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Thermal investigation of a PEM fuel cell with cooling flow field

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A B S T R A C T

Efficient operation of a proton exchange membrane fuel cell (PEMFC) is hugely dependent on an effective cooling system. Nonuniformity of temperature causes a varying rate of electrochemical reactions at different places causing hot spot formation which decreases the PEM fuel cell lifetime. In this study, PEMFC is simulated with cooling flow field simultaneously. Two conventional serpentine and parallel types of flow field of cooling plates are considered and compared with typical isothermal model (without cooling flow field) used in Ansys Fluent software. This comparison based on effective physical parameters such as pressure drop, the minimum and maximum temperature gradient, Index of uniform temperature (IUT) and etc. In the same working conditions, maximum temperature ratio between parallel and serpentine model is 1.0028 but for index of uniform temperature this study revealed 24% improvement for serpentine cooling flow field than parallel one. The results show that changing the heat transfer rate can be effective on the performance of PEM fuel cell and PEMFC with serpentine cooling flow field compared with parallel one. Serpentine flow field has better cooling performance with regard to effective physical parameters.

1. Introduction

Fuel cell is an electrochemical converter that converts chemical energy of fuel directly into electric current and heat and it is taken into consideration for various reasons, including better environmental compatibility and high efficiency Barbir [1]. Thermal management and water management are two important interconnected topics in the design and increase the efficiency of PEM fuel cells. Suitable cooling flow field design with proper performance is an important factor in increasing the lifetime of PEM fuel cell, because non-uniformity of temperature causes a varying rate of electrochemical reaction at different places leading hot spot formation which reduces the stability and durability of PEM fuel cell. The usual cooling method in the fuel cell stack is designing bipolar plates which have internal cooling channels between anode and cathode [2]. Chen et al. [3] conducted a thermal analysis of the coolant flow field configuration by constant heat flux wall to optimize the cooling flow field design of a PEMFC stack. A concept of the Index of Uniform Temperature (IUT), which is the temperature variation over the entire area of cooling plates, was proposed to evaluate the degree of uniform temperature profile across the cooling plates. Six configurations, including three serpentine-type and three parallel-type, were analyzed and compared. It was found that serpentine configurations had lower IUT (better cooling effects) than parallel configurations. The pressure drop of the cooling passages was also compared and it was found that parallel-type configuration had a lower pressure drop than serpentine-type configuration. Therefore, the optimization between the cooling effects and the pressure drop was suggested for further investigation. A numerical investigation by Choi et al. [4] also addressed the effects of the coolant flow field configuration on the cooling effects and similar results were obtained. Ju and Wang [5] simulated a single channel PEM fuel cell with cooling channel. Water is employed as cooling liquid and investigated the effect of cooling channel on water saturation and temperature distribution. Sangseok Yu and Jung [6] investigated the thermal management strategy of a PEM fuel cell system with a large active area. They improved a thermal model of a PEM fuel cell and a thermal management system to investigate the criteria of thermal management. Their fuel cell model was composed of sub-models for the water transport through the membrane electrolyte, the electrochemical reaction in the cathode catalyst layer and the two-dimensional temperature distribution within the fuel cell. The thermal management system model was included radiator, cooling pump. In addition, fan was employed for the investigation of the trade-off

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Nomenclature

a	specific surface area on anode, m^{-1}
$C_p^{(g)}$	specific heat capacity of gas mixture, kJ $kg^{-1}K^{-1}$
$C_{i,ref}$	reference molar concentration of species i, mol m^{-3}
$D_i^{(g)}$	diffusivity of species diffusivity of species i, m^2s^{-1}
$D_{H_2O}^{(m)}$	diffusivity of water in the membrane, m^2s^{-1}
E_{cell}	cell voltage, V
EW	Equivalent weight of membrane, kg mol^{-1}
F	Faraday's constant, C mol^{-1}
h	Height, m
IUT	Index of uniform temperature
j	Exchange current density, Am^{-2}
k	thermal conductivity, $Wm^{-1}K^{-1}$
L	Length, m
mem	membrane
$\dot{m}_{H_2O}$	interphase mass transfer due to condensation or evaporation of water, kg $mol^{-1}s^{-1}$
M_i	molecular mass of species i, kg mol^{-1}
$M^{(m)}$	equivalent weight of the dry membrane, kg mol^{-1}
n_d	Electro osmotic drag coefficient
$n_i^{(g)}$	mass flux of species i, kg m^2s^{-1}
$p^{(c)}$	Capillary pressure, Pa
$p^{(g)}$	Absolute gas pressure, Pa
P_i	Power, W
Q	Heat transfer rate, W
R	Universal gas constant, J $mol^{-1}K^{-1}$
s	liquid saturation
S	source term
St	stoichiometry
T	temperature, K
u, v, w, U	Velocities, ms^{-1}
x, y, z	coordinates, m
$\omega_i^{(g)}$	mass fraction of species i
α	transfer coefficients
ζ	relative humidity,%
η_{pump}	Efficiency of pump

Greek

ε	porosity
ε_{mc}	Volume fraction of ionomer in anode/cathode catalyst layers
λ	water content
μ	dynamic viscosity, kg m^2s^{-1}
ρ	density, kgm^{-3}
σ	total stress tensor, Nm^{-2}
$\sigma^{(s)}$	electric conductivity, sm^{-1}
$\sigma^{(m)}$	protonic conductivity, sm^{-1}
$\varnothing^{(m)}$	ionic phase potential, V
$\varnothing^{(s)}$	solid phase potential, V

Superscripts

(c)	capillary
(cool)	cooling
eff	effective
(g)	gas phase
in	inlet
(l)	liquid phase
(m)	membrane
ref	reference
(s)	solid
sat	saturation

Subscripts

a	anode
avg	average
bp	Bipolar plate
c	cathode
ch	Channel
cl	catalyst layer
CV	Control volume
d	diameter
dry	dry
ff	Fluid flow
FC	Fuel cell
gdl	gas diffusion layer
gross	Gross
h	hydraulic
H_2	hydrogen
H_2O	water
i	species i
m	membrane
mass	mass
net	net
O	out
O_2	oxygen
OC	Open cirqute
pot	potential
ref	reference
rib	rib
temp	temperature

between the temperature distribution effect and the pump parasitic loss. Their output result was including the following sections: The maximum temperature of the fuel cell was suggested as the representative operating temperature because the maximum temperature can be more conveniently measured and monitored than other possible temperatures. The cooling fan is suggested to be feedback controlled with the maximum operating temperature as the feedback signal. The reference value of the operating temperature is system dependent and should be determined by considering membrane durability and system transient safety margin. The coolant pump should be controlled to achieve higher net power generation by considering the trade-offs between the temperature distribution effect on the fuel cell performance and the pump parasitic loss. Kandlikar and Lu [7] investigated thermal management and water management in the PEM fuel cells. The coupled water and heat transport mechanisms were as discussed since they are closely interrelated. They calculated the heat generation in any part of the fuel cell, including bipolar plates, catalyst layers, gas diffusion layers and membrane and showed heat generation at cathode catalyst layer was more than anode catalyst layer. Siegel [8] presented a complete review about different models of computational heat and mass transfer in PEM fuel cells. He explained a detailed literature overview of models, ranging from one-dimensional, single-component to complete three-dimensional, large-scale setups. Important topics such as the simulation strategies, popular numerical algorithms and computational techniques are summarized. Also, mode accuracy and convergence problems are explained. Finally, the commonly