Journal of Power Sources 196 (2011) 5595–5598

Contents lists available at ScienceDirect

Journal of Power Sources

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

Short communication

Behavior of a unit proton exchange membrane fuel cell in a stack under fuel starvation

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ARTICLE INFO

Article history:
Received 12 January 2011
Accepted 20 February 2011
Available online 26 February 2011

Keywords:
Proton exchange membrane fuel cell (PEMFC)
Fuel starvation
Current distribution
Localized interfacial potential
Manifold
Stack

ABSTRACT

Durability is an important issue in proton exchange membrane fuel cells (PEMFCs) currently. Fuel starvation could be one of the reasons for PEMFC degradation. In this research, the fuel starvation conditions of a unit cell in a stack are simulated experimentally. Cell voltage, current distribution and localized interfacial potentials are detected in situ to explore their behaviors under different hydrogen stoichiometries. Results show that the localized fuel starvation occurs in different sections at anode under different hydrogen stoichiometries when the given hydrogen is inadequate. This could be attributed to the “vacuum effect” that withdraws fuel from the manifold into anode. Behaviors of current distribution show that the current will redistribute and the position of the lowest current shifts close to the anode inlet with decreasing hydrogen stoichiometry, which indicates that the position of the localized fuel starvation would move towards the inlet of the cell. It is useful to understand the real position of the degradation of MEA.

1. Introduction

Durability appears to be one of the barriers of proton exchange membrane fuel cells (PEMFCs) commercialization [1]. Fuel starvation, which could be a potential cause for the early failure of PEMFCs, usually occurs under harsh operating conditions such as sub-zero start-up and rapid load change with the high fuel utilization [2]. Uneven flow distribution caused by poorly designed flow field, stack or assembly structure would also induce fuel starvation in a single cell or some cells in a stack [3]. When fuel starvation occurs, irreversible degradation of the membrane electrode assembly (MEA) would happen due to the carbon corrosion [4]. Several authors have investigated the degradation mechanism under fuel starvation in PEMFCs [4–9]. Behaviors of cell voltage and potentials of anode and cathode under completely fuel starvation were detected by Taniguchi et al. [5]. Lauritzen et al. [10] and Baumgartner et al. [11] found that the localized fuel starvation occurs at anode outlet regions of the cell under high fuel utilization conditions by detecting the localized anode and cathode potentials. However, damages caused by fuel starvation were observed not only in the anode [5,6], but also in the cathode [10,11].

In our previous paper [6], the reversal processes of a single cell under fuel starvation conditions were well discussed, in which only a separate cell was focused on. In this work, the behaviors of a unit cell in a stack under different degrees of fuel starvation were explored, and the effects of the manifold of a stack on the starved cell were discussed in detail. The experimental results of this paper could supply some useful information for durability researches on fuel cell vehicles (FCVs).

2. Experimental

A segmented cell including a specially designed MEA and cathode end plate was constructed to measure the current distribution and local electrode potentials. The MEA with a total active area of 230.36 cm^2 consisted of Nafion® 212 membranes as the electrolyte, catalyst layers with the total Pt loading of 0.8 $mg\,cm^{-2}$ and Toray paper as diffusion layers. A G100 fuel cell test station from Greenlight Innovation Corp. in Canada was used to control the operating conditions of the segmented cell and the load. A homemade stack test station was used to control the operating conditions of the stack. To simulate a manifold, the anode exhaust of the segmented cell was combined with that of the stack as shown in Fig. 1. A detailed description of the segmented cell structure and measuring methods could be found in our previous paper [6].

Both the segmented cell and the stack utilized normal hydrogen (99.5% hydrogen and 0.5% nitrogen) and air as fuel and oxidant respectively. During the experiments, the loading current was kept

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doi:10.1016/j.jpowsour.2011.02.064

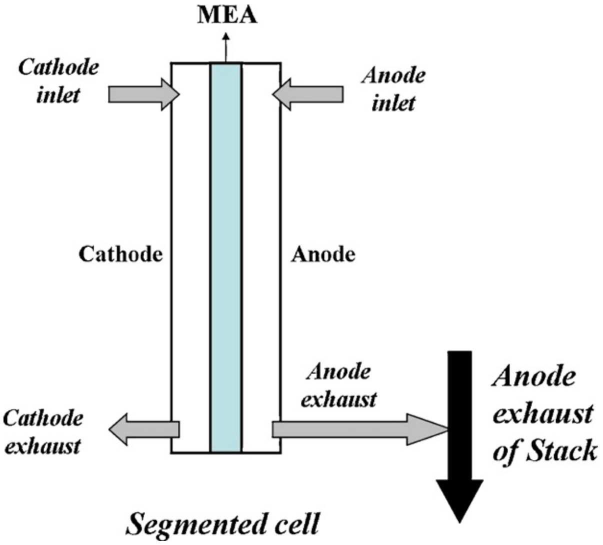

Fig. 1. Schematic of gas flow of the segmented cell.

