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Efficient fuel utilization by enhancing the under-rib mass transport using new serpentine flow field designs of direct methanol fuel cells

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ABSTRACT

New serpentine flow field designs of direct methanol fuel cells have been developed to enhance the under rib reactant mass transport without affecting the electronic conductivity to boost up the fuel utilization and fuel cell efficiency. The flow field design is based on three main criteria including the number of paths, the rib lengths, and the flow-path patterning in channels. Therefore, six different flow field designs are developed, including one design with two paths, two designs with three paths and different patterning and rib lengths, and three designs with four paths, different patterning and rib lengths. A three-dimensional single phase model for the direct methanol fuel cell is developed, simulated numerically and validated using the available experimental data. Results revealed that a significant enhancement of fuel cell performance is attained using the new designs. The design with the longest ribs and four paths attains the highest under-rib flows, and the lowest pressure drop between inlet and outlet. Furthermore, the power density has shown a 52.9% and 35.8% increase using an enhanced serpentine flow field with four paths compared to the conventional serpentine flow field design, at 0.5 M and 0.25 M inlet methanol concentrations. Using the new designs allows for the operating of the direct methanol fuel cell at a lower methanol concentration without a significant reduction of the output power.

1. Introduction

The fast depletion of the fossil fuel resources and the descending environmental pollution problems increase the necessity to promote use of sustainable and clean energy resources. Fuel cells are highly appealing applications for sustainable energy. Hence, a great deal of attention and research has been oriented toward fuel cells and their applications in the past several decades. Fuel cells are characterized by high electrical efficiency, power and capacity flexibility, a lengthy lifetime, and ecological balance [1,2]. Among the various types of fuel cells, the direct methanol fuel cell has the potential to power microelectronic and portable applications. This is due to its low working temperature and simple design as well as ease of storing and handling methanol, due to its liquid nature at room temperature [3].

Direct methanol fuel cell performance depends on efficient mass transport through the different layers of the cell, and the apace transport of the electrons between the sides of the cell. Many researchers studied the effects of the design and operating parameters on the mass transfer characteristics and electronic conductivity of the direct methanol fuel cells. Liu et al. [4] investigated the effect of diffusion layer components on these parameters through the study of the cell performance under different diffusion layer components. From another point of view, Liu et al. [5] attempted to optimize the assembly force of the DMFCs by investigate the internal resistance and performance of the fuel cell at different values of that force. Similarly, Mahmoudi et al. [6] proved numerically that, the cell performance and limiting current density increased as the gas diffusion layer compression increased due to the enhancement of the under rib flow. One of the main components of the fuel cell which has a direct effect on the mass transfer characteristics and the electronic conductivity is the flow field. The main functions of the flow field in cells are to obtain uniform distribution of the reactant over the electrode surface, and to quickly remove the products of electrochemical reactions, such as CO_2 bubbles, which lead to utilize the catalyst layer efficiently. Furthermore, the solid ribs that separate the flow field channels collect the produced electrons from the electrochemical reactions and work as a current collector [7–10]. Accordingly, different experimental and numerical efforts were conducted to produce the most appropriate flow field

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Nomenclature

$\mathbf{u}$	velocity vector (m/s)
ρ	density (kg/m^3)
p	pressure (Pa)
k	permeability (m^2)
Q_{br}/R_i	mass source or mass sink ($kg/(m^3 \cdot s)$)
F	gravity and other volume forces ($kg/(m^2 \cdot s^2)$)
CO_2	carbon dioxide
NO_x	nitrogen oxides
T	tensor/temperature (K)
$\mathbf{I}$	unit vector
$\mathbf{j}_i$	mass flux vector (kg/m^2)
$\mathbf{d}_k$	diffusion driving forces (1/m)
D_{ik}	diffusion coefficient (m^2/s)
$\mathbf{g}_k$	external force per unit mass (m/s^2)
x_k	mole fraction
c	concentration (mol/m^3)
j_a/j_c	the reaction rate (A/m^3)
aj_{0a}^{ref}	the electrochemical active area per unit catalyst volume times the exchange current density (A/m^3)
i_k	the current
Q_k	the general source term
σ_k	the conductivity (S/m)
ϕ_k	the potential (V)
D_{eff}	the effective hydraulic diameter of the channel
Q	the volume flow rate (m^3/s)
L_R	the rib length (m)

