Paper-based water management system for microfabricated packageless fuel cell

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Abstract. In this paper, we report the first successful implementation of a complete paper-based water management system (WMS) that collects the excess water at the cathode of a microfabricated packageless fuel cell (PLFC) and redistribute it to its anode and to an evaporation surface that simulate a hydride-based hydrogen generator. Five configurations of WMS were tested on a 1 cm² air-breathing PLFC and show that with the best configuration, the power output of the cell can be improved by 90% for at least 24h. We experimentally demonstrate that not only cathode flooding issues must be address to obtain an efficient WMS but also that anode drying plays a major role in poor performance of small air-breathing fuel cells. Finally, with the optimal configuration of WMS, the PLFC in air-breathing mode shows similar performances as with humidity controlled air forced-flow.

1. Introduction

Low battery life of portable electronics devices is currently a major concern for developers and consumers because of the slow growth in performances of lithium batteries [1]. Because of their theoretical high energy density and their instantaneous recharge, small air-breathing polymer electrolyte membrane fuel cell (PEMFCs) with hydride hydrogen generator are often seen as potential substitutes to power portable electronic devices. For the moment, bulky packaging issues combined with the absence of efficient water management systems decrease energy density of these systems to a level well below the performances of lithium batteries.

To reduce the volume of the packaging of small air-breathing PEMFC, a new approach to integrate all the necessary components of a fuel cell system on a single polyimide layer has been successfully developed in a previous work [2]. This packageless fuel cell (PLFC), reduced the thickness of the cell to 80µm while providing a 97% increase in volumetric power density.

Despite these encouraging results, small air-breathing fuel cell systems still suffer from low efficiency due to poor water management. Because of their size and low power output, they are not equipped with auxiliary components to stabilize their temperature and humidity level which lead to simultaneous flooding of the cathode and drying of the anode. Flooding of the cathode is well known and documented and happens when the cell produce more water than it can evaporates. Many systems using capillary channels integrated in the cathode current collector have been tested successfully on small air-breathing fuel cells and generated surface power density improvement from 10% to 30% [3–5]. Nevertheless, these systems are bulky and can hardly be optimized since they must be integrated in the current collector. On the anode side, strong electro-osmotic drag flow, combined with poor water
diffusion through Nafion dries up the anode and increase its ionic resistance. This phenomenon is often neglected, but it has been showed that humidifying adequately the anode during operation can improve power density of the cell up to 30% [6,7].

Also, in a hydride based hydrogen generator, about half of the volume is occupied by a water reservoir required to complete the hydrolysis reaction. Therefore, the integration of a simple and passive water management system (WMS) which uses excess water produced at the cathode to humidify the anode and feed the hydrogen generator could increase maximal power output and energy density of the system (Figure 1). The integration of such system is significantly eased by the PLFC configuration where the current collectors are underneath the catalyst layers, which free the entire surface to collect and redistribute water.

Figure 1. a) Integration of PLFC with hydride based H₂ generator showing poor water management and large water reservoir. b) Intended integration of paper-based water management system that collects liquid water at the cathode and redistribute it to anode and H₂ generator.

In this paper, we introduce for the first time a simple and efficient paper-based WMS that stabilize and increase significantly power output of the air-breathing PLFC without the injection of external energy. Five configurations of WMS are tested showing that power output improvement due to optimal humidification of the anode is as important as the one due to excess water removal at the cathode. Finally, we show that near to ideal working condition can be reached when the key dimensions of the WMS are adequately selected.

2. General design and test setup

Five water management system designs were prepared by patterning strips of 200µm thick hydrophilic paper (Berkshire® cleanroom wipes) with a commercial laser (LPKF protolaser U3). WMSs were divided in four regions; (1) Cathode draining, (2) Anode humidification, (3) Cathode to anode path and (4) Evaporation path (Figure 2a). At first, WMSs were used without evaporation path (4) to evaluate only the performance of the systems to transfer excess water of the cathode to the anode. The best configuration was then selected and an evaporation path added to test the whole system. WMSs were differentiated by the surface coverage of the hydrophilic paper on the catalyst layers, β, and the mean distance that a water droplet has to travel before reaching a hydrophilic strip, Dm (Figure 2b).

