Energy 133 (2017) 306–316

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Numerical modeling of a proton exchange membrane fuel cell with tree-like flow field channels based on an entropy generation analysis

Cesar E. Damian-Ascencio [a], Adriana Saldaña-Robles [b], Abel Hernandez-Guerrero [a], Sergio Cano-Andrade [a], *

[a] Department of Mechanical Engineering, Universidad de Guanajuato, Salamanca, Gto. 36885, Mexico
[b] Department of Agricultural Engineering, Universidad de Guanajuato, Irapuato, Gto. 36500, Mexico

ARTICLE INFO

Article history:
Received 17 September 2016
Received in revised form
27 April 2017
Accepted 22 May 2017
Available online 26 May 2017

Keywords:
PEM fuel cell
Flow distributors
Tree-like pattern
Entropy generation

ABSTRACT

This paper presents a three-dimensional numerical modeling of a PEM fuel cell with tree-like flow field channels. Four different tree-like configurations are considered for the study based on a statistical analysis of the veins of the leaves of different trees. The number of bifurcations of the vein and their inclination are considered as parameters for the characterization. Four different configurations are the most recurrent, corresponding to one level of bifurcation at 37° and 74° and two levels of bifurcation at 37° and 74°. The model considers a complete solution of the mass, momentum, energy, and electrochemical equations. An entropy generation analysis is developed as a post processing once the solution of the models is obtained. Because new geometries for the channel configuration in the bipolar plates are introduced, special attention is considered for the entropy generation due to mass flow. Results indicate that the configuration with two levels of bifurcation at 37° is efficient at removing water from the cathode channels, resulting in a good current density production. In addition, a better performance of the PEM fuel cell (higher current density production and lower entropy production) is obtained by increasing the number of bifurcations.

1. Introduction

A proton exchange membrane (PEM) fuel cell is an electrochemical device that directly converts the chemical energy of hydrogen into electricity without the need of a combustion process [1,2]. PEM fuel cells are a promising substitute for fossil-fueled technologies because of their relatively high efficiency (40–60%), fast start-up, silent performance, near-zero emissions to the environment (residues are only liquid water and heat), and they are not limited by the Carnot efficiency [1,2]. PEM fuel cells are also a good alternative when coupled with other technologies in form of microgrids [3–6].

The main drawbacks of a PEM fuel cell to date are the high investment costs and short periods of durability associated with the materials (especially for the platinum in the catalyst layers that is expensive and is highly affected by CO_2 poisoning), and also the non-homogeneous current density production due to an inadequate distribution of the reactants in the fuel cell [1,2,7]. With respect to the latter, the shape of the channel cross sectional area, the channel dimensions, and the gas flow channel configuration have to be properly designed. The motivation of the present work is on the design of the gas flow channel configuration, where much effort has been devoted during the past years [8–10].

For the gas flow channels, four configurations are considered as conventional, i.e., straight, parallel, serpentine, and interdigitated. The straight channel configuration [11,12] provides a good production and distribution of current density, but its main limitation is the geometry itself because a very long channel is needed to produce an acceptable amount of energy. However, the straight channel configuration is the base for most of the subsequent geometries proposed. The parallel channels configuration [13–15] provides a high current density production, but presents zones of water accumulation and, as a consequence, a non-uniform current density production. The serpentine configuration [13,15–18] provides a high current density production and a good removal of the water generated at the cathode, but its main drawback is the high pressure drop for the gas flow due to the length of the channel and the many sharp turns along the path. The interdigitated

---

* Corresponding author.
E-mail address: sergio.cano@ugto.mx (S. Cano-Andrade).

http://dx.doi.org/10.1016/j.energy.2017.05.139
0360-5442/

configuration [8,19–23] is a modification of the parallel channels configuration that forces the gases to pass through the porous media, improving the water removal and having a better use of the reactants, but its main limitation is the high pressure drop for the gas flow which limits the overall performance of the fuel cell.

New gas flow channel configurations are proposed as an alternative to the conventional geometries. A radial configuration [24] shows a low pressure drop for the gas flow and areas of high current density production, but also areas where water is accumulated, showing a negligible current density production in these areas. A spiral configuration [13,25] allows the PEM fuel cell to have an uniform current density production on the active area and a low pressure drop for the gas flow, but still the overall fuel cell performance is limited. A parallel channel configuration in which the injection of the gases to the channels is modified in order to have a more uniform and homogeneous flow distribution in all the channels [26], and Pin-type configurations [13,27], provide an uniform current density production and a low pressure drop for the gas flow, but the overall fuel cell performance is still limited. A maze flow configuration [15] shows a rapid voltage decay at high values of current density, thus, presenting a very poor overall fuel cell performance. Other alternatives are to combine gas flow geometries, for instance, serpentine (anode) and interdigitated channels (cathode) [28], which show a good fuel cell performance in terms of water removal. Recently, porous media instead of channels are also proposed as gas flow distributors [29–31], showing a good mass distribution of both, hydrogen and oxygen, as well as a good overall fuel cell performance.

