Journal of Power Sources 239 (2013) 433–442

Contents lists available at SciVerse ScienceDirect

Journal of Power Sources

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

Ultra-high current density water management in polymer electrolyte fuel cell with porous metallic flow field

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HIGHLIGHTS

- Stable operation up to 90 °C is demonstrated with the open metallic element architecture and high current density.
- Flooding is not limiting at high current, operation is limited by dry-out.
- Net water drag measurement reveals that back diffusion controls cell operation.

ARTICLE INFO

Article history:
Received 17 November 2012
Received in revised form
20 February 2013
Accepted 20 March 2013
Available online 3 April 2013

Keywords:
Fuel cell
Water management
High current
Porous flow field
Dry out
Back diffusion

ABSTRACT

Anode dry-out is the main mechanism identified to limit operation in an open metallic element (OME) PEFC. The fundamental water transport mechanisms in the OME PEFC were examined in order to engineer further improved performance and higher temperature operation required for efficient heat rejection. Specifically, the net water drag (NWD) was measured over a range of conditions and analyzed with respect to electrochemical impedance spectroscopy and performance. As the cell operating temperature was increased, the effect of back diffusion was reduced due to the diminishing liquid water content in the cathode catalyst layer, and at critical liquid water content, anode dry-out was triggered primarily through electro-osmotic drag. Addition of cathode humidity was shown to promote high temperature operation mostly due to improved water back diffusion. The same mechanism can be achieved by creating a pressure differential across the membrane, with higher pressure on the cathode side. Stable operation was demonstrated at 90 °C using a polymer electrolyte membrane. Real time NWD measurements during transient anodic dry-out conditions were consistent with gradual membrane dehydration. The trade-off between liquid water overshadowing cathode catalyst sites and its contribution in promoting back diffusion is a key factor in systems with anode dry-out limited operation.

1. Introduction

Growing concerns about preserving the environment and finding sustainable sources of energy have brought hydrogen to the forefront of clean energy carriers. Polymer electrolyte fuel cells (PEFCs) are prominent candidates as power generating devices, converting energy stored in hydrogen gas into useable electric power. PEFCs operating on renewable hydrogen are of particular interest to the automotive industry since they are highly efficient, with zero-emissions, and operate at high-power density. The next decade will play a major role in commercializing fuel cell vehicles as most major car manufacturers plan to enter early commercialization by 2015 [1–4]. Continual improvement in performance, cost, and durability is required for successful market implementation.

In PEFCs, the cathode performance is often limiting [5,6]. This is due to both the slower oxygen reduction reaction (ORR) kinetics at the cathode compared to fast hydrogen oxidation reaction (HOR) at the anode, and mass transport limitation caused by limited oxygen

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http://dx.doi.org/10.1016/j.jpowsour.2013.03.145

diffusion and liquid water flooding at high current density [5–9]. The conventional bias in the design of fuel cell flow fields using alternating channel/land configuration is a result of the functional requirements of a flow field [10–17]. Channels distribute reactants and remove products, while lands are needed to provide adequate support, compression, and conduction of heat and current.

Various methods for excess water removal have been identified, and can involve modification of different components. Generally speaking, the modification can be in the flow field design, operating parameters, or in the soft materials such as diffusion media (DM), microporous layer (MPL) or catalyst layer (CL). Compared to a conventional parallel channel/land (C/L) design, a properly designed serpentine flow field at the cathode removes more residual water due to increased pressure drop and enhanced convective forces at the same stoichiometry [18,19], while an interdigitated flow field forces reactant flow convectively toward the active layer [20]. Modification of the C/L flow field material properties has also been proposed. Hydrophilic treatment of channel walls enhances liquid suction from locations under the land while polytetrafluoroethylene (PTFE) treatment of the C/L interface was demonstrated to increase water storage in the DM and promote flooding [21,22]. A C/L flow field made of porous carbon was devised to distribute gas in a conventional way and to act as a passive wick for water removal and redistribution of humidity [23]. Component level modifications have also been proposed to mitigate flooding. For example, it was shown that DM with relatively low in-plane gas permeability accounts for a greater amount of liquid water retention under the lands. An increase in PTFE content in the DM and MPL was shown to promote removal of water from the cathode, but an excess amount of PTFE leads to increased electrical contact resistance and reduction in performance [24,25]. In recent studies, DMs were altered by laser perforation to investigate the effect of structural change on water management [26–28]. Results indicated that perforations acted as water reservoir pools and redistributed water in low humidity conditions. At high current or wet conditions performance was poor. Even though the aforementioned strategies differ, they all deal with conventional architecture fuel cell consisting of alternating channel and lands. As some of them improve water removal and enhance performance, the main limit in typical operation is still due to flooding and mass transport at the cathode, an inherent characteristic of the channel land bias.

