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Effect of flow field with converging and diverging channels on proton exchange membrane fuel cell performance

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ABSTRACT

In this study, a novel bipolar flow field design is proposed. This new design consists of placed sequentially converging and diverging channels. Numerical simulation of cathode side is used to investigate the effects of converging and diverging channels on the performance of proton exchange membrane fuel cells. Two models of constant and variable sink/source terms were implemented to consider species consumption and production. The distribution of oxygen mole fraction in gas diffusion and catalyst layers as a result of transverse over rib velocity is monitored. The results indicate that the converging channels feed two diverging neighbors. This phenomenon is a result of the over rib velocity which is caused by the pressure difference between the neighboring channels. The polarization curves show that by applying an angle of 0.3° to the channels, the net electrical output power increases by 16% compared to the base case.

1. Introduction

A hydrogen fuel cell is an electrochemical device that directly produces electricity by using hydrogen and oxygen through electrochemical reactions [1]. Among various type of fuel cells, Proton Exchange Membrane Fuel Cell (PEMFC) is of greatest interest due to its advantages of low operating temperature, high power density, fast start-up, and low emissions, and they are also the current focus of research for hydrogen fueled vehicles [2]. However, some of the problems with fuel cells include high cost, high degradation rate, excessive losses at high current densities, durability and reliability of the Bipolar Plates (BPs) and Membrane Electrode Assembly (MEA). Fuel cell performance can be improved by optimizing individual components of the cell [1]. As one of the most important repeated components in a PEMFC stack, bipolar plates typically account for 60–85% of the weight and occupy most of the volume of a fuel cell stack. The cost contribution of the BPs in a stack is 20–60% that is influenced by a diverse range of factors, such as material, structure, manufacturing processes, and technology [3]. The bipolar plate of a fuel cell is a layer that is expected to provide efficient mass transport and uniform distribution of reactants (hydrogen and oxygen) and to allow as uniform as electrical current production leading to enhanced cell power density. Among the above characteristics, a critical function of the bipolar plates is the distribution of the reactants to the reaction sites. Therefore, the flow field design of the bipolar plates is crucial for ensuring continuous and steady supply of the fuel and oxygen to the Catalyst Layers (CLs) at the sides of the MEA. These plates also help in collecting the current, maintaining a steady temperature, and separating each mono cell from the next one as well as eliminating flooding due to excessive water generation. Water management is one of the most important issues that must be considered in low operating temperature fuel cells. As a rule of thumb, a pressure gradient of 23 mbar/m can push the condensate out [4]. Bipolar plates are normally made of metals, metal alloys or graphite. The metals that are used for manufacturing bipolar plates are selected mainly based on the criteria of long durability, low cost and weight, good conductivity, chemical compatibility, strength as well as being able to diffuse the reacting gas.

Optimal bipolar plate flow field design is one of the main means to improve the performance of a PEMFC. Various flow filed designs and different bipolar plates configurations were reviewed by Li and Sabir

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Nomenclature

c	mass fraction
d	rib width, mm
F	Faraday number, =96,485 J/(V mol)
h	channel height, mm
i	current density, A/cm^2
i_0	exchange current density, A/cm^2
L_1	channel length projected on z-direction, mm
L_2	active area length in z-direction, mm
L_3	active area width, mm
M	molecular weight, kg/mol
P	pressure, Pa
$\dot{m}$	mass flow rate, kg/s
R	gas constant, J/(kg K)
S	volumetric consumption/generation, kg/(m^3 s)
T	temperature, K
u	utilization factor (in model I)
V	velocity, m/s
w	channel width at channel mid length, mm
y	mole fraction
z	axial distance from center, mm
z'	axial distance from inlet, $= z + L_1/2$

Greek symbols

α	cathode charge transfer coefficient
η	concentration loss, V
σ	Ohmic resistance, Ω cm^2

Subscripts

avg	average
c	cathode
cell	cell
CL	catalyst layer
dp	dew point
GDL	gas diffusion layer
H_2O	water
in	inlet
max	maximum
mix	mixture
net	net
O_2	oxygen
OC	open circuit
op	operating
out	outlet
pump	pumping
ref	reference
x	in x direction
z	in z direction

