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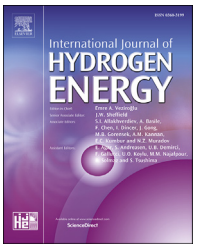

Three-dimensional modeling and investigation of high temperature proton exchange membrane fuel cells with metal foams as flow distributor

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ABSTRACT

Flow field design of fuel cells has a significant impact on the distribution of the reactants over the active surface area. In this work, the cell performance and transport characteristics of high temperature proton exchange membrane fuel cells with metal foams as flow distributor were numerically investigated by a three-dimensional and non-isothermal model. Compared to the fuel cell with conventional straight flow channels, the cell performance is considerably improved by the application of a metal foam as flow distributor. The current density improvements at the operating cell voltages 0.6 V and 0.3 V are 4.96% and 6.45%, respectively. Moreover, the species, temperature and current density are uniformly distributed because the reactants can also flow through the area covered by the ribs in the conventional design. It is concluded that a metal foam can be used as the flow distributor due to its high electrical conductivities and low weight advantages compared to the conventional graphite and metallic bipolar plates. In addition, the effects of permeability, operating pressure, operating temperature, and stoichiometry ratio on the cell performance were investigated. The present results provided and improved the fundamental understanding of the application of metal foams as flow distributor and its effects on transport characteristics and cell performance.

Introduction

Fuel cells are energy conversion devices where the electrical energy is directly generated through electrochemical reactions. Proton exchange membrane fuel cells (PEMFCs) have been considered as the most promising alternative energy technology for automotive, portable and stationary applications [1]. The cell performance of traditional low temperature proton exchange membrane fuel cells (LT-PEMFCs) with an operating temperature range of 50–80 °C can be significantly affected by the water flooding problem, which means that complicated thermal and water management are required [2–4]. In order to avoid the water flooding problem, high temperature proton exchange membrane fuel cells (HT-PEMFCs) with the operating temperature above 100 °C have been proposed and investigated by several researchers [5–16]. Compared to the LT-PEMFCs, the HT-PEMFCs have the following advantages: high carbon monoxide tolerance, fast chemical reaction kinetics, easy waste heat recovery and water management [13–16]. However, the HT-PEMFCs still have some challenges to improve the conductivity and

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stability of the membrane, and manage the heating strategies for start-up and operation processes due to the high operating temperatures [15].

The computational fluid dynamics (CFD) approach has become an effective tool to investigate and analyze the transport processes and characteristics within fuel cells. Compared to experimental measurements, numerical simulations can provide more detailed transport phenomena within fuel cells due to its compact characteristic. Cheddie et al. [6] developed a three-dimensional model to investigate the oxygen and temperature distributions, as well as the cell performance. Oxygen depletion under the ribs and a greater ohmic concentration were observed due to the presence of ribs, which could not be predicted by a two-dimensional model [7]. The effects of the coolant flow channels with three constant thermal gradient conditions on local transport characteristics and cell performance were numerically investigated by Chippar et al. [8]. In addition, it was observed that the irreversible reaction heat was the major heat generation sources among the irreversible reaction heat, ohmic heat and reversible heat. Also, the gas crossover effects in HT-PEMFCs were numerically studied by Chippar et al. [9]. The results showed that the species and local current density distributions became more uneven when the membrane was degraded and the gas crossover diffusion was enhanced. To obtain an optimal operating temperature for a certain lifetime period of HT-PEMFCs, a mathematical model and a temperature dependent durability model were developed to estimate the cell performance and durability, respectively [10]. The effects of stoichiometric ratio and membrane conductivity on cell performance were numerically investigated by a three-dimensional, isothermal model [11].

PEMFCs consist of several components: the anode/cathode bipolar plate (BP), the anode/cathode gas diffusion layer (GDL), the anode/cathode catalyst layer (CL), and the membrane between the anode and cathode electrodes. The gas flow channels fabricated on the BPs guide the reactant gases to diffuse through the GDLs to the reaction sites in the CLs where the electrochemical reactions take place. To improve the cell performance, the gas flow channels with blockages have been investigated by many researchers. The application of in-line and staggered blockages in gas flow channels of PEMFCs was experimentally and numerically investigated by Heidary et al. [17,18]. The effects of wavy surface gas flow channel on transport processes in PEMFCs were numerically studied by Li et al. [19]. In general, two types of plates have been used for the BPs, namely, graphite plates and metallic plates, which have large thermal and electrical conductivities. Compared to the metallic plates, the mostly used graphite plates have excellent corrosion resistance. However, the graphite plates easily crack during the fabrication and assembly processes due to their low mechanical strength. The metallic plates have several advantages including flexible selection, low cost, and high mechanical strength [20]. Furthermore, the low corrosion resistance of metal materials can be improved by coating techniques. In recent years, the application of metal foams in the fuel cell field has attracted attention of researchers due to its attractive characteristics such as high porosity, flexible permeability, and low weight [21]. Moreover, the corrosion resistance of metal foams can be improved by coating on the surface, and the contact resistance also can be minimized by compression. There have been several numerical and experimental investigations and analyses of metal foam application in fuel cells reported in the literature. A three-dimensional model developed by Wang [22] was applied to investigate the heat and electron transport characteristics of LT-PEMFCs with porous media filled in the gas flow channels. It was found that the electron transport was enhanced and thus the cell performance was also improved due to the porous structure in the gas flow channels. The effect of stainless steel metal foams on the cell performance of direct methanol fuel cells (DMFCs) was experimentally investigated by Shudo et al. [23]. The cell performance of LT-PEMFCs with metal foams as the flow distributor was experimentally investigated by Tseng et al. [24]. The effects of operating conditions and metal foam property parameters on the cell performance were systematically examined and analyzed. Furthermore, the effect of metal foam flow field design on cell performance was studied [25]. It was concluded that the cell performance is significantly improved by a three-zone design where the reactant is split up into three streams to gain a uniform reactant distribution within the flow field. In addition, metal foam flow field has also been considered in the HT-PEMFCs [26]. The experimental results showed that the cell performance was improved and the cell was also relatively stable during the operation test period. Further application of metal foams in LT-PEMFCs can be found in the relevant literature reported by Odabaee et al. [27], Afshari et al. [28], and Carton et al. [29].

Although there have been several investigations on the application of metal foams in fuel cells, the detailed information and knowledge of HT-PEMFCs with metal foams as flow distributor are still rather limited. Consequently, the present work has been carried out to study and improve the understanding of transport behavior within such fuel cells. In this work, a three-dimensional, non-isothermal and steady-state model based on the finite volume method was developed and applied to investigate the effects of metal foam flow field on the transport phenomena and cell performance in HT-PEMFCs with a H_3PO_4 doped polybenzimidazole (PBI) membrane. In addition, the effects of permeability, operating pressure, operating temperature, and stoichiometry ratio on the cell performance were studied. By this study, the knowledge frontier is taken to the next level.

Model description

Physical model and assumptions

The schematic of a three-dimensional fuel cell unit physical model being used in the present study is depicted in Fig. 1. As shown in Fig. 1a, a conventional straight channel is used for the gas flow field which is referred to as Case A. In addition, the metal foam design is applied for the flow field instead of the straight channel and ribs in Fig. 1b. This is referred to as Case B. The cross-sectional area of the flow channel in Case A is 1 mm × 1 mm, while the cross-sectional area of the metal foam is 2 mm × 1 mm. In a real application, the metal foam is generally compressed to decrease the contact resistance and obtain good thermal and electrical conductivities [24,26]. In