Energy Conversion and Management 110 (2016) 356–366

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Enhancement of PEM fuel cell performance by flow channel indentation

A. Ghanbarian [a], M.J. Kermani [b,c,*]

[a] Department of Aerospace Eng., Amirkabir Uni. of Tech., 424 Hafez Ave., 15875-4413 Tehran, Iran
[b] Department of Mechanical Eng., Amirkabir Uni. of Tech., 424 Hafez Ave., 15875-4413 Tehran, Iran
[c] Centre for Solar Energy and Hydrogen Research (ZSW), 89081 Ulm, Germany

ARTICLE INFO

Article history:
Received 18 September 2015
Accepted 15 December 2015
Available online 30 December 2015

Keywords:
CFD
Channel partial blockage (indentation)
Fuel cells
Performance enhancements
Parametric study

ABSTRACT

A three-dimensional, steady, single-phase flow of oxygen, nitrogen and water vapor mixture in the cathode of proton exchange membrane (PEM) fuel cell was numerically studied here. It was shown that the performance of the cell was enhanced by partial blockage of the flow channels in a parallel flow field. Since, channel indentation could increase oxygen content within the catalyst layer. It was observed that the influence of channel indentation in high current density regions was noticeable. Various types of blocks with profile shapes: square (SQ), semicircle (SC) and trapezoid (TR) were considered. Enhancements were compared with the no-dent (ND) called as the base case. The voltage to current relation was modeled using the Tafel equation. This provided the distribution of current density at a prescribed cell voltage. The computations were performed at 333 K, 100,000 Pa, water dew point temperature 313 K, and 50% utilization within the range of 0.2–0.8 V. It was predicted that the flow turns to be two-phase in high current density regions (say cell voltages less than 0.4 V). To push the condensate out of the flow field, adequate pressure gradient were required. This prerequisite was already taken into account in this study. A parametric study considering the influences of dent heights and arrangements, exchange current density, fluid viscous resistance and rib sizes were considered providing enhancements over 25% in the net power. The present study gives a very helpful guideline for flow field manufactures.

1. Introduction

Fuel cells are considered as the power sources for the future, and proton exchange membrane fuel cell (PEMFC) is one of the most important alternative clean power generators for portable, mobile and stationary applications. PEMFCs produce zero to low emission, can operate at low temperatures, provide high power density and enjoy fast start up [1–13]. PEMFCs use hydrogen as the fuel. Hence, efficient hydrogen production techniques for future development of PEMFCs in large scale should be taken into account [14,15]. To achieve better operation and performance for fuel cells, enhanced design and optimization of them is necessary [2]. The flow field design in the bipolar plates is one of the key parameters for the efficient utilization of catalyst layers (CLs) [16,17]. The PEMFC's channels act as the reactant distributor. The reactants, as well as the products, are transported to and from the cell through the flow channels. An appropriate flow field design can enhance the reactant delivery and water removal from the cell to minimize the concentration losses occurring usually at high current densities [1,3].

Because of slow reaction rates in the cathode side of PEMFCs, this side can be considered as a performance limiting component. This has lead researchers to mainly focus most of their efforts to improve reaction rates in cathode electrodes [18]. In 1998, a novel concept for convective heat transfer enhancement was presented by Guo et al. [19]. They underlined three ways to enhance convective heat exchange in internal flows such as (1) increasing flow velocity, (2) increasing temperature gradient at the wall and (3) deviating the angle between flow velocity vector and temperature gradient from 90° [19]. Deviating the intersection angle between velocity vector $\vec{V}$ and temperature gradient $\vec{\nabla}T$ from 90° boosts the advection phenomena $\vec{V}.\vec{\nabla}T$ by conduction heat transfer mode $\vec{\nabla}.(k\vec{\nabla}T)$ in energy equation. As a result, the convection heat exchange between the wall and the core flow increases [6]. This is called field synergy principle [20–22]. The intersection angle between flow direction and temperature gradient can be changed using some partial blocks or indents [6]. Due to the analogy between heat and mass transfer problems, the mass exchange between the channel and the catalyst layer in PEMFC is expected

* Corresponding author at: Department of Mechanical Eng., Amirkabir Uni. of Tech., 424 Hafez Ave., P. Code 15875-4413 Tehran, Iran. Tel.: +98 (21) 6454 3421; fax: +98 (21) 6641 9736.
E-mail address: mkermani@aut.ac.ir (M.J. Kermani).