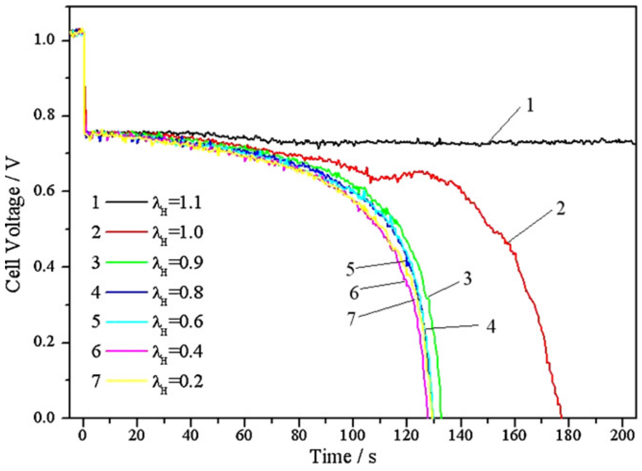

Fig. 2. Changes of cell voltages with time under different hydrogen stoichiometries.

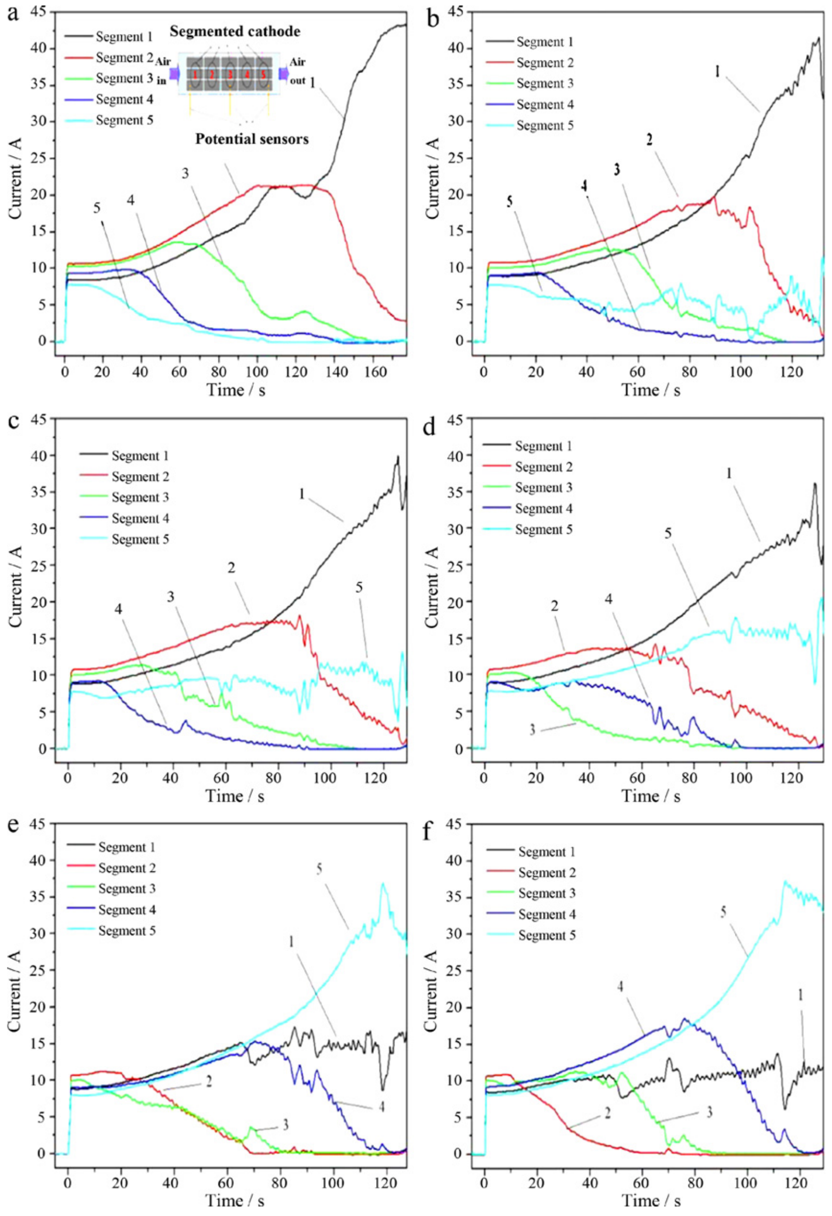

Fig. 3. Changes of current distributions with time under different hydrogen stoichiometries (a, $\lambda_H = 1.0$; b, $\lambda_H = 0.9$; c, $\lambda_H = 0.8$; d, $\lambda_H = 0.6$; e, $\lambda_H = 0.4$; f, $\lambda_H = 0.2$).

at 46 A. The temperature of the segmented cell and the dew point temperatures of the humidified gases were all kept at 60 °C. Reaction gases were kept at ambient pressure and operated in co-flow mode. The air flowrate was fixed at 2.3 L min^{-1} ($\lambda = 3.0$), and the fuel flowrate was varied to control the segmented cell at different hydrogen stoichiometries to simulate different fuel starvation conditions. In each experiment, the cell was unloaded to avoid the effect of cell reversal on the cell performance when the voltage dropped to zero. After this series of experiments, another experiment was carried out, and the cell was kept loaded until the voltage seriously reversed under hydrogen stoichiometry of 0.4.

3. Results and discussion

3.1. Behavior of cell voltage

Fig. 2 depicts the changes of cell voltage with time under different hydrogen stoichiometries (1.1–0.2). When the hydrogen stoichiometry is 1.1, the cell keeps running steady and the cell voltage is ca. 0.75 V. Then the cell voltages all decrease to zero after loading when the fed hydrogen stoichiometries are lower than or equal to 1.When the fed hydrogen stoichiometry is 1.0, the cell only runs for 178 s. An interesting phenomenon can be seen that the voltage curves are very similar when the hydrogen stoichiometries are lower than 1, and the duration of the cell suffering from fuel starvation are all ca. 130 s. In such situation, the reversal time is prolonged, unlike that (several seconds) observed in the case of a separate cell under fuel starvation [6]. The reason for this could be the “vacuum effect” mentioned by Liu et al. [3] and Kim et al. [12], which could withdraw gas from the manifold into the anode when the fed hydrogen is not sufficient, until obtaining the balance pressure. Then under