The WMSs were directly laid on the catalyst layers of a 1 cm² PLFC and hold in place with kapton tape. Fuels cell with water management system were finally inserted between two rigid metallic plates to prevent gas leakage between cathode and anode (Figure 2c).
Figure 2. a) WMS 5 prior to installation on a PLFC. Cathode (1) : 0.5mm wide hydrophilic paper strips separated by 1mm, Anode (2) : fully covered. b) Hydrophilic coverage and mean water travel distance for the tested WMSs. c) Test setup to measure power improvement generate by the integration of a water management system on a PLFC.

3. Surface power density improvement of the PLFC with WMS introduction

3.1. Cathode and anode configuration optimisation

The WMSs were tested on a PLFC in air-breathing condition at ambient temperature until cathode flooding. Two PLFCs (PLFC 1 and 2) were used to conduct the tests to prevent unreliable results caused by their deterioration. VI curves were performed every 30 minutes to evaluate the performances of the PLFC and figure 3 illustrates the best result for each WMS.

Figure 3. Power output increase caused by the water management system if a) cathode (PLFC 1) and b) anode (PLFC 2) configuration is optimized.

Figure 3a reveals that in the anode case, a higher coverage in hydrophilic material increase power output of the cell. The best result was obtained with a fully covered anode and generated about 60% more power than a cell without WMS. Consequently, the anode drying does have a significant impact on the power output of the cell and the catalyst layer alone does not provide enough water diffusion to ensure its proper humidification.

As presented at figure 3b, on the cathode side, minimal hydrophilic coverage with adequate reparation of the hydrophilic strips lead to an even greater increase of the power output. WMS 4 which has two 1mm wide strips separated by 2.6mm combined with a totally covered anode showed 90% surface power density improvement compared to a cell without WMS. Since hydrophilic strips on the cathode side tend to be saturated in water, oxygen can’t reach the reaction sites located underneath. Therefore, a higher hydrophilic coverage doesn’t result in better performances. At identical $\beta$, a better repartition of the hydrophilic strips (smaller $D_m$) will result in higher power output (Figure 3b).
3.2. Water management system vs forced flow conditions
A 1mm wide evaporation path (Figure 2c) was added to WMS 4 to test the long term performances of the system and compared the results with the same PLFC working in forced flow conditions. At figure 4a, it is shown that the addition of the evaporation path prevented the apparition of the cathode flooding that initially degraded dramatically the performances of the cell after 10h. Moreover, the evaporation path did not affect the maximal power output of the cell for 24h.

Finally, the PLFC without WMS was inserted in a test bench (Fuel Cell Technologies inc.) with controlled temperature, humidity and flows to extract its maximal performance under ideal conditions at 25°C. Figure 4c shows the comparison between the PLFC working in ideal conditions to the same cell operating in air-breathing mode with and without WMS. We can see that the cell with WMS 4 almost reach the performance of the cell in the ideal case. It confirms that the poor performances of small air-breathing fuel cell system are mainly due to poor water management and not oxygen diffusion at the cathode and that the simple paper-based WMS offers close-to-optimal performances.

Figure 4. a) Power output stabilization by adding an evaporation path to WMS 4. b) Power comparison between a PLFC with and without an optimized WMS and a PLFC with optimal controlled forced flow at 25°C.

4. Conclusion
In this work, we showed that the PLFC configuration allow the integration of a simple and efficient WMS that improved its power output by 90% and stabilized it for at least 24h. The laser etched paper-based WMS allowed the air-breathing cell to reach comparable performances to its forced flow counterpart which proved that water management is the main issue to address to improve small air-breathing fuel cell. It also confirmed that even if this phenomenon is often disregarded in water management studies, anode drying is critical and solution must be integrated in future systems.

This work is an important step to solve water management issues in air-breathing fuel cell which delay the maturity for market readiness of this technology.

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