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A segmented cell approach for studying the effects of serpentine flow field parameters on PEMFC current distribution

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ABSTRACT

A serpentine flow field is a commonly used design in proton exchange membrane fuel cells (PEMFCs). Consequently, optimization of the flow field parameters is critically needed. A segmented cell system was used to study the impact of the flow field's parameters on the current distribution in a PEMFC, and the data obtained were analyzed in terms of voltage overpotentials. 6-Channel and 10-channel serpentine flow field designs were investigated. At low current the segments performance was found to slightly decrease for a 10-channel serpentine flow field. However, increasing the number of channels increased the fuel cell performance when operating at high current and the cell performance became more uniform downstream. The observed improvement in fuel cell performance was attributed to a decrease in mass transfer voltage losses (permeability and diffusion), due to an increased pressure drop. Spatially distributed electrochemical impedance spectroscopy (EIS) data showed differences in the local segment impedance response and confirmed the performance distribution and the impact of the flow field design.

1. Introduction

PEMFCs are being developed as potentially clean and efficient energy sources. There are, however, several issues that still require improvement. It is well known that the current distribution along the flow field is not uniform, especially while operating at high current. This non-uniformity can result in the loss of performance, a lower reactant utilization, and starvation processes in the cell [1]. Among the processes that can cause a non-uniform downstream current distribution are: (1) O_2 depletion along the flow field; (2) accumulation of water along the flow field; and (3) insufficient reactant supply. Inhomogeneities in the current distribution appear to be mitigated by improving the mass transfer characteristics of the membrane electrode assembly (MEA) and by efficient design of the flow field.

The bipolar flow field plate is an important component of the PEMFC and performs the functions of a current collector and mechanical support for the MEA. It provides access channels for the fuel and oxidant to the anode and cathode, respectively; and removal of water formed during cell operation. The flow field plate serves as a barrier against mixing of the oxidant, fuel, and coolant; and also participates in heat management [2,3].

Three major types of flow field are currently in use: parallel, serpentine, and interdigitated. An early flow design consisted of several parallel channels, with relatively large cross-sectional areas, formed in an electrically conductive plate [4]. This type of flow field resulted in water accumulation in the channels and poor gas distribution over the active area. Spurrier [5], Granata and Woodle [6], and Watkins and Dircks [7] attempted to solve these problems by using a serpentine flow field. The serpentine flow field increases the pressure drop between the channel inlet and outlet, reducing the accumulation of the water produced and resulting in a more uniform reagent distribution. The serpentine flow field remains one of the most commonly used design for research applications due to its simplicity and efficiency. Flow field parameters, such as the widths of the ribs and channels, as well as channel depth and shape, need to be optimized to achieve high fuel cell performance. Few experiments have been reported by researchers on flow field design parameter variations because these are costly and time consuming investigations [8–11]. Studies of the impact of operating parameters and flow field design were conducted by Yan et al. [8]. Neutron and optical imaging have been used to investigate the effect of flow field design on the water content and dynamics of the PEMFC [9]. The effects of a single pass serpentine flow field dimensions (channel/rib widths) were studied in [11] for different operating parameters. These reports mainly focused

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on different types of flow field and comparisons between them. Many researchers have used mathematical models for studying the impact of the flow fields on PEMFC performance [12–19]. Several models describing mass transport effects have been developed to predict fuel cell performance and provide information on specific flow field parameters.

Application of a segmented cell system can provide valuable information on the effect of current distribution on the PEMFC, gas/water management, and fuel cell diagnostics [1,20–42]. Measurements over the entire active area of the PEMFC only lead to average values for the cell parameters such as current density or cell impedance. These measurements are only meaningful if local operating conditions are uniform (homogeneous) throughout the cell. However, for a commercially sized fuel cell local operating conditions are not homogeneous, and spatially resolved in situ diagnostics are needed for explaining and detecting inhomogeneities in cell performance. In other words, the measurement of current, voltage, and impedance responses over the entire fuel cell provide only zero dimensional (0D) information about processes inside of the cell. The use of a segmented cell enables 1D measurements which are often neglected [43]. Thus, the application of segmented cell systems for studying physicochemical processes within the fuel cell provides complementary and more insightful data for electrodes, flow field design, and operating conditions optimization.