Biomimetic configurations [32] are also proposed as an alternative to the conventional geometries. These configurations are inspired on the observation of nature, under the premise that systems that reflect the natural configuration of biological systems are more efficient [33]. Biomimetic geometries are obtained using a deterministic principle for the generation (optimization) of geometric form in natural systems, limited to global and local constrains in order to improve the performance of the system under analysis [33]. Along this line, a tree-like pattern which results from a multiparametric optimization [34,35] shows a reduction of the pressure drop and a maximization of the net power produced. Fractal geometries based on respiratory systems [36,37] provide a low pressure drop for the flow of gases, but large areas of the cell are not used well, obtaining a non-uniform current density production. Other fractal geometries [38] produce a flooding of the channels due to the poor water management of the geometry. A configuration based on the geometry of the veins of leaves [39] provides a good performance of the fuel cell, but for the particular geometry proposed, the water management is not efficient because areas of water stagnation are present.

Although all these different non-conventional configurations for the gas flow channels, including nature-based and non-nature-based configurations, provide improvements for the PEM fuel cell performance, they still are not able to provide a better fuel cell performance than the conventional serpentine configuration. Also, only numerical studies are presented for most of these non-conventional geometries, leaving experimental studies as an open area of research.

In this paper, an analysis of the performance of a PEM fuel cell using four different tree-like configurations for the gas flow distributors is presented. The channel configurations mimic the distribution of the veins of a leaf, and consist of configuration models with one and two bifurcations and with two different angles for the inclination of the veins with respect to the main channel.

The paper is organized as follows: section 2 presents a description of the PEM fuel cell system under analysis; section 3 outlines the mathematical model used for the analysis; section 4 presents the numerical results of the PEM fuel cell performance with the four different configurations, including an entropy generation analysis; and section 5 concludes the paper.

2. System description

In order to define the tree-like configurations for the flow field channels, 30 of the most common trees in the Bajío region of México are randomly chosen, and 20 leaves from each tree are photographed. Measurements of the number of bifurcations and the bifurcation angles of the veins of a leaf are taken for all the images from the collection of pictures obtained for the analysis. The data is analyzed to define the most recurrent number of bifurcations and their inclination angles.

With respect to the number of bifurcations on the veins of leaves, two different configurations are found as the most statistically repetitive, i.e., a configuration with one level of bifurcation (one main channel and one flow branch), and a configuration with two levels of bifurcation (one main channel and two flow branches). A configuration with three levels of bifurcation is not studied because it causes the channels to cross with each other, thus, causing turbulence and instabilities in the gas flows. These instabilities cause that the PEM fuel cell reduce its current density production because the gases are not uniformly distributed on the active area. With respect to the bifurcation angles, the leaves collected are categorized in two sets. For the first set of leaves, the mean value of the bifurcation angle is 37° and the standard deviation is 0.823°, with a confidence interval of 95%. For the second set of leaves, the mean value of the bifurcation angle is 74° and the standard deviation is 0.947°, with a confidence interval of 95%.

The combination of the number of bifurcations and the different angles results in four different configurations for the flow channels, that is, one level of bifurcation at 37° and at 74° (Fig. 1a) and two levels of bifurcation at 37° and at 74° (Fig. 1b).

The PEM fuel cell system consists of current collectors, flow channels, diffusion layers, and catalyst layers for each side of the cell (anode and cathode), and a membrane between the catalyst layers. The catalyst layers are 0.03-mm thick, the diffusion layers are 0.5-mm thick, and the membrane is 0.05-mm thick. The total active area for the PEM fuel cell is 9-cm^2 for all configurations. The flow channel configuration at the anode is chosen to be the same than that at the cathode. The cross sectional area of the flow channels is square (1×1 mm for the main vein), and decreases according to Murray's Law [40,41] by a factor of $2^{-1/3}$ from one branch to the other. The branches are at the same level with the main vein. The design of the bifurcations are in line with the

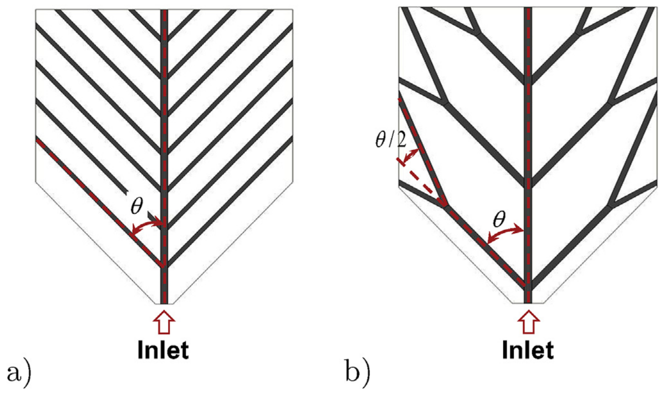

Fig. 1. Channel flow field pattern with: a) one level of bifurcation at $\theta = 37°$ (or 74°) and b) two levels of bifurcations at $\theta = 37°$ (or 74°).