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Optimal design of current collectors for microfluidic fuel cell with flow-through porous electrodes: Model and experiment

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HIGHLIGHTS

- A 3D model for MFC with flow-through porous electrodes is developed.
- Characteristics of electron transport in MFC are investigated.
- Effects of different current collector design parameters are examined.
- Design principles of current collectors are derived.
- Experimental investigation is performed to verify the key findings.

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ABSTRACT

Design optimization of current collectors has been performed to reduce the significant ohmic resistance observed in microfluidic fuel cell (MFC) with flow-through porous electrodes. A three-dimensional computational model is developed to investigate the electron transport characteristics in the porous electrodes, where lateral electron transport is found to encounter high resistance. Influences of different current collector design parameters on the transport resistances are examined and analyzed. The modeling results indicate that current collector position is the most influential factor due to the non-uniform flow rate distribution. Optimal current collector position is located at the high flow rate region instead of the conventional exposed end of the porous electrode. Experimental studies are performed to support the modeling analysis. The experimental results demonstrate that the optimized current collector position can boost the maximum power density by 61%. This study highlights the significance of the current collector design in achieving high performance MFC with flow-through porous electrodes. Based on the results, some general rules have been set for the current collector designs in this energy system, which can provide useful guidance for the future development of MFC.

1. Introduction

Microfluidic fuel cell (MFC) is a promising microscale power source for portable electronics [1]. In an MFC, the co-laminar nature of multi-stream flow in microchannels is utilized to maintain separation between fuel and oxidant streams without the need of a physical barrier such as a membrane while still allowing ionic transport [2]. This unique membraneless feature brings many distinct advantages against conventional proton exchange membrane fuel cells, such as elimination of membrane-related problems, easy fabrication and low cost [3].

By now, various MFC systems have been demonstrated using different fuel-oxidant combinations [4–8], electrode materials [9–13] and micro-channel configurations [1,14–16]. Among all of these studies, the vanadium redox based MFC with flow-through porous electrodes demonstrated a remarkably high power density (131 mW cm^{-2} at room temperature) [17]. The outstanding performance was mostly due to the large reaction interfaces brought about by the exceptionally high surface-to-volume ratio of the porous electrodes [18]. As the interest in MFC is growing rapidly, a series of works were conducted to further ameliorate the design in various aspects, including: optimization of the porous electrode volume [19], determination of kinetic parameters of the vanadium redox reactions on carbon based electrodes [20], development of novel porous electrode materials [9] and novel electrode configurations [2], introduction of new MFC architectures [21,22] and

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Nomenclature

a	specific surface area, m^{-1}
A	center of the interface between external wire and current collector
B	center of the interface between current collector and electrode
c	bulk concentration, mol m^{-3}
c^s	surface concentration, mol m^{-3}
d	diameter, m
D	diffusion coefficient, m^2 s^{-1}
E	equilibrium potential vs. SCE, V
E^0	standard equilibrium potential vs. SCE, V
F	Faraday constant, 9.65×10^4 C mol^{-1}
h	thickness in the z-direction, mm
$\vec{i}$	current density, A m^{-2}
i^0	exchange current density, A m^{-2}
i	charge transfer current density, A m^{-2}
K	permeability, m^2
k	standard reaction rate constant, m s^{-1}
k_{mj}	mass transfer coefficient of species j, m s^{-1}
L	length in the y-direction, mm
P	pressure, Pa
Q	charge source term, A m^{-3}
R	universal gas constant, 8.314 J mol^{-1} K^{-1}
S	species source term, mol m^{-3} s^{-1}
t	time, s
T	temperature, K
$\vec{U}$	velocity vector, m s^{-1}
V	vanadium species
V_{cell}	cell voltage, V
W	width in the x-direction, mm
z	charge number

Greek symbols

α	charge transfer coefficient
γ	constant
ε	porosity
ε_p	percolation threshold
ρ	density, kg m^{-3}
σ	electrical conductivity, S m^{-1}
τ	tortuosity
$\varnothing$	potential, V
μ	viscosity, Pa s
ω	constant
η	overpotential, V

Superscript

eff	effective

Subscripts

1	anode
2	cathode
a	anodic reaction
c	cathodic reaction
j	species {V^{2+},V^{3+},VO^{2+},VO_2^+ and H^+}, marked as {II, III, IV, V and H}
f	fiber
s	electrode
l	electrolyte
cl	current collector
ew	external wire

construction of MFC stacked systems [23].

Despite the high power density output feature of porous flow-through MFCs, high ohmic resistance and associated voltage loss were often observed [24]. As the ionic resistance is fixed at a small value (about 2 Ω) by excess supporting electrolyte, the significant ohmic resistance was mainly attributed to the electron transport in the cell. The electrons generated at the anode were drawn to the external circuit via the anode current collector, and then transported to the cathode via the cathode current collector. At this point, the current collectors should be designed carefully as they must ensure an effective transport of electrons between the reaction sites and the external circuit.

Work in search of an optimal current collector design has already been demonstrated in other fuel cell systems, especially the passive direct methanol fuel cells (DMFCs) [25–27]. Unfortunately, the current collector design principles derived for DMFC cannot be directly applied to MFC. In DMFC, current collectors offer passages for reactant distribution and product removal, in addition to providing good electrical contact for electron transport. Thus, the size of the current collector should be large enough to cover the whole active area of the electrode to ensure an effective mass transport. Open ratio (*i.e.* the ratio of the electrode area exposed to the reactant) is the most influential factor in DMFC current collector design as a tradeoff must be considered between the mass transport and electron transport [28]. In MFC, current collectors only serve to provide good electrical contact between the electrodes and the external circuits. Hence planar current collector with the open ratio equaling to zero is preferred. In addition, the current collector does not need to cover all the active area of the electrode. It can be attached to different parts of the electrode's active area, which offers room for optimization. However, by now, limited literature is available on the optimal design of current collectors in MFCs [29]. Therefore, deriving effective principles for current collector design is essential for future MFC design.

In this work, modeling studies are performed to accomplish design optimization of current collectors for MFC with flow-through porous electrodes. A comprehensive three-dimensional computational model has been developed for this purpose. Different from the existing models in the literature, the present model has restored the geometries of the current collectors and part of the external circuits in the modeling domain for the parametric analysis of the influences of current collector design parameters on the cell performance. The studied parameters include the current collector area, positioning, thickness, electrical conductivity and connecting position of the external wire. After analysis and discussions, conclusions and recommendations are derived for optimal and economical current collector design. Experimental verifications of the theoretical findings are also carried out and good agreement is achieved between the experimental results and the modeling predictions.

2. Numerical model

A three-dimensional computational model of MFC with flow-through porous electrodes is built up to perform the design optimization of current collectors. Fig. 1 shows the schematic of the modeling domain. This is an all vanadium MFC with V^{2+}/V^{3+} sulfate solution as the anolyte, VO^{2+}/VO_2^+ sulfate solution as the catholyte and carbon paper as the porous electrode material. In the operation, the anolyte and catholyte enter the fuel cell via two inlets on both sides passing through the inlet reservoirs heading to the carbon paper electrodes. The two streams then flow through the porous electrodes. Electrochemical reactions take place at the interface between the electrode and

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