Zhang et al. [20] used a segmented cell system to compare serpentine and interdigitated designs under different operating conditions. They showed that the interdigitated design provided a more uniform current distribution at high gas humidification than the serpentine flow field. However, the serpentine flow field presented a better and more uniform fuel cell performance at dry or low gas humidification. Four different flow channel geometries (serpentine, pin-type, parallel, and interdigitated) were studied using a segmented cell system developed by the S++ company [21]. The results demonstrated that the four-step serpentine and pin-type geometries distributed reactants most effectively, providing relatively uniform current density distributions compared to parallel or interdigitated geometries. The four-step serpentine and pin-type geometries also yielded the maximum power, up to 25% or higher, when using oxygen. With air as the chosen oxidant, interdigitated flow channels perform almost as well as serpentine or pin-type channels. I. Alaefour et al. investigated local current distributions for a PEMFC using a serpentine flow field and three different flow arrangements for the anode and cathode streams, including co-flow, cross-flow, and counter-flow [22]. The counter-flow arrangement was shown to yield the most uniform current density distribution, whereas the co-flow arrangement produced considerable variation in the current density from the reactant gas stream inlet to the exit. The flow channel orientation can also impact the overall cell performance. To our knowledge, there are few experimental reports in the literature that have used the segmented cell system and spatially resolved diagnostic methods, such as EIS, to investigate the effects of serpentine flow field parameters on fuel cell performance distribution. These methods are critically needed to provide more reliable and meaningful data on local performance.

In our previous papers, we demonstrated the capability of the Hawaii Natural Energy Institute's (HNEI) segmented cell system in investigating PEMFC performance distribution and recording spatially resolved cyclic voltammetry (CV), linear sweep voltammetry (LSV), and EIS [44,45]. The purpose of this work is to study the impact of serpentine flow field parameters on the current distribution, using the segmented cell system, spatially distributed polarization measurements, and EIS to provide guidance on flow field design optimization.

2. Experimental

The segmented cell system design was based on a Los Alamos National Laboratory design [1,46] using an improved data acquisition system that allowed simultaneous measurement of the spatial EIS, LSV and CV. The segmented fuel cell was operated as a single cell using a standard fuel cell test station. The maximum current and power for the test station used in these experiments were 240 A and 1.2 kW, respectively. The segmented cell system contained the cell hardware and data acquisition system, which included a custom-built current transducer system, and a National Instrument PXI data acquisition system using a LabView control program developed in-house. A closed loop Hall sensor device from Honeywell (Model CSNN191) was employed for current sensing. The data acquisition system allowed the investigation of up to 10 current and 10 voltage channels in a high-current mode and 16 current and 16 voltage channels in a low-current mode. The high-current mode is typically used for fuel cell mode experiments, e.g., in H_2/air configurations, providing the measurement of segment current densities up to 2 A cm^{-2}. The maximum current density in the low-current mode can reach ±50 mA cm^{-2}, which is optimal for CV and LSV measurements.

Standardized single fuel cell testing protocols were applied while recording spatially resolved data using the segmented cell hardware and the data acquisition system. The segments' current and voltage, and cell voltage responses were recorded at fixed overall cell load. For the present system design, the segments' voltage and cell voltage responses were the same (relatively small fuel cell active area). Such operation minimized any impact from the segmented cell system and facilitated properties distributions measurements without interference on the segments' performance. The segmented cell system is also operated under conditions that mimic those used in real systems because only the overall current is controlled whereas both segments current and voltage are floating.

The segmented cell hardware was based on an existing HNEI 100 cm^2 cell design. The hardware contains a standard, non-segmented flow field and a segmented flow field consisting of 10 consecutive segments in the path of the 6- or 10-channel serpentine flow field. Fig. 1 presents pictures of these two flow fields with different channel designs. The geometrical parameters of the flow fields are shown in Table 1. Each segment has an area of 7.6 cm^2 and has its own distinct current collector and, if desired, distinct gas diffusion layer (GDL) and catalyst area. The cell hardware and electrode segmentation can be applied to either the anode or the cathode. The same channel designs were used for both the segmented and standard flow fields using a co-flow arrangement for the gas flow.

The hardware was operated with a standard 100 cm^2 Ion Power MEA. The anode and cathode electrodes were made of a 50% Pt/C catalyst coated onto a DuPont™ Nafion® NRE212 membrane at a loading of 0.4 mg_{Pt} cm^{-2}. The gasket material was made of Teflon® with anode and cathode thicknesses of 203 μm and 178 μm, respectively. Sigracet® 25 BC was used for the anode and cathode GDLs. In this work, a segmented GDL and a gasket were used at the cathode, whereas a single GDL was applied at the anode. The compression force applied to the cell was 50 in. pounds (or 5.649 N m) for 6- and 10-channel flow fields.

Experiments were performed with H_2/air, H_2/He + O_2 (21 vol.% O_2), and H_2/O_2 configurations, at cell operating temperatures of 60 and 80 °C. The anode/cathode standard operating conditions were as follows: 2/2 stoichiometry flow rates, 48.3/48.3 kPa_g back-pressure, and 100/50% relative humidity (RH). For He + O_2 and O_2 operation, the same flow rates were used as for the air configuration to maintain the driving force for sweeping water out of the flow channels at any given overall cell current density. Consequently, the stoichiometry for He + O_2 remained at 2, while the