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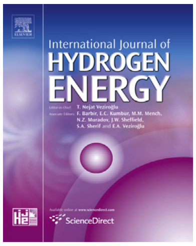

Novel architectures of polymer electrolyte membrane fuel cells: Efficiency enhancement and cost reduction

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ABSTRACT

Three novel architectures of proton exchange membrane fuel cells (PEMFCs), called circular, square and octagonal duct-shaped architectures, are introduced and analyzed numerically. A three-dimensional computational fluid dynamics (CFD) code is used to solve the equations for a single domain of the cell under steady state and non-isothermal conditions. The numerical results are in reasonable agreement with the experimental data over a wide range of current density. The distributions of oxygen, hydrogen and water mass fraction, current density and temperature are studied for the three introduced configurations. The circular- and square-duct configurations show considerably better performance and offer several advantages over the conventional PEMFC configuration. These advantages are related to the way in which the reactant gases are supplied to the flow field, to the shorter channels used and to the lower cost of the PEMFC due to the less bipolar plates needed.

Among the three configurations having the same active area and the same inlet area, the square-duct geometry shows considerably higher current density and more uniform water and temperature distributions. The square-duct configuration is, therefore, the best candidate to enhance the PEMFC efficiency while reducing its size and cost, and can be considered for the design of new generation of PEMFCs.

Introduction

The performance, durability and cost of PEMFCs are the main challenges to their full commercialization [1–4]. Many promising efforts have been made to date to tackle these challenges [5–8], yet some issues remain unresolved [9,10]. The design of flow field and the way of supplying and distributing reactants inside the stack play crucial roles in PEMFC's performance, durability and cost [11–13]. The

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conventional architecture of PEMFCs has a limited potential to resolve issues such as the high amount of the brittle graphite bipolar plates needed, the non-uniformity of temperature and current distribution, the uneven distribution and low diffusion of reactants into the catalyst layer and the relatively large volume of the PEMFC stack.

A few novel configurations and architectures have been recently explored to improve PEMFC efficiency and solve technical problems such as species transportation. Pourmahmoud et al. [14–19] worked on different channel geometries in order to enhance PEMFC's performance. They showed that an elliptical and circular channel cross-section have the potential to produce higher current density in comparison with the conventional PEMFCs. Moreover, the elliptical- and circular-channel configurations facilitate the reactant transportation, lead to more homogenous distribution of reactants and effectively reduce mass transport loss. These issues decrease cathode overpotential known as the main cause of loss in PEMFCs. Wang et al. [20] showed an enhanced performance in PEMFC at low operating voltage by using a baffle in serpentine channel. They also optimized the serpentine pattern by varying the channel heights for better reactant distribution into the membrane electrode assembly (MEA) [20]. Alvarado et al. [21] improved power generation by changing serpentine symmetric flow pattern. Chen et al. [22] studied novel flow field as z-type and interdigited channels. In general, several flow field geometries including radial and spiral geometries have been simulated and fabricated to enhance the PEMFC performance by providing larger reaction area along the channel [23–27]. Tiss et al. [28] designed several blocks along the channel to force reactants into the gas diffusion layer. They observed an improvement to the output current density. Walckzy et al. [29] investigated ribbon MEA architecture providing even current distribution and lower fuel cell cost. Khazaee and Ghazikhani [30] introduced annular and duct-shaped PEMFCs, which are fundamentally new architectures.

According to the above explanation, it can be concluded that appropriate architectures and well-designed flow fields can enhance the cell performance. Fig. 1 proposes three novel MEA and channel configurations in which each channel is in connection with two MEAs. This type of PEMFC configuration enhances the reactants diffusion and leads to an increases in the reaction area. These architectures have the same boundary conditions as the conventional PEMFC do and any feed compositions, relative humidity and flow rates can be considered for both anode and cathode. In the present study, a three-dimensional, single phase, non-isothermal and parallel flow model is considered for three different circular, square and octagonal duct-shaped PEMFCs. Through computational fluid dynamics (CFD) analysis and by comparing the polarization curves, the present study investigates the advantages of these three novel architectures over the conventional PEMFCs and the benefits that they can provide in terms of the uniformity of the temperature, current and reactant distributions inside the stack and the cost and size reduction of PEMFCs. These novel architectures will be analyzed in terms of the potential that they offer for the new generation of PEMFCs.

Model description

System description

Constant mass flow rate at the channel inlet, constant pressure condition at the channel outlet, and no-flux conditions are applied to the mass, momentum, species and potential conservation equations at all the boundaries except for the inlets and outlets of the anode and cathode flow channels. The side's faces are symmetrical.

Fig. 2 shows the conventional domain of the base model and Table 1 summarizes the geometric parameters and operation conditions for the base model. The cell consists of hydrogen and oxygen channels, bipolar plates on the cathode and anode sides of the cell, which act as current collectors. The membrane electrode assembly (MEA) is located between gas channels.

The three architectures proposed for PEMFCs, shown in Fig. 2, have the same active area and operation condition as the base model (a conventional PEMFC) does. This allows comparing these four PEMFC configurations at the same conditions. The reactant gases are supplied from inlet channels into the cell and leave it from the areas at the outer edge of the cell. As Fig. 2 shows, each cathode flow field is in contact with two anode reaction areas and vice versa. This configuration leads to a new type of channels ever introduced, especially in terms of the way the reactants are supplied, the less volume occupied due to having shorter lengths, and the potential for enhancing the PEMFC performance. All the geometric parameters of these three architectures are presented in Table 2.

Model assumption

The model presented here is aimed to study the electrochemical kinetics, current distribution, reactant flow fields and multi-component transport of oxidizer and fuel streams in a multi-dimensional domain. It is built upon the following assumptions: (i) non-isothermal steady state conditions under constant load are considered; (ii) all gases are assumed to obey ideal gas behavior; (iii) gas diffusion and catalyst layers are considered to be homogeneous and isotropic porous media; (iv) flow is incompressible and laminar due to the low pressure gradients and velocities; (v) the membrane is impermeable to the cross-over of reactant gases and assumed to be fully hydrated; (vi) the species diffusion and electrochemical reaction are based on the dilute solution theory and Butler–Volmer kinetic equation, respectively; (vii) the fully humidified inlet condition is considered for the anode and cathode; and (viii) the amount of liquid-phase water produced from electrochemical reactions is negligible and phase change or two phase transports are not considered. This issue can be considered and added to the model for future work.

Model equations

Gas flow fields

In a PEMFC, the gas velocity is calculated from the continuity and momentum equations: