The micro-scale analysis of the micro direct methanol fuel cell

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ARTICLE INFO

ABSTRACT

In this paper, the behavior of micro-scale effect in a micro direct methanol fuel cell (μDMFC) is investigated through both simulations and experiments. A model is built to describe the methanol distribution in the diffusion layer with different feature sizes. In addition, the dynamic movement of a single CO_2 bubble is also simulated to study the two-phase characteristics in the micro channels with various aspect ratios. Furthermore, a metal-based transparent μDMFC with the active area of 0.64 cm^2 is designed and fabricated to evaluate the two-phase flow characteristic as well as the corresponding cell performance. The experimental results reveal that when the feature size scales down to 0.6 mm and 0.4 mm, the peak power density of 27.1 mW cm^{-2} and 26.3 mW cm^{-2} are achieved at room temperature. Finally, the effect of adjusting channel aspect ratio is experimentally investigated to improve the inner convection transport and the cell output, and the results are well in agreement with the simulation.

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1. Introduction

With the rapid development of Micro Electro Mechanical System (MEMS) technology, μDMFC has been considered as a promising power candidate for portable applications due to its high energy density, high efficiency and environmental-friendly [1–4]. The miniaturization of portable electronic devices requires the power supply unit to be scaled down proportionally. The volume of micro direct methanol fuel cell is determined by the size of current collector, in which the most critical part is the inner flow channel [5–7]. The main function of the flow channel is to ensure the uniform fuel supply for reaction region and to maintain the equilibrium between the fuel distribution and the current collection [8–10]. Therefore, significant attentions have been devoted to the effect of inner channel on μDMFC performance recently. Park et al. [11] studied four different types of serpentine flow-channel geometry structures, and the corresponding current density distributions and the polarization were observed. Wong et al. [12] investigated the effect of the anode flow field design on the performance of μDMFC. The experimental results indicated that the serpentine flow field exhibited higher cell voltages than that of the parallel flow field at high current densities. Based on the single serpentine flow channel, Xu et al. [13] presented a convection-enhanced serpentine flow channel. The results indicated that the

novel flow field created larger pressure difference between adjacent flow channels, and enhanced in-plane forced flow through the electrode porous layer. However, previous studies focused only on fixed cell dimension and lack in-depth theoretical analysis about the influence of the scale-down effect on the cell performance. Under the operating condition, the decrease of cell feature size would introduce micro scale effect and affect the motion state of two-phase flow, which has a great influence on the output performance. Therefore, it is essential to conduct a comprehensive study on both simulation and experiment to fully explore the relationship between the feature size and inner transport characteristics.

The aim of this paper is to reveal the methanol/CO_2 convection and the μDMFC performance by applying the flow channel with different feature sizes and aspect ratios. A two-phase, three-dimensional cell model coupled with mass/momentum transports is established. In this model, the scale-down effect on inner transport and the channel aspect ratio on gas dynamic are numerically defined. In addition, a 0.64 cm^2 stainless steel-based μDMFC is fabricated using laser-cut technology, at which the effects of feature size and aspect ratio on cell performance are experimentally investigated to verify the simulation. The results from a series of experiments show that the μDMFC behaviors are influenced by the cell feature size in a complex manner. An optimized structure with the cell feature size of 0.6 mm and the channel aspect ratio of 2:1 is then determined to enhance the methanol mass transport efficiency, CO_2 emission rate and the output performance.

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2. The model analysis

2.1. Model description

The size of μDMFC is mainly determined by three factors: the type of the flow field, the dimensions of the channel and the rib, and the thickness of the gas diffusion layer. The micro scale effect on inner mass transfer is characterized by the feature size, denoted as F in Fig. 1.

With the same external methanol supply, the linear velocity of methanol solution inside the micro channel is inversely proportional to the feature size, and the corresponding relationship can be described as:

$$N = Av = nA_i v = C \tag{1}$$

where N, A, v, n and Ai represent the methanol volume from the external supply, the cross-section of the anode flow channel, the linear velocity, channel number and the cross-section of a single channel, respectively.

Therefore, the relationship between the linear velocity and the feature size can be given by:

$$v = \frac{N}{nA_i} \propto \frac{N}{F} \tag{2}$$

Based on equation (2), under the same external supply condition, the linear velocity of methanol in anode flow channel is increased when the feature size is scaled down. Therefore, a 3D physical model covering the solution region of anode flow channel, anode gas diffusion layer (AGDL) and anode catalyst layer (AGL) is established in this paper. Fig. 2 shows the calculation domain of three micro-scale designs with different aspect ratios (1:1, 2:1 and 4:1). The diffusion layer is defined as homogeneous porous electrode while the μDMFC is assumed under steady-state. In this model, the effective mass transfer area is 0.8 cm × 0.8 cm, the width of the channel and rib are both 0.6 mm, and the open ratio is remained the same for all three designs. In order to better analyze the gas dynamic in the micro channel, a typical L-shape unit was presented as the calculation domain, as shown in Fig 2.