Porous metal and metallic mesh fuel distributors have been suggested for direct methanol fuel cells [29–34], and an improvement in performance is noted compared to conventional flow fields caused by improved methanol distribution and CO_2 removal. In PEFC, Kumar et al. modeled the performance of a multi-parallel flow field and the effect of filling the rectangular channels with porous metal of different permeability. The addition of porous metal in the rectangular channels leads to improved performance, and more importantly to a more uniform local current distribution. The highest simulated current density was 842 mA cm^{-2} [35]. Tsai et al. examined the effect of the location of manifolds in a porous metal flow field fuel cell on fuel distribution and concluded that dividing the metal foam into multiple regions and using multiple inlets effectively increases the gas distribution and utilization rate [36].

A single cell with an open metallic element (OME), designed and developed by Nuvera Fuel Cells Inc (Billerica, MA), was tested at 60 °C in our previous work, and compared to a conventional parallel C/L architecture cell [37,38]. Results showed that mass transport limitation was drastically reduced in the OME cell. No sign of flooding was visible up to 3 A cm^{-2}. This was attributed to the elimination of conventional lands that usually overshadow electrode active area, trap water inside the cell, and block reactant access to the CL. Unlike an interdigitated flow field, in which through plane convection promotes water removal under land segments, the mode of through plane transport in the OME architecture is diffusion [38]. A cross sectional schematic representing gas and liquid-phase direct flow in an OME architecture cell is presented in Fig. 1a.

Part of the water introduced in the humidified reactant streams crosses the membrane electrode assembly (MEA), and contributes to electrolyte-phase hydration. The ORR at the cathode is another source of water. Water is also moved from the anode to the cathode side of the membrane via electroosmotic drag induced by proton transport. This is due to water forming a hydration shell around a proton, or hydrodynamic pumping due to ionic and hydration shell movement [39–41]. Because electroosmotic drag affects water management in a fuel cell, it has a local and general contribution to the performance and durability. A local dry out on the anode side of the membrane can be induced by electroosmotic drag. This affects the conductivity of the membrane and therefore increases ohmic resistance and heat generation. Both water generation and

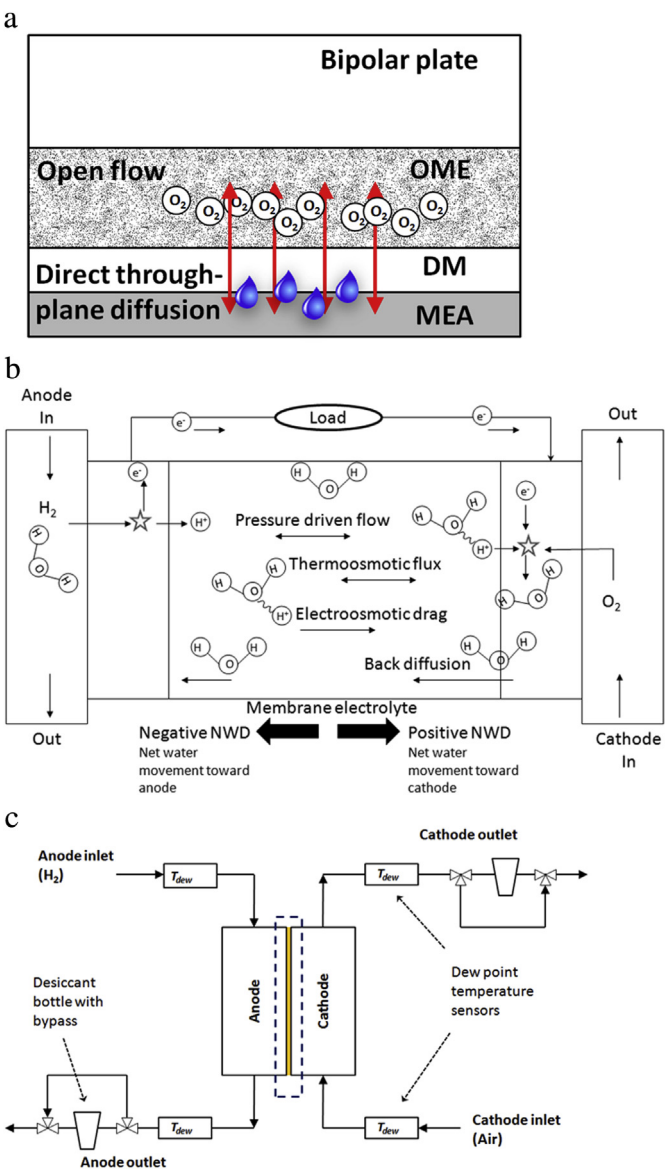

Fig. 1. a) Cross section of cathode side showing OME and improved mass transport (not to scale), b) through-plane water transport in a PEFC and net water drag (NWD), c) schematic representation of PEFC with in-line dew point temperature sensors and water desiccant bottles for live and average water measurement, respectively.