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Computational modeling of air-breathing microfluidic fuel cells with flow-over and flow-through anodes

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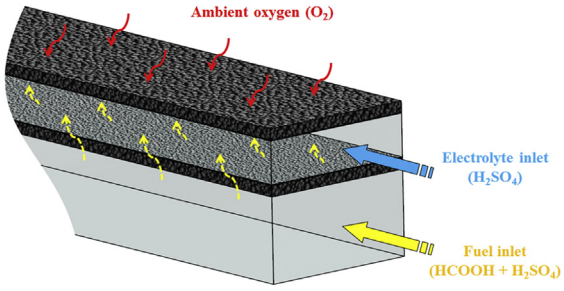
HIGHLIGHTS

- A 3D computational model for air-breathing microfluidic fuel cells is developed.
- An in-house air-breathing microfluidic fuel cell with a flow-through anode is tested.
- Fuel transport to the flow-over anode is limited by the concentration boundary layer.
- Flow-through anodes can enhance fuel transport and improve electrode utilization.
- Flow-through anodes enable lower fuel crossover current densities at low flow rates.

GRAPHICAL ABSTRACT



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ABSTRACT

A three-dimensional computational model for air-breathing microfluidic fuel cells (AMFCs) with flow-over and flow-through anodes is developed. The coupled multiphysics phenomena of fluid flow, species transport and electrochemical reactions are resolved numerically. The model has been validated against experimental data using an in-house AMFC prototype with a flow-through anode. Characteristics of fuel transfer and fuel crossover for both types of anodes are investigated. The model results reveal that the fuel transport to the flow-over anode is intrinsically limited by the fuel concentration boundary layer. Conversely, fuel transport for the flow-through anode is convectively enhanced by the permeate flow, and no concentration boundary layer is observed. An unexpected additional advantage of the flow-through anode configuration is lower parasitic (crossover) current density than the flow-over case at practical low flow rates. Cell performance of the flow-through case is found to be limited by reaction kinetics. The present model provides insights into the fuel transport and fuel crossover in air-breathing microfluidic fuel cells and provides guidance for further design and operation optimization.

1. Introduction

A pacing item in the rapid development of portable electronic devices (e.g. smart phones and tablet computers) is the trade-off between autonomy and weight/volume of batteries. This has

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spurred research and development of micro fuel cells, and in particular microfluidic fuel cells (MFCs) [1,2] as promising alternative miniaturized power sources. MFCs features include high energy density, orientation independence and unique membraneless architecture.

Unlike conventional micro fuel cells that rely on proton exchange membranes to separate the fuel and oxidant, MFCs exploit the co-laminar nature of a multi-stream flow in microchannel to segregate the reactants. Consequently, the membrane and membrane-related problems (e.g. degradation and water management) are eliminated, and fabrication costs and system complexity are also reduced. However, the interdiffusion of fuel and oxidant becomes one of the main limitations to cell performance. The other important problem is the reactant depletion in the boundary layers along the electrodes. In practice, the interdiffusion can be handled by properly adjusting the flow rate or the channel aspect ratio [3,4], but the concentration boundary layer issue is more complex.

The performance of the first generation MFCs was limited by oxidant transport [5–7], mainly due to the relatively low concentration and diffusivity of dissolved oxygen. In order to enhance oxidant transport as well as reaction kinetics, high concentration aqueous oxidants (hydrogen peroxide [8,9], potassium permanganate [5,10,11] and hypochlorite [12]) can be employed. However, the interdiffusion zone becomes broader at higher oxidant concentrations, which may induce oxidant crossover. More importantly, the broader interdiffusion zone inherently reduces the cell efficiency since the mixed reactants are unusable. Air-breathing cathodes provide a more practical way of enhancing oxidant transport by allowing oxygen from ambient air to diffuse to the cathode catalyst layer [7]. Numerical studies have shown that air-breathing cathodes for both membraneless [13] and PEM based architectures [14,15] can maintain a nearly constant oxygen concentration during cell polarization, therefore providing optimal conditions for the oxygen reduction reaction. Furthermore, the fuel/oxidant interdiffusion issue is also eliminated and hence allows the possibilities of fuel recycling [16].