Superscript

O_2	oxygen

[3]. In their study, pin-type, series parallel, serpentine, interdigitated and other proposed configurations of the BP flow fields were studied. Hsieh et al. [5] experimentally studied the effects of operating parameters of PEMFC for three different flow fields of interdigitated, mesh and serpentine. It is concluded that among three flow field configuration, the interdigitated type has better cell performance, while the mesh type shows smaller pressure drop. Perng and Wu [6] numerically analyzed effect of trapezoid baffles placed in flow channels on net power in a PEMFC. They reported an enhancement of 90% in net power by using baffles with angle of 60° and height of 1.125 mm. Wang et al. [7] numerically investigated the effect of channel size on performance of PEMFC with serpentine flow fields. The results reveal that smaller channel sizes enhance water removal as well as the oxygen mole fraction in the reacting sites. In addition, smaller channel sizes provide more uniform current density distribution in the fuel cell and cause more pressure drop. They proposed an optimum cross section of 0.535 × 0.535 mm^2. Heidary and Kermani [8] conducted a 2D numerical simulation of heat transfer and flow in a PEMFC with wavy channel configuration. Effects of the Reynolds number, wave number, wave amplitude and Darcy number were investigated. Their results showed that for optimal values of the aforementioned variables, an enhancement of 100% is observed in heat transfer. Wang and Wang [2] investigated a U-type arrangement, including single serpentine, multiple serpentine, straight parallel, and interdigitated configurations for the PEMFC flow field. Their results based on the pressure drop and flow distribution in different layout design, showed that uniform distribution of the flow can be achieved by a balance between the length and number of the channels in multiple serpentine configurations. Finally, some suggested criteria of the flow field designs were reported. Heidary and Kermani [9] studied effect of partial block (indents) on enhancement of heat exchange between duct wall and the core flow as well as the pressure drop along the duct in a direct methanol fuel cell. Heidary et al. [10] performed numerical simulation of PEMFC and direct methanol fuel cell using four corrugated channel beds including rectangular, trapezoidal, triangular and wavy (sinusoidal) shape. Effects of shape boundaries, Reynolds number, triangle block number and triangular block amplitude on the fuel cell performance were studied. Liu et al. [11] presented optimal dimensions of a serpentine flow channel such as width, rib size and their ratio. They verified their analysis by an experimental setup and concluded that minimizing the total width and ribs as well as the rib ratio can improve the fuel cell performance. Santamaria et al. [12] analyzed channel length effect on an interdigitated flow field in a PEMFC by conducting numerical and experimental studies. It is deduced that by increasing the channel length, distribution of cross flow deviates from uniform distribution. Abdollahzadeh et al. [13] studied the performance of a PEMFC with different configuration of gas feeding channels. Multi-component model is used to simulate two-phase flow and transport phenomena, lessening the computational costs by reducing the number of nonlinear governing equations. Dehsara and Kermani [14] investigated 3D configuration of three different channel beds including flat, semi-circular and wavy shaped. Results showed that due to increase in penetration of the reacting gases towards the reaction sites in the CLs, fuel cell performance is enhanced up to 18–22%. Perng et al. [15] numerically studied effect of installation of a rectangular cylinder in flow channel in a PEMFC. The results revealed that cell performance is enhanced. Jia and Liu [16] studied five MEAs partially catalyzed in different regions to evaluate lateral distribution of current density in a PEMFC with serpentine flow field using an experimental setup. It was shown at high voltages maximum local current density is observed under center of over rib area. In addition, the local current density decreases toward center of channel area. For low voltages inverse behaviors were reported. Perng et al. [17] numerically investigated effect of a modified flow field obtained by rectangular obstacles opposite and staggered with the protuberant catalyst layer surface or narrowed flow channels, with ribs opposite or staggered with the protuberant catalyst layer surface. Comparison between results of the modified flow filed with the conventional one, reveals that an enchantment of 8% is observed in the fuel cell performance. Sierra et al. [18] performed a 3D numerical study of three well-known flow field configurations for fuel cell (serpentine, interdigitated