The continuity equation suitable for methanol solution can be described as:

$$\nabla \cdot (\rho_{l,a} \overrightarrow{u}_{l,a}) = m_{l,a} \tag{3}$$

where $\rho_{l,a}$ represents the average density of the liquid phase substance, $\overrightarrow{u}_{l,a}$ is the average velocity, and $m_{l,a}$ is the source term.

Similarly, the continuity equation of gas is given by:

$$\nabla \cdot (\rho_{g,a} \overrightarrow{u}_{g,a}) = m_{g,a} \tag{4}$$

where $\rho_{g,a}$ denotes the average density of the gas phase substance, $\overrightarrow{u}_{g,a}$ is the average velocity, and $m_{g,a}$ is the source term of gas phase substances.

The liquid/vapor phase material are not produced or consumed in the anode gas diffusion layer because there is no electrochemical reaction. Meanwhile, CO_2, electrons and protons are produced in the anode catalyst layer. According to Faraday's law, the source term methanol solution can be expressed as:

$$m_{l,a} = \begin{cases} 0 & AGDL \\ -M_{MeOH}\dfrac{j_a s_a}{6F} - M_{H_2O}\dfrac{j_a s_a}{6F} & ACL \end{cases} \tag{5}$$

where j_a is the anode oxidation reaction rate and s_a is the specific surface area.

Similarly, the source term of anode CO_2 is defined as:

$$m_{g,a} = \begin{cases} 0 & AGDL \\ M_{CO_2}\dfrac{j_a s_a}{6F} & ACL \end{cases} \tag{6}$$

The momentum transport in diffusion layer can be described by Darcy law:

$$\overrightarrow{u}_{l,a} = \frac{-Kk_{rl}}{\mu_l}\nabla p_{l,a} \quad \overrightarrow{u}_{g,a} = \frac{-Kk_{rg}}{\mu_g}\nabla p_{g,a} \tag{7}$$

where K and k_r represent the absolute permeability and the relative permeability, and μ is the viscosity. k_r in Equation (7) can be further modified as:
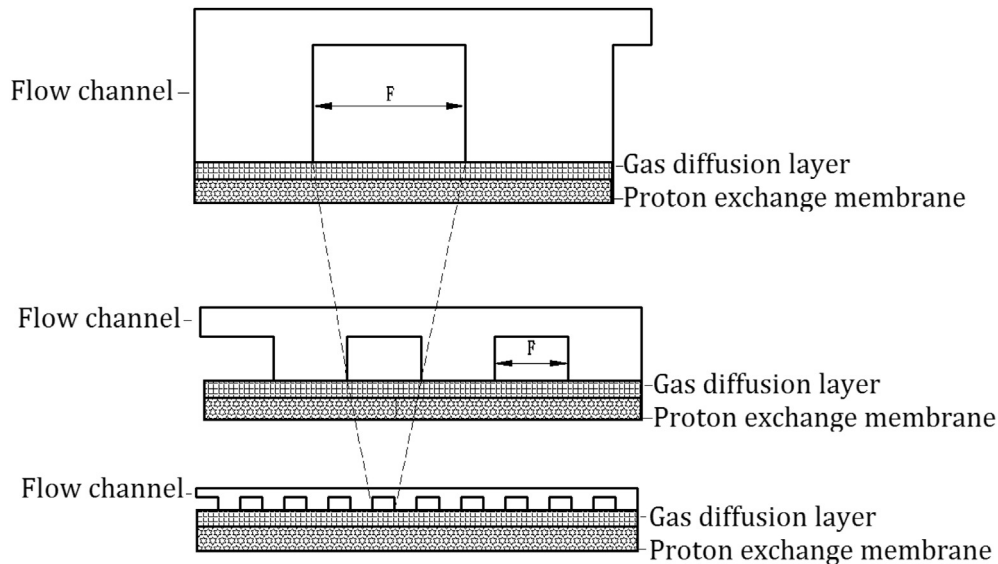
$$k_{rl} = s^3 \quad k_{rg} = (1 - s)^3 \tag{8}$$

Fig. 1. The feature size schematic of DMFC anode flow field.