Abbreviations

DMFC	direct methanol fuel cell
MEA	membrane electrolyte assembly
URC	under rib convection
CESFF	convection enhanced serpentine flow field
DL	diffusion layer
CL	catalyst layer

Superscript and subscript

MeOH	methanol
ref	reference
a	anode
c	cathode

Greek symbols

μ	dynamic viscosity ($kg/(m \cdot s)$)
ε_p	porosity
ω_i	mass fraction
α	the transfer coefficient
η	the overpotential (V)

design that allows for all of these functions with the minimum pressure drop.

The serpentine flow field is commonly used and considered as the standard industry flow field design for the fuel cells [11]. There are many research directions to improve the flow field design. One direction is to develop the under-rib mass transport. The roles of the under-rib mass transport were previously studied [2,12–22]. It was reported that for a specified mass flow rate, the under rib convection is mainly affected by different factors such as the rib width, the pressure difference between the adjacent channels, and the diffusion layer permeability [9,23]. For polymer electrolyte fuel cells, Choi et al. [1] stated that the under-rib convection enhanced the mass transport of reactants, electrochemical reaction, water removal, and output power. Wang et al. [22] approved numerically that, the smaller channel size improves the cell performance by enhancing the species transport toward the porous layer through the promoting of the under-rib convection. Heidary et al. [24], Ghanbarian et al. [25] and Tiss et al. [26] studied the impact of the flow channel blockage on the PEM fuel cell performance. Their results revealed that, the higher blockage of the flow channel led to more under-rib convection species transport, more uniform distribution over the catalyst layer, and in turn higher cell performance. Several researchers investigated the serpentine flow field with adding sub-channel and bypasses between the conventional channels to control the under-rib convection. They concluded that these additions enhance the reactant transport, enable more effective utilization of the electrocatalysts, and improve the reaction products removal [12,13,18,22].

Park et al. [7] experimentally and numerically investigated the direct methanol fuel cells performance with four different geometries for the serpentine flow field. They revealed that higher power and efficiency could be obtained from the cell with narrow rib width and an appropriate open area ratio. On the other hand, the flow fields with very narrow ribs and extremely large open active areas can increase the internal resistance of the cell and the methanol permeation area. This in turn results in higher methanol crossover through the membrane, adversely impacting cell performance [27]. Therefore, the open ratio should be around 50 percent to obtain the best performance results with the fuel cells. Any increase or decrease in the open ratio beyond this limit could mitigate cell performance [27]. Yang and Liang [28] reported that increasing rib width leads to a reduction of the limiting current density and power density due to the increase of mass transport resistance. The mass transfer at the channel diffusion layer interface depends on the contact area, and the diffusion flow occurs mainly underneath this open space. Accordingly, inefficient mass-transfer and reduction of the diffuse flux cause a decrease in performance.

As previously reported, the pressure difference between the adjacent channels considerably influences the under-rib reactant mass transport. This pressure difference depends on the flow traveling distance between the adjacent channels. At the same time, the flow traveling distance and hence the pressure difference between the two adjacent channels could be characterized by the rib length. This pressure difference varies from the maximum at the rib root to zero at the rib head [9,23]. More detailed discussions about the effect of the rib length on the pressure difference between the adjacent channels were documented in [9,23]. Yang and Liang [28] concluded that under-rib-convection, associated with the pressure difference between the adjacent channels, had a significant effect on the performance of DMFCs. Xu et al. [19] studied the methanol mass transport in the anode of the DMFCs. They found that the overall mass transport from the flow field channels to the diffusion layer could be increased significantly by enhancing the under-rib convection in the serpentine flow field. This enhancement could be achieved by using the optimal design of the flow field and the diffusion layer. Xu and Zhao [9] suggested a flow field design to enhance the under rib convective mass transport in the serpentine flow field by re-patterning the flow channel. They examined the serpentine flow field with single path, and three paths, where the path is the route from the inlet to the outlet region or vice versa. Xu and Zhao found that the new design