Applied Thermal Engineering 50 (2013) 293–301

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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

Investigation of fin based oxygen supply modules on the performance of air-breathing polymer electrolyte membrane fuel cells

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HIGHLIGHTS

- Fin structures on cathode plate for an air-breathing PEM fuel cell were tested at room temperature, 30, 40 and 50 °C.
- Schlieren images were taken to visually compare the airflow around the cell.
- The fin structures increased airflow at high temperatures leading to an increase in fuel cell performance.
- EIS data showed individual characteristics of fin structures and orientations at different temperatures.
- To prevent overheating from the electrochemical reaction, oversized thermal mass was added to the cell.

ARTICLE INFO

Article history:
Received 5 March 2012
Accepted 25 June 2012
Available online 2 July 2012

Keywords:
Air-breathing
Polymer electrolyte membrane fuel cell
Fin structure
Temperature effects
Schlieren

ABSTRACT

In an effort to identify an optimized performing top-layer for air-breathing polymer electrolyte membrane (ABPEM) fuel cells, the following strategies were employed to evaluate thin-fin and duct top-layer arrangements: polarization testing, electrochemical impedance spectroscopy testing, Schlieren imaging, and infrared imaging. The duct arrangement was tested under a vertical configuration, while the thin-fin top-layer was tested for both horizontal and vertical orientations. The two top-layers under consideration were introduced and tested at temperatures ranging from room temperature to 50 °C. To maintain the fuel cell temperature at the desired testing conditions, an external heater was used. Additionally, the fuel cell itself was designed to have a large thermal mass, in order to minimize self-heating temperature fluctuations resulting from the electrochemical reactions. From the experiments, it was found that vertical configurations for both top-layers show similar performance. However, the performance of the horizontal configuration is the least efficient due to water droplet formation on the Gas Deficient Layer (GDL) and impeded airflow by the large cathode plate. It is concluded that, due to thin-fin top-layer's simplicity in design and suitability to a variety of configurations and temperatures, the thin-fin design presents a potentially effective solution as a top-layer for ABPEM fuel cells among the prototypes.

1. Introduction

Energy demands continue to rise as the world becomes ever more globalized; meanwhile, the natural resources that have been relied on for so long continue to dwindle. Fossil fuels are predicted to last for only another half a century; hence, a growing interest in alternative energy systems has manifested over recent years. Fuel cell technology is an attractive approach to electricity production. Not only is this technology environmentally friendly, but fuel cells are also a highly efficient alternative [1]. The number of fuel cells is as diverse as their applications. Some common types in use are: polymer electrolyte membrane (PEM) fuel cells, direct methanol fuel cells, and alkaline fuel cells, among many others. The PEM fuel cell, in particular, has been drawing significant attention, due to its low operating temperature, high efficiency, and relatively high energy density. Additionally it can be suited for a broad range of power needs. For example, the PEM fuel cell can be used in everything from portable electronic devices, such as cellular phones, to powering automotive vehicles [2–4].

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http://dx.doi.org/10.1016/j.applthermaleng.2012.06.039

Currently, the majority of portable devices, including laptops and cellular phones, are powered by batteries. As technology advances, consumer demands request increasingly long-lived power sources. To meet these demands, newer batteries need greater efficiencies with high energy densities. Current battery technology will not be able to keep pace with this demand; thus, the PEM fuel cell will be a suitable replacement in the future [2,4,5].

PEM fuel cells can be configured in a number of ways, depending upon the application. It can be setup as a forced convection fuel cell, where oxygen or air is supplied to the device, or as a natural convection fuel cell, in which oxygen is scavenged from the atmosphere. However, careful consideration is needed when selecting between the two since a forced convection PEM fuel cell is roughly twice as large as a natural convection configuration. The reason for this has to do with the need for fans, heaters, oxidant storage, supply systems, and humidification systems that are required to induce forced convection, while a natural convection PEM fuel cell configuration eliminates these needs [6–9]. Thus, natural convection PEM fuel cells have enhanced desirability for small and portable applications. However, because they do not feed air or oxygen to the reaction region, ABPEM fuel cell performance is also limited by oxygen mass transport [7,10,11]. Therefore, minimizing the oxygen starvation effect of naturally convecting PEM fuel cells may further enhance their performance.

Natural convection ABPEM fuel cells have been a topic of much recent investigation. Jeong et al. performed extensive studies on the relationship between the open area of the cathode side and fuel cell performance [12]. Tabe et al. showed improved performance for a channel type cathode structure, in comparison with an open type cathode structure, by increasing the contact pressure and enlarging the channel width [13]. Oosthuizen et al. performed an experiment to show the distribution of pressure and temperature in the channel [14]. Furthermore O'Hayre et al. demonstrated that the performance limitations of air-breathing PEM fuel cells are caused by deficient heat removal and mass transport barriers that arise in convective boundary layers. Their recommendations in minimizing these effects include the addition of a fin or chimney structure to enhance heat transfer [6]. Similarly, Paquin et al. employed a heat sink to maintain the fuel cell temperature at a constant level [7]. In these studies, the adverse effects of flooding, at lower temperatures, were correlated with the formation of water droplets on the GDL, which led to an impeded airflow on the large cathode plate. Their studies suggest that the potential benefits of the heat sink can be utilized to reduce temperature fluctuations in the fuel cell and improve its overall performance.

