Energy 113 (2016) 1071–1089

Contents lists available at ScienceDirect

Energy

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

In situ investigation of proton exchange membrane fuel cell performance with novel segmented cell design and a two-phase flow model

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ARTICLE INFO

Article history:
Received 28 March 2016
Received in revised form
19 May 2016
Accepted 20 June 2016
Available online 4 August 2016

Keywords:
Proton exchange membrane fuel cell
Segmented cell
Two-phase flow model
Relative humidity distribution
Temperature gradient
Local current

ABSTRACT

A novel segmented fuel cell device based on the multi-layered printed circuit board (PCB) flow field plates is designed to study the localized fuel cell performance with various operation conditions. With embedded sensors, distributions of current density, relative humidity (RH) and temperature for both anode and cathode are measured simultaneously along the direction of straight parallel flow channels. Meanwhile, a stationary two-phase flow fuel cell model is developed to study the internal reaction parameter distributions and the results are compared with the in situ experimental measurements. In the co-flow operation mode of hydrogen and air, current density and reactants' RH distributions are sensitive to the stoichiometry of air but the effect from hydrogen is minor. Water transfer behavior, local reactants' RH status, temperature gradients and their impacts on current distributions are analyzed based on the in situ measurements and the coupled model analysis. The segmented cell device discussed in this paper, as well as the experimental and modeling results can be employed to optimize stack design and operating parameters with "visible" internal distributions of water, RH and temperature inside membrane electrode assembly (MEA). Further investigation on fuel cell performance and lifetime with different reactant flow directions is also suggested.

1. Introduction

Proton exchange membrane fuel cell (PEMFC) is one of the most promising electrical power generation devices for transportation and stationary applications due to its high energy efficiency and power density [1]. There are many research efforts devoted to PEMFC design optimizations during last decades with significant progress achieved [2–14]. However, improving performance and lifetime of PEMFC stack are still the most important technical challenges to promote its wide commercialization. Among various research activities and efforts, the local information detection and analysis of reacting conditions and degradation processes is the key to optimize fuel cell stack design and operation parameters [15–19]. To experimentally study the mechanism of fuel cell performance degradation, it is necessary to characterize the major parameters and their distributions inside stack such as current density, relative humidity (RH) and temperature.

In recent years, different segmented fuel cell approaches with various local current measuring techniques are proposed to study operation conditions and stack design effects on performance and durability [19–32]. T. V. Reshetenko et al. developed a segmented fuel cell device based on Hall sensors to measure the current distribution of the 5 × 2 segmentations [20–24]. D. Liang et al. proposed a single fuel cell with a segmented cathode current collecting end plate design to study the current distribution of 5 sections for the active area of 270 cm^2 [25–27]. G. Maranzana et al. designed a segmented single cell with parallel straight channels to investigate internal currents during startups and shutdowns [28–31]. D. G. Strickland fabricated a 3 × 3 current mapping fuel cell device with segmented flow field plate and current collector based on printed circuit board (PCB) designs [32].

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http://dx.doi.org/10.1016/j.energy.2016.06.097
0360-5442/

The modeling is also a significant tool to investigate the internal PEMFC performance distributions and a number of PEMFC numerical studies have appeared in the literature [2–11,33–43]. L. Xing et al. developed a two-dimensional (2D) PEMFC model to analyze the two-phase flow effects on the fuel cell performance [4–6]. S. Cordiner et al. [42], Q. Ye et al. [43] and H. Meng et al. [36] developed a three-dimensional (3D) two-phase flow model, respectively, and studied the water saturation distributions inside the porous electrode. J. G. Carton et al. proposed serial numerical and experimental work on PEMFC flow channel designs and optimizations with investigation of different flow patterns and liquid water behaviors in the flow channels [39–41].

The mentioned works mainly focus on the current distribution measurements and local fuel cell performance analysis, however, few of them characterize localized operation parameter effects, such as RH and temperature as well as their distributions. In the presented work, a novel segmented fuel cell device is designed and assembled to characterize internal distributions of current density, RH and temperature simultaneously with controllable temperature gradient of the fuel cell. Based on the experimental results, a stationary two-phase flow fuel cell model is developed to analyze the fundamental mechanisms of internal distributions of reaction parameters. With the in situ measurements and the coupled model analysis, water transfer behavior, local reactants' RH status, temperature gradients and their impacts on current distributions are analyzed in details to understand the fuel cell performance variations.