the balance pressure, the total gas flowrate (including the gas fed from inlet and the gas drawn back from the manifold at outlet) would be equal to the equivalent flowrate of hydrogen consumed. Thus, the actual hydrogen stoichiometries are all close to 1 even though the given stoichiometries are lower than 1, so the cell voltages are almost independent of the fed hydrogen stoichiometries in such situation. These results demonstrate that the cell would get benefits from the “vacuum effect” under fuel starvation conditions, i.e., the duration of the cell suffering from fuel starvation would be prolonged.

3.2. Behaviors of current distributions

The process of fuel starvation can also be illustrated through behaviors of current distributions in the cell. The current distribution under different hydrogen stoichiometries as shown in Fig. 3 exhibits significant variation across the cell plane. When the hydrogen stoichiometry is 1.0, the local current decreases from gas inlet to outlet. At segment 1 the hydrogen concentration is the highest, the local current density is the greatest. As hydrogen is consumed along the anode channels, the hydrogen concentration decreases down the flow direction, resulting in a drop in current density in segments downstream. Then with decreasing hydrogen stoichiometry (0.9, 0.8, 0.6, 0.4, and 0.2), the current of segment 1 reduces while that of segment 5 increases gradually. When the hydrogen stoichiometry decreases to 0.4 and 0.2, the current of segment 5 is largely higher than that of segment 1 as shown in Fig. 3e–f, which is different from the current distribution (the local current decreases from gas inlet to outlet) observed in the case of a separate cell under fuel starvation [11]. The reason could be that the local current distribution along the channels is mainly dominated by the gradient of hydrogen concentration. The lower the hydrogen stoichiometry is, the lower the hydrogen concentration of segment 1 is, while that of segment 5 benefits from the “vacuum effect” which draw back higher proportion of fuel from the manifold, leading to higher current. At last, the current of segment 5 significantly exceeds that of segment 1.