Further studies of air-breathing microfluidic fuel cells (AMFCs) based on the flow-over anode (i.e. planar anode, see Fig. 1a) have however shown that significant concentration gradients are present during operation and performance is limited by the fuel transport through the resulting concentration boundary layer [17–19]. An expected way to enhance fuel transport is to simply increase flow rates to reduce the thickness of the concentration boundary layer; this would enhance not only cross transport, but also the fuel replenishing rate. However, this strategy penalizes fuel utilization [17,20]. Another approach is to introduce the flow-through electrodes based on porous carbon paper [21,22]. Because of the extended inner reactive area and enhanced mass transport, both better performance and higher fuel utilization rate can be obtained.

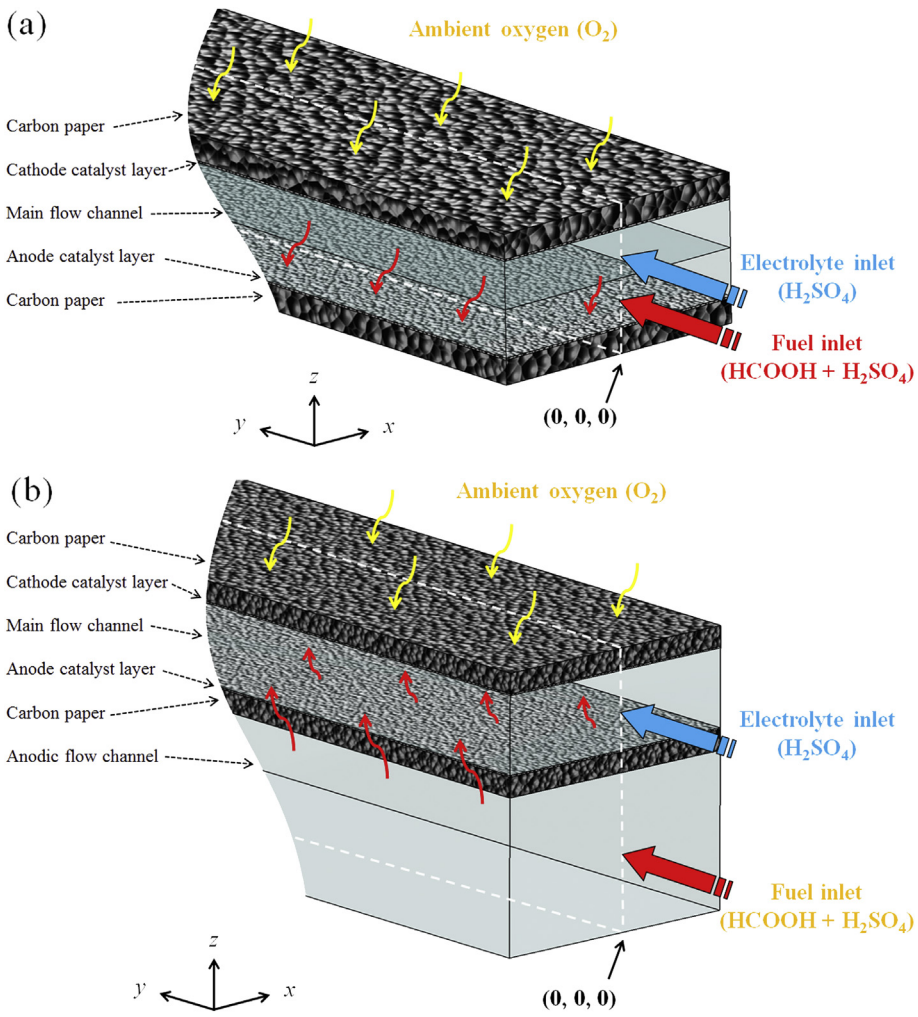

Fig. 1. Schematic illustrations of the air-breathing microfluidic fuel cell with a (a) flow-over and (b) flow-through anode. The computational domain is bisected about the y–z plane due to the symmetric architecture.