2. Experimental

2.1. Segmented fuel cell structure

The presented segmented fuel cell is based on the multi-layered PCB reactants distributing flow field plates with integrated RH and temperature sensors. On the two side of the membrane electrode assembly (MEA), the anode compartments are symmetrical to the cathode ones. As shown in Fig. 1, each side of segmented cells includes a PCB flow field plate, graphite coolant water flow plate and end plate. Both anode and cathode reactants flow field plates are composed of the two-layered PCB plates, as a consequence the difference of RH and temperature between anode and cathode reactants could be measured. The first layer of the PCB plates which attaches MEA constructs ten 20 mm × 20 mm segmentations with gold coated copper ribs to collect current individually. The second layer integrates eleven RH and temperature sensors, of which the dimension is 3 mm × 3 mm × 1.1 mm. Each sensor is located between the neighbored individual segmentations to record the real-time values of RH and temperature. To enhance the measuring precision, the paralleled straight flow channels for different segments are electrically isolated and the interference of the embedded RH sensors on reactants flow processes is minimized.

Fig. 2 shows photos of segmented fuel cell under operation in which hydrogen, air and coolant water flow into the cell with the same direction (co-flow mode). Data acquisition cards are designed to transfer the signals of current, RH and temperature to the computer respectively from both anode and cathode PCB plates. In this study, the MEA, illustrated in Fig. 2(b), is fabricated by Dongfang Electric Corporation (DEC) with a long strip structure. With catalyst coated membrane (CCM) method, Pt/C catalyst with Pt loading of 0.4 mg/cm^2 is sprayed onto each side of the membrane (Nafion 115 from Dupont) directly with optimized adherence. For anode and cathode reactants flow field plates, paralleled straight-channels are designed in PCB plates with 11 embedded RH and temperature sensors shown in Fig. 2(c). For the coolant water flow field plates (Fig. 2(d)), serpentine channels are constructed in graphite plates so that the temperature gradient of the fuel cell can be controlled by adjusting coolant water flow rate. The inlets and outlets for hydrogen, air and coolant water are structured in the two aluminum alloy end plates respectively.

In the cross section structure of the segmented cell (Fig. 3), ten 2.5 mΩ resistors are applied to detect current of each segment for both anode and cathode. The current passing through each resistor generates a voltage signal which is amplified by the data acquisition card and then transferred to the computer through the data cable. In the first layer of the PCB plate, each segment's current is collected by the gold coated copper ribs and then conducted via connectors to the copper current collector at the other side of the PCB plate. Each segment of the PCB plate is electrically isolated from the others. The deviations of RH and temperature values are 3% and 0.4 °C, respectively, due to the measurement precision of the embedded sensor in the segmented fuel cell. The current deviation for each segment is 5 mA, which is derived from the current sensor precision and the sampling resolution of the current signal.

2.2. Test system and experimental details

The experiments are carried out with a fuel cell test station developed by DEC of which the flow chart is shown in Fig. 4. The

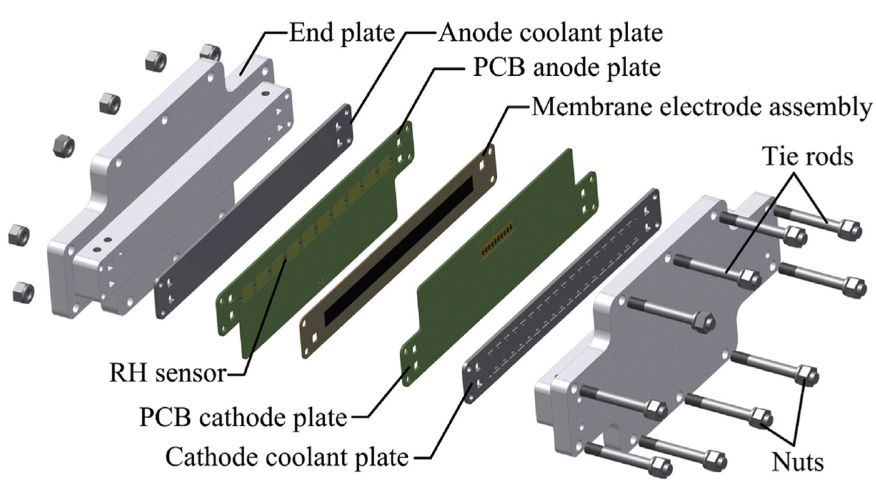

Fig. 1. The schematic of proposed segmented fuel cell structure.