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Polymer electrolyte membrane fuel cell flow field design criteria – Application to parallel serpentine flow patterns

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ABSTRACT

One key strategy for maximizing the performance of fuel cells is the choice of proper flow field pattern. In this paper, a procedure was developed for the proper design of parallel serpentine flow field for proton exchange membrane fuel cells. Several parameters including the channel width and height, the rib between two adjacent channels, and the numbers of parallel channels and serpentine turns were considered and all the possible flow field configurations within the range of these design parameters were defined. In the next step, six consecutive constraining filters were defined and enforced to all the possible flow field configurations. In the final step, a complete three dimensional simulations were conducted for the remaining cases. Based on the results of the simulations, these cases were ranked, with the best case corresponds to the flow field with the minimum pressure drop, the maximum oxygen content at the surface of catalyst layer, maximum uniformity of oxygen distribution within the catalyst layer and minimum content of the condensate produced within the catalyst layer.

1. Introduction

Proton exchange membrane fuel cells (PEMFCS) are considered as one of the most important alternative clean power sources for portable, mobile and stationary applications [1]. PEMFCs use hydrogen as fuel and are the most popular type of fuel cells. They generate electric current from chemical reaction between hydrogen and oxygen [2]. PEMFC constitutes of polymer membrane, catalyst layers (CLs) at anode and cathode sides, gas diffusion layers (GDLs) and bipolar plates (BPs) [3]. They produce low to zero emission [4], can operate at low temperatures [5], provide high power density [1] and benefit from fast start up [6]. The commercialization of PEMFCs still faces challenging issues of cost reduction, compactness, high power density, long-term durability and fuel economy. The fuel cell performance improvement and cost reduction demands enhanced design and optimization of operating conditions [7] and the complex processes within the fuel cell [8]. The necessary improvements for fuel cell operation and performance can be achieved by better design and optimization of the fuel cell components.

The bipolar plates (BPs) and gas flow channels (GFCs) are one of the important components of PEMFCs [9]. BPs provide mechanical support for the membrane electrode assembly (MEA) and conductive passages for both heat and electron transport. Gas flow channels, which are located within the bipolar plates, have the role to evenly supply and distribute reactant gases (fuel and oxidant) over the respective active electrode surface and remove byproduct water while maintaining a minimum pressure drop [10]. The flow field design in the bipolar plate influences the heat, mass and current transport inside fuel cells in a complex manner [11]. Effective supply of reactants and product-water removal are the key issues in PEMFCs from the performance view point [12]. Evenly distributing reactants over the entire catalyst layer (CL), results in uniform current distributions, high power density, better fuel utilization and minimum concentration over potential [9]. A proper flow field design can enhance the reactant transport and effectively improve water management to minimize the concentration polarization and avoid flooding [13]. Insufficient supply of reactants at high current densities will lead to hydrogen/oxygen starvation and maximum concentration over potential, reducing cell performance and durability [14].

Three basic type of flow fields are commonly used for PEMFCs, namely, parallel, serpentine and interdigitated flow fields. The parallel version is the simplest and includes a number of separate parallel flow channels connected to the gas inlet and outlet. In this design, the water drainage from the cell tends to be inadequate and the reactant gas has a very small pressure drop due to equal distribution of the flow rate into

