency can be improved more effectively by increasing relative humidity rather than increasing operating temperature because the ionic conductivity of the membrane was strongly influenced by the relative humidity.

1. Introduction

Proton exchange membrane fuel cells (PEMFCs) have been widely used in transportation applications due to its advantages of high power density, rapid start-up, and high efficiency [1]. However, a large decrease in the cell performance of a low-temperature PEMFC with reduced gas transport under flooding conditions has been a big challenge to overcome [2]. High-temperature PEMFCs have drawn strong interest with regard to overcoming the water flooding problem [2–4]. At the elevated operating temperature, it is very important to maintain high ionic conductivity for optimum operation in the PEMFC [5]. In addition, at the elevated temperature, the PEMFC requires higher relative humidity and a very large amount of water vapor because the saturation water vapor pressure increases exponentially with the operating temperature. Therefore, it is necessary to analyze the performance of PEMFCs under elevated temperature and humidity conditions with regard to system efficiency.

The effects of the temperature and relative humidity on the performance of a PEMFC have been investigated extensively [6–10]. Zhang et al. [6,7] investigated the effect of the temperature and relative humidity on fuel cell reaction kinetics. Song et al. [8] reported that the intrinsic exchange current densities increased with increasing temperature in the range of 23–120 °C. In addition, the system efficiency of a PEMFC was investigated by considering fuel energy, power output, balance of plant (BOP) components and combined power and heat production (CHP) [11–13]. Han et al. [11] analyzed the stack efficiency and BOP efficiency of a PEMFC-powered portable freezer. Zuliani and Taccani [12]

* Corresponding author. Tel.: +82 2 3290 3366; fax: +82 2 921 5439.
E-mail address: yongckim@korea.ac.kr (Y. Kim).

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Nomenclature

A	electrocatalytic surface area per unit volume, m^{-1}
a	water activity
c_i	molar concentration of species i, kmol m^{-3}
c_i^{ref}	reference molar concentration of species i, kmol m^{-3}
c_p	specific heat, kJ kg^{-1} K^{-1}
$D_{0,i}$	mass diffusion coefficient of species i at reference temperature and pressure, m^2 s^{-1}
$D_{eff,i}$	effective mass diffusion coefficient of species i, m^2 s^{-1}
F	Faraday constant, 9.64853×10^4 C mol^{-1}
h	enthalpy of mixture, kJ kg^{-1}
h_{fg}	heat of vaporization of water, kJ kg^{-1}
h_i	enthalpy of species i, kJ kg^{-1}
I	current, A
i_m	ionic current density, A cm^{-2}
i^{ref}	reference exchange current density, A cm^{-2}
i_0^{ref}	reference exchange current density at reference temperature, A cm^{-2}
j_a	volumetric transfer current at the anode catalyst layer, A cm^{-3}
j_c	volumetric transfer current at the cathode catalyst layer, A cm^{-3}
J_i	diffusion flux of species i, kg m^{-2} s^{-1}
K	permeability
k_{eff}	effective thermal conductivity, W m^{-1} K^{-1}
k_f	thermal conductivity of fluid, W m^{-1} K^{-1}
k_s	thermal conductivity of solid, W m^{-1} K^{-1}
LHV_{H_2}	lower heating value of hydrogen, 241.83 kJ mol^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
M_i	molecular weight of species i, kg $kmol^{-1}$
$\dot{n}_{H_2}$	molar flow rate of hydrogen, kmol s^{-1}
p	pressure, N m^{-2}
p_∞	ambient pressure, N m^{-2}
p_{in}	inlet pressure of the unit cell, N m^{-2}
p_{sat}	saturation vapor pressure, N m^{-2}
p_w	partial pressure of water vapor, N m^{-2}
$Q_{exhaust}$	thermal energy supplied from the exhaust gas, W
Q_{humid}	thermal energy for humidification, W
$Q_{preheat}$	thermal energy for preheating, W
R^2_{adj}	adjusted coefficient of determination
r_{O_2}	oxygen content in air
S_h	source term of energy conservation, kJ m^{-3} s^{-1}
S_k	source term of species conservation, kg m^{-3} s^{-1}
S_m	source term of mass conservation, kg m^{-3} s^{-1}
S_u	momentum source in porous medium, N m^{-3}
S_ϕ	source term of charge conservation, A cm^{-3}
T	temperature, K
T_∞	temperature of ambient air, K
T_{in}	inlet temperature of the unit cell, K
u_i	velocity, m s^{-1}
V_{OC}	open circuit voltage, V
W_{comp}	compression work, W
W_e	power output, W
W_{fuel}	chemical energy of the fuel supplied to the system, W
X_1	operating temperature, K
X_2	relative humidity
X_3	stoichiometric ratio
Y_1	power output, W
Y_2	system efficiency
Y_i	mass fraction of species i

Greek

α	transfer coefficient
β	coefficient of the second-order response surface model
γ	specific heat ratio
ΔS	entropy change for the oxygen reduction, J $kmol^{-1}$ K^{-1}
ε	porosity
ζ	stoichiometric ratio
η_a	anode activation overpotential, V
η_c	cathode activation overpotential, V
η_{comp}	compression efficiency
η_{sys}	system efficiency
κ_m	ionic conductivity, S cm^{-1}
κ_s	electrical conductivity, S cm^{-1}
λ	water content
μ	viscosity, N m^{-2} s^{-1}
ρ	density, kg m^{-3}
ϕ	potential, V
φ	relative humidity
φ_∞	relative humidity of ambient air

Subscripts

a	anode
a_in	anode inlet
a_out	anode outlet
c	cathode
c_in	cathode inlet
c_out	cathode outlet
$comp\_outlet$	compressor outlet
m	membrane phase
s	solid phase

evaluated the electrical efficiency and thermal efficiency of a PEMFC-based micro-cogeneration system.

Generally, higher operating temperatures and relative humidity yield better cell performance. Under elevated temperature and humidity conditions, a large amount of thermal energy is required for preheating and humidification. However, the thermal energy for preheating and humidification has been rarely considered when evaluating the efficiency of a PEMFC [11–13]. Barelli et al. [14] defined the first law efficiency of a PEMFC by considering the thermal power for preheating and humidification. However, they did not consider BOP components in the first law efficiency and semi-empirical correlations were used for the electrochemical reactions. It is necessary to evaluate the system efficiency more accurately by considering the thermal power for preheating and humidification and the compression work for BOP components [11,12].

Based on the literature review, it is difficult to find an accurate model for the system efficiency of a PEMFC with the consideration of the fuel energy, thermal energy for preheating and humidification, and compression work for BOP components. In this study, a three-dimensional computational fluid dynamics simulation was carried out to overcome the limitations of the previous studies. A unit cell with a serpentine flow field was simulated with consideration of the compression work for the BOP component along with the heat for preheating and humidification. The operating conditions were optimized using the response surface methodology by considering both the fuel cell output and system efficiency. The performances of each energy component were also compared based on a case study. In addition, the effects of operating parameters such as the temperature, relative humidity, and stoichiometric ratio on the fuel cell power, system efficiency, and energy component were investigated.