However, temperature balance is difficult to obtain within ABPEM fuel cells because heat is generated from the electrochemical reactions that occur inside the device, which lead to the self-heating of the fuel cell. This heat generation is dependent upon current density and is, thus, a variable factor, making it difficult to control fuel cell temperature during the experiment [6,15,16]. Therefore, in the experiment under discussion, a large thermal mass was added to the fuel cell in order to minimize self-heating temperature fluctuations so that an approximately constant fuel cell temperature could be attained. The inclusion of this thermal mass allows for better heat removal from the reaction zone because its addition to the device's surface area causes a proportional increase in convective heat transfer. Thus, the fuel cell temperature effects are nearly independent of self-heating. However, environmental factors, such as ambient temperature, are still of concern since they may impact the heat transfer rate from the device. Therefore, in order to eliminate these environmental variables and accurately control the temperature at a desired point, a thermocouple and an external heating system were added to the fuel cell apparatus.

In this study, we expand upon the research of O'Hayre et al. [6] and Paquin et al. [7] to investigate the influence of fin structures on fuel cell performance, at controlled temperatures, using polarization testing, electrochemical impedance spectroscopy testing, Schlieren imaging, as well as various infrared imaging techniques. The aim of this current investigation is the introduction of a new top-layer design. To our knowledge, this is the first study conducted that explores the effects of top-layer structures in vertical configurations on the heat transfer of a temperature controlled PEM fuel cell, which will provide guidelines for the further optimization of next-generation fuel cell systems.

2. Experimental setup and procedures

2.1. The ABPEM fuel cell

An exploded view of the ABPEM fuel cell used in the experiment, with labeled components, can be seen in Fig. 1. The fuel cell's base plate (a) is made from 6061-T6 aluminum with an alodine 1200 chromic outer coating. Adhered to it are cartridge heater and thermocouple ports, and its design is integrated with Swagelok fittings for hydrogen gas use. Mounted to the base plate is the anode electrode (b), which is composed of printer's copper, a nickel base plating, and is coated in 0.0004 ± 0.0001 inches of gold. The cathode possesses like material properties of the anode, both coated in a thin gold layer with a platinum loading of 0.5 mg/cm. Following the anode is an AFX-5Q pyrosealed Poco graphite block (c) with machined serpentine flow channels for hydrogen gas. Two, 3/16 inch diameter Nafion tubes, inserted through the holes of the base plate and anode electrode, are used to feed gas to the graphite block flow channel. The membrane electrode assembly (MEA) (e) – a 5-layer, HP-A Nafion 212 self-humidifying model from FuelCell-Store – which houses the reactions inside the fuel cell, comes next and is sandwiched between two gaskets (d), immediately above the graphite block. Different types of gaskets were used in order to prevent potential hydrogen leakage that could result from the low bolt torque used to secure the fuel cell components. The bottom gasket (anode side of the MEA) is made from 0.010 of Silicon rubber, while a 0.006 inch thick, Teflon gasket is employed above the MEA. Finally, the slotted plate assembly (f), which consists of a gold plated cathode electrode and an air-breathing opening, sits on top of the device, exposing roughly 50% of the MEA's surface area to the ambient air through the slots contained on the assembly. The above fuel cell components were secured with eight 1/4-28 bolts, each tightened with 10 in-lbs of torque.

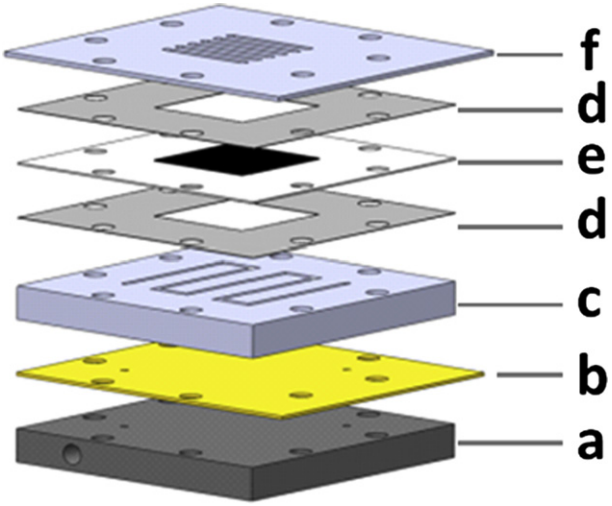

Fig. 1. Exploded view of the air-breathing PEM fuel cell.