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Nomenclature

A	cell active area (m^2)
a	active area edge size (m)
C	molar concentration ($mol\cdot m^{-3}$)
$C_{O_2}^{ref}$	reference O_2 concentration ($mol\cdot m^{-3}$)
D_h	hydraulic diameter (m)
D_k^{eff}	effective diffusion coefficient for species k in the mixture ($m^2 s^{-1}$)
d	rib width (m)
E	total energy (J)
F	Faraday constant (96487 $C\cdot mol^{-1}$)
f	friction factor
h	channel height (m)
I	current density ($A\cdot cm^{-2}$)
I_0	exchange current density ($A\cdot cm^{-2}$)
k_{eff}	effective Thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$)
K	permeability (m^2)
L	channel length (m)
M_k	molecular weight of species k ($kg\cdot mol^{-1}$)
$\dot{m}$	mass flow rate ($kg\cdot s^{-1}$)
n	number of parallel channels
p	pressure (Pa)
p_{sat}	saturation pressure (Pa)
Re	Reynolds number
R	gas constant (8.314 $J\cdot mol^{-1}\cdot K^{-1}$)
S_T	volumetric heat sources ($W\cdot m^{-3}$)
S_u	momentum equation source term ($kg\cdot m^{-2}\cdot s^{-1}$)
S_m	continuity equation source term ($kg\cdot m^{-3}\cdot s^{-1}$)
S_k	source term of species conservation equation ($kg\cdot m^{-3}\cdot s^{-1}$)
s	number of serpentine turns
T	temperature (K)
t	time (s)
$\vec{u}$	velocity vector ($m\cdot s^{-1}$)
V	inlet velocity ($m\cdot s^{-1}$)
V_{cell}	operating voltage (V)
V_{oc}	open circuit voltage (V)
Vol	volume (m^3)
w	channel width (m)
Y_k	mole fraction of species k
X_k	mass fraction of species k
RH	relative humidity
R_{cell}	electrical ohmic resistance ($\Omega\cdot cm^2$)

Greek letters

ρ	density ($kg\cdot m^{-3}$)
ψ_1	the function representing the weight of pressure drop in Ψ
ψ_2	the function representing the weight of oxygen content at the GDL/CL interface in Ψ
ψ_3	the function representing the weight of oxygen uniformity level at the GDL/CL interface in Ψ
ψ_4	the function representing the weight of generated condensate in Ψ
Ψ	goal function
α	charge transfer coefficient
$\vec{\tau}$	stress tensor
ε	porosity
μ_g	gas mixture viscosity ($kg\cdot m^{-1}\cdot s^{-1}$)
Δp	pressure drop along the channel (Pa)
η	over potential (V)
ξ	stoichiometry

Subscripts

c	cathode
H_2O	water
m	mixture
O_2	oxygen
g	gas phase
avg	average
sat	saturation
ref	reference
cl	catalyst layer

Abbreviations

CFD	computational fluid dynamic
GDL	gas diffusion layer
MEA	membrane electrode assembly
PEMFC	proton exchange membrane fuel cell
GFC	gas flow channel
BP	bipolar plate
CL	catalyst layer
MPSFFs	multi-path serpentine flow fields
CESFF	convection-enhanced serpentine flow field
GCI	grid Convergence Index
UDF	user defined functions
SIMPLE	semi-implicit pressure linked equation

many relatively short straight and parallel channels without directional changes. As a consequence, non-uniform distribution of the reactant gases among the parallel paths can occur in this type of flow fields [14]. However, serpentine flow field designs have been proposed to tackle the problems inherent to parallel flow fields. In these types of flow fields, the flow is forced to move through some parallel long and meandering paths that occupy the entire active area. This channel layout results in a substantial pressure drop from the flow inlet to outlet. This effect forces the reactant flow to traverse the active area of the corresponding electrode thereby eliminating areas of stagnant flow and facilitating condensate purge towards the exit of gas flow channels in the expense of higher pumping powers [3]. An interdigitated flow field consists of dead-ended flow channels built on the flow distribution plates [15]. In this design, the reactant flow is forced under pressure to go through the porous electrode backing layer to reach the flow channels connected to the exit manifold [16]. Such flow-field design can provide better mass transfer and effective water removal from the electrode structure [17] in the expense large pressure losses compared with parallel and serpentine flow fields [18].

The impact of flow field layout on the PEMFC performance is a results of complex interactions between the electrochemical reactions, hydrodynamic effects and multi-component transport mechanisms in the gas flow channels. Therefore, optimizing the flow field is a very difficult task and very complicated to treat. In addition, defining the geometry of a fuel cell flow channel requires several parameters, e.g., flow channel pattern, channel depth and width. In fact, it is extremely difficult to consider the effects from all arrangements of these factors concurrently. Among various flow field designs, the serpentine design is one of the most widely used flow channel configurations. Thus, the focus of the present study is to provide guidelines for the design of serpentine flow field considering design constraints, channel-land dimensions, pressure drop and mass transfer. Despite of the availability of