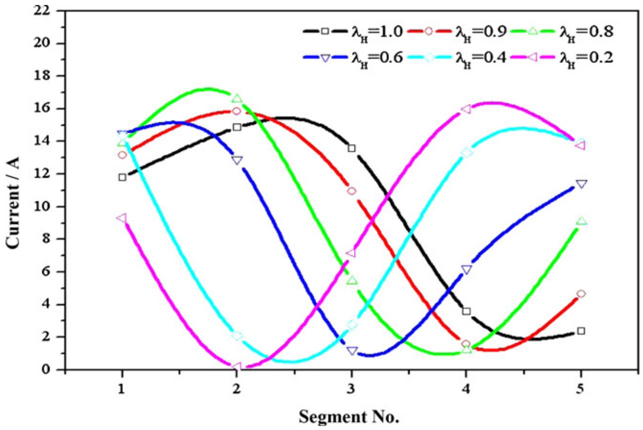

Fig. 4. Current distributions at the 60th second after loaded under different hydrogen stoichiometries.

Current distributions along the channels at the 60th second after loaded are shown in Fig. 4. It could be clearly seen that the position of the lowest current shifts close to the anode inlet with the decrease of hydrogen stoichiometry, which indicates that the location where localized fuel starvation occurs firstly in the cell varies with the hydrogen stoichiometry although the cell runs for a similar time. This phenomenon could be illuminated by a schematic chart of hydrogen distribution shown in Fig. 5. As indicated in Fig. 5, the gray scale represents the hydrogen concentration. When the hydro-

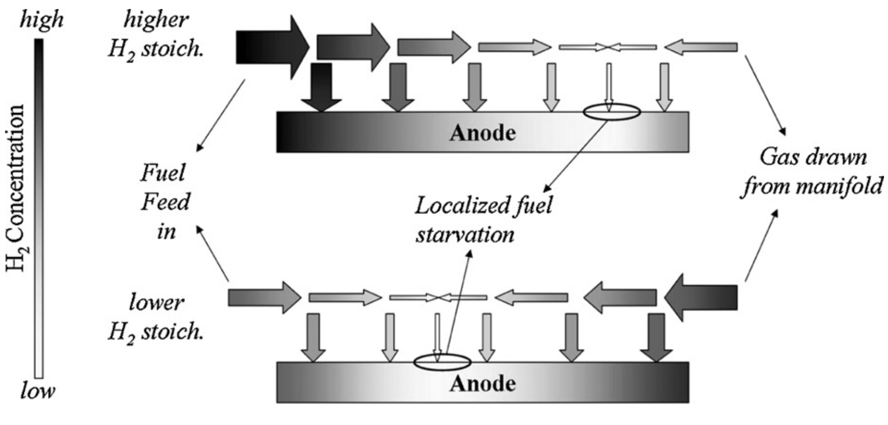

Fig. 5. Schematic of the hydrogen distribution in anode under different stoichiometries.

gen stoichiometry is lower than 1, the fed hydrogen is inadequate and the “vacuum effect” occurs. Under this condition, fuel is fed into the anode from inlet meanwhile gas is drawn back from the manifold at outlet. Thus impurities (nitrogen in this experiment) would accumulate gradually at the section where the two fluxes meet and localized fuel starvation occurs firstly. So under a comparatively lower hydrogen stoichiometry, less hydrogen is fed into the anode from inlet while more hydrogen is drawn back from manifold at outlet, the section where two fluxes meet would be closer to the anode inlet. In reverse, the section would be closer to the anode outlet under a comparatively higher hydrogen stoichiometry. The results above illustrate that with decreasing hydrogen stoichiometry (all lower than 1), the proportion of the fuel drawn back from the manifold increases and the region where localized fuel starvation occurs firstly would be closer to the anode inlet due to the “vacuum effect”.

4. Conclusions

In this research, the behaviors of a unit cell in a PEMFC stack under fuel starvation conditions have been explored. Experimental results show that the localized fuel starvation occurs in different regions of the anode under different hydrogen stoichiometries. The actual hydrogen stoichiometry is almost 1 even though the fed hydrogen is not sufficient due to the “vacuum effect” that gas would be drawn back into the anode from the manifold. The positions where localized fuel starvation occurs firstly in the cell of a stack are different with the different hydrogen stoichiometries. When the hydrogen stoichiometry is lower, the position where localized fuel starvation occurs firstly would be closer to the anode inlet. This could be useful to understand the real position of the degradation of MEA. The future efforts would focus on the research of the degradation of the electrode when localized fuel starvation occurs in the cell in a stack.

Acknowledgement

This work was financially supported by the National Natural Science Foundations of China (nos. 20876155, 20936008).

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