http://dx.doi.org/10.1016/j.enconman.2015.12.036
0196-8904/

to increase in the same order as that of heat transfer in dented channel cases. As a result, oxygen consumption within the catalyst layer is enhanced and the performance of the fuel cell could be improved. Kuo et al. in [23] numerically studied the PEMFC's flow fields with obstacles (interruption) within the fluid. The obstacles imbedded within the channels had different shapes such as wave, trapezoid and ladder. They compared the performances with that of the straight conventional form of the gas flow channel. Their numerical results show, the channels containing the obstacles (wave, trapezoid and ladder obstacles) increases the mean Nusselt number by a factor of approximately two [23]. Choghadi and Kermani demonstrated 15% efficiency enhancement in a PEM fuel cell using a partial blockage of the serpentine flow field in an experimental test [3]. Similar observations have been reported by Perng et al. [8], in which they showed that transverse installation of rectangular cylinders in flow channels effectively enhances the cell performance of a PEMFC. Tiss et al. in [24] numerically studied the mass transport in PEM fuel cells using partial blockage in the gas flow channels. They showed that partial blockage improves the performance of PEM fuel cell. Heidary and Kermani [25] investigated heat transfer in wavy flow channels linked to porous gas diffusion layer (GDL). They showed that the level of heat transfer in wavy channels, depending on the wave amplitude, wave number and flow Reynolds number, can enhance up to 100%. Heidary and Kermani [26] numerically considered heat transfer enhancement using nano-fluids in channels containing partial blocks. They concluded that heat transfer in channels can enhance by addition of both nano-particles, and partial blocks by 60%. Dehsara and Kermani have investigated the influence of semicircular obstacles placed at the bed of gas flow channels on the performance of PEM fuel cells [27]. Their results indicate that the semicircular obstacles in anode and cathode sides of gas flow channels can enhance the cell efficiency by 18.1% at the maximum power density point. Perng et al. in [28] analyzed how a modified flow field can affect transport characteristics of the reacting species, and the cell performances in PEMFCs. They predicted performance enhancements approximately 8% [28].

Bilgili et al. [29] studied a three dimensional computational model to investigate the performance of PEMFCs with partial block placement in anode and cathode gas flow channels. Their simulations show that the obstacles inside the gas flow channels improve the concentration distribution along the channels and the transport of the reactant species through the gas diffusion layer. As a result, an improvement of the order 4–6.5% in the cell performance is achieved [29].

In general, for a given cell active area and fixed flow field sketch, the performance of a cell can be correlated to the flow field in the following manners:

I. By either sudden or gradual area changes of the flow field channels. The noted area changes if performed suddenly, like channel indentation (either partial or fully blockage), sudden contraction of the channels, etc. would result in abrupt variations in the local electrical current density [3,6,8,24–30]. On the other hand, gradual changes in channel cross sectional areas like tapering the flow field channels, decreasing and increasing channel widths along the duct, making the channel-walls or -beds in wavy shapes, etc. [31–33], would consequence the local current density to undergo steady changes.
II. The shape of the channel cross sectional area, e.g. channels with triangular, semicircular, trapezoid, rectangular shapes with different aspect ratio values, etc. [1,2,11,15–17,22,34–41].

In this paper, performance enhancement of PEM fuel cells were numerically studied using gas flow channel indentation. The ANSYS®-FLUENT® 14.5 software packages were used for these purposes. The User Defined Function (UDF) capability of the package was used to incorporate the kinetics of reaction within the catalyst layer via the Tafel equation. Although the present study models the cathode side only, the so called half-cell model, but appropriate boundary conditions have been used to take into account the rest of the cell. Hence, the performance of the whole cell could be predicted here. Three different dent profile shapes (square, semicircle, and trapezoid dent shapes) and two types of dent arrangements (symmetric and zigzag) were considered. The performance of each dent cases was compared with a base case (No Dent case referred as ND in this paper) for the enhancements. It was observed that channel indentation could enrich the content of oxygen within the catalyst layer that locally crowned the current densities in regions right over the dents. As a result, the average current density of cells could increase. It is known that channel indentation increases the pressure drop and pumping power of the working fluid through the channels. So to quantitatively address the cost-to-benefits of the problem, the net power extracted from the cell (P_{net}) was considered in this study. Also a sensitivity study considering the influences of dent arrangements, dent heights, rib sizes, GDL and CL fluid viscous resistances, and exchange current densities were performed in this study. It is observed that appropriate selection of the noted parameters, were lead to 26.75% performance enhancements.

A complete detail of the problem is described in the next section.

2. Problem definition

In this study, the performance enhancements of PEMFCs caused by flow channel indentation in a parallel flow field are considered. Two different dent arrangements in the flow field are considered, namely, symmetric and zigzag as shown in Fig. 1. In the case of symmetric dent arrangements, the repeating unit is composed of a single channel and two-half ribs at the sides of the channel, as shown in Fig. 1(a)–(d), connected at the top to a gas diffusion layer (GDL) over which the catalyst layer (CL) is placed. However, in the case of zigzag dent arrangements, the repeating unit is composed of one complete rib with two half-channels at the sides of the rib, as shown in Fig. 1(e).

Four cases are considered, including three dented cases, and a no-dent (labeled as ND). Fig. 1(a) shows the schematics of the domain in the case of no-dent along the channel. This is called the base case geometry in the present study. Generally speaking, the geometrical parameters of a flow field can be defined using channel width, height and length, respectively w, h, L, and the ribs between two adjacent channels d. The numerical values for these parameters and the number of meshes used in the present study are denoted in Table 1. To enhance the performance of the cell, some dents are placed along the channel as shown in Fig. 1(b)–(e). As shown in Fig. 1, the distance between two consecutive dents are taken as Δx = 10 mm. This distance is large enough to avoid any influence of a dent to another. Six dents were embedded in all of the dented cases along the channel, as shown in Fig. 1. Various types of dent profile shapes are used to study the fuel cell performance enhancements. Two types of dent arrangements (namely symmetric and zigzag) are considered. Fig. 1(b)–(d) shows the symmetric arrangements and Fig. 1(e) depicts the zigzag dent arrangement. Included in the geometrical parametric studies is the influence of the dent height (percentage that dents occupy the cross section of a channel).

To measure the level of enhancements, a voltage to current (V-to-C) relation is implemented. The User Defined Function capability of the ANSYS® FLUENT® software package is used to