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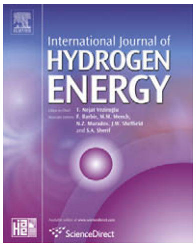

Determination of the optimal active area for proton exchange membrane fuel cells with parallel, interdigitated or serpentine designs

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ABSTRACT

Effects of active area size on steady-state characteristics of a working PEM fuel cell, including local current densities, local oxygen transport rates, and liquid water transport were studied by applying a three-dimensional, two-phase PEM fuel cell model. The PEM fuel cells were with parallel, interdigitated, and serpentine flow channel design. At high operating voltages, the size effects on cell performance are not noticeable owing to the occurrence of oxygen supply limit. The electrochemical reaction rates are high at low operating voltages, producing large quantity of water, whose removal capability is significantly affected by flow channel design. The cells with long parallel flow field experience easy water accumulation, thereby presenting low oxygen transport rate and low current density. The cells with interdigitated and serpentine flow fields generate forced convection stream to improve reactant transport and liquid water removal, thereby leading to enhanced cell performance and different size effect from the parallel flow cells. Increase in active area significantly improves performance for serpentine cells, but only has limited effect on that of interdigitated cells. Size effects of pressure drop over the PEM cells were also discussed.

1. Introduction

Proton exchange membrane (PEM) fuel cells convert chemical energy of hydrogen and oxygen directly into electricity. The performance of PEM fuel cell depends on numerous material characteristics, including membrane ion conductivity, catalyst distribution and its reaction rate in the catalyst layer (CL), and gas diffusion rate and water removal rate in the gas diffusion layer (GDL). Additionally, the fuel cell performance also impacted by the operating conditions, such as the fuel and air fluxes, temperatures, pressures and humidities, and by the cell size and the flow channel configuration. Numerical fuel cell models were adopted to analyze cell performance [1–34]. Wang [35], Tao et al. [30] and Li et al. [36] provided an up

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Nomenclature

Aj_0^{ref}	Exchange current density, A m^{-3}
a	Water activity
C	Mass fraction
C_F	Quadratic drag factor
d_{porous}	Equivalent surface diameter of porous media, m
D	Mass diffusivity, m^2 s^{-1}
D_λ	Water diffusivity in the membrane
F	Faraday constant, 96,487 C/mol
i	Current density, A m^{-2}
I	Average current density in the fuel cell, A m^{-2}
j	Transfer current density, A m^{-3}
k_c	Coefficient of water vapor condensation rate, s^{-1}
k_e	Coefficient of water vapor evaporation rate, atm^{-1} s^{-1}
k_{rl}	Relative permeability of the liquid water
k_p	Permeability, m^2
k_{rg}	Relative permeability of the gaseous mixture
M	Molecular weight, kg mol^{-1}
M_m	Membrane equivalent weight, kg mol^{-1}
n_d	Electro-osmotic drag coefficient
p	Pressure, atm
p_c	Capillary pressure, atm
p_{sat}	Saturated water vapor pressure, atm
R	Universal gas constant, 8.314 J mol^{-1} K^{-1}
s	Ratio of the liquid water volume to the pore volume
S'	Surface area, m^2
S_c	Source term in the species equation
S_j	Source term in the phase potential equation
S_L	Source term accounting due to phase change of water
$S_{\vec{u}}$	Source term in the momentum equation
T	Cell temperature, K
t	Time, s
$\vec{u}$	Velocity vector, m s^{-1}
V'	Volume, m^3
V_{cell}	Operating voltage, V
x_{H2O}	Mole fraction of water vapor
x	x Direction coordinate, m
y	y Direction coordinate, m
z	z Direction coordinates, m
Greek	
α_a	Electrical transfer coefficient in forward reaction
α_c	Electrical transfer coefficient in backward reaction
ϵ	Porosity
η	Overpotential, V
η_m	Ohmic overpotential in the membrane, V
θ	Contact angle of water on the porous material, arc
λ	Water content in membrane
μ	Viscosity, kg m^{-1} s^{-1}
ρ	Density, kg m^{-3}
ρ_{dry}	Membrane dry density, kg m^{-3}
σ	Surface tension, N m^{-1}
σ_m	Proton conductivity, S m^{-1}
σ_s	Electron conductivity, S m^{-1}
τ	Tortuosity of the pores in the porous material
Φ_m	Ionic phase potential, V
Φ_m	Electronic phase potential, V
Subscripts	
a	Anode
c	Cathode
eff	Effective
g	Gaseous phase
H_2	Hydrogen
H_2O	Water
k	kth Species of the mixture
l	Liquid phase
O_2	Oxygen
porous	Porous medium
ref	Reference value
sat	Saturation
total	Total

to date summary of current development of PFM fuel cell models.

Flow channel design in the bipolar plates is one of the key factors affecting PEM fuel cell performance. Effects of various flow field designs, such as the parallel, serpentine, and interdigitated flow fields, on the cell performance were studied [37–53]. The PEM fuel cells could be fabricated at different active areas for specific applications. The cell power increases with increasing active area, but not in a proportional manner. This occurrence is attributable to the fact that long flow channels are commonly fabricated with cells of large active area to provide high power, which nonetheless render water removal uneasy for keeping sufficient oxygen transfer rate at cathode. Restated, cell size effect can be noticeable in PEM fuel cell applications. However, to the best of our knowledge, up to present the size effect has not been satisfactorily analyzed.

The objective of this study was to investigate the effects of active areas on the performances of cells with parallel, interdigitated and serpentine flow designs. A three-dimensional fuel cell model was adopted to simulate steady-state characteristics of a working PEM fuel cell considering local current densities, local oxygen transport rates, oxygen concentrations, and liquid water transport. The cell size effect was clearly demonstrated and analyzed.

2. Numerical model

A three-dimensional, two-phase, multi-component PEM fuel cell model was adopted. In brief, the cell was composed of anode flow channels, anode GDL, anode CL, proton exchange membrane, cathode CL, cathode GDL, and cathode flow channels. The model assumed a steadily operated PEM fuel cell with the porous layers, such as the GDLs, CLs and PEM to be isotropic and isothermal. The inlet reactants were regarded as ideal gases; the flow was laminar; the water produced at cathode catalyst layer was in its vapor phase; water was