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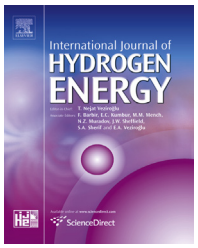

Study of water accumulation dynamics in the channels of an open-cathode fuel cell through electro-thermal characterisation and droplet visualisation

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ABSTRACT

Open-cathode polymer electrolyte fuel cells have the advantage of simplified construction and the potential for cost reduction. However, effective water and temperature management calls for a different approach to conventional fuel cells. Improved understanding of the link between current density, temperature, water formation and hydration of the membrane is required to optimise cell design. This work uses thermal imaging, optical visualisation, gravimetric analysis and electrochemical impedance spectroscopy to study the links between these factors and also examines the effect of cell orientation on performance.

The results reinforce the importance of cell temperature for water management, which is a function of current density. Regions of the cell with higher temperature avoid flooding by promoting vapour phase water; however, this can lead to higher membrane resistance due to dehydration. The results reveal that transition in the water balance regime from continuous hydration and flooding to drying with increasing current density occurs between 34 °C–40 °C (at 250 mA cm^{-2}) and water generation is balanced with evaporation at ~50 °C (550 mA cm^{-2}). Finally, fuel cell orientation affects performance after extended operation due to the effect of water accumulation and evaporation, with the cathode in a 'flat upwards' orientation found to be most resistant to flooding and cathode in a flat downwards orientation the most likely to flood.

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Introduction

Polymer electrolyte fuel cells (PEFCs) are a promising alternative to batteries for portable power applications due to their high energy conversion efficiency, low temperature operation, high power density and the energy content of [1–4] systems require auxiliary components such as fans, pumps, humidifiers and heat sinks and add to the size and complexity of the system [5]. For portable applications in particular, designs have to minimise size and simplify the system, while matching the robustness and cost of battery technologies [6].

Water management is important for most polymer electrolyte fuel cells [7,8]. The electrolyte membrane needs to be well-hydrated to enhance proton conductivity. However, excessive water in the fuel cell leads to flooding of the electrodes [9]. This occurs when the rate of water accumulation is greater than water removal, leading to accumulation of liquid water in the electrodes/gas diffusion layer (GDL). This results in mass transport limitations, as reactants cannot diffuse to the active sites. On the other hand, insufficient water production leads to membrane and catalyst layer dry out, causing an increase in resistive and activation losses. It is therefore vital to achieve the right water balance during fuel cell operation.

Various water management strategies exist, including the use of high air stoichiometry [10], reactant humidification [11], transient purge [12] and integrated electro-osmotic pump [12]. While these strategies are executed in different ways, they often require the use of additional components which are not conducive to portable applications.

Open-cathode air-breathing PEFCs are attractive for portable power applications, as they do not require forced convection of air to the cathodes, thereby avoiding blowers and reducing balance-of-plant requirements. In air-breathing fuel cells, the cathode is exposed to the atmosphere and supply of oxygen is achieved through free or natural convection of air [13–17]. For such systems, heat and water management are much more dependent on the interface with the surrounding environment than in conventional forced-convection fuel cells. In such systems there is no active means of controlling temperature and the water and thermal management for each cell is a sensitive function of current density. The propensity of water to accumulate as a liquid on the surface of the electrodes, or evaporate out of the membrane, is sensitive to the temperature of operation and rate of production of water (current density) [18]. Therefore, for open-cathode fuel cells, it is particularly important to understand the link between current density, temperature and water management to optimise for practical operation.

Manoj Kumar and Parthasarathy [19] designed an air breathing fuel cell with low thermal conductivity materials in order to keep the fuel cell at higher temperature, thereby preventing vapour saturation until higher current densities were attained which helped with water management and increased the peak power density by 36%.

In this study, thermal imaging, gravimetric analysis and optical water visualisation are applied to an open-cathode passive air-breathing fuel cell constructed using printed circuit board (PCB) current collector plates and the dynamics of water transport and accumulation its channels is studied as a function of current density and fuel cell orientation.

Thermal imaging of fuel cells

Infrared thermal imaging is increasingly being employed to measure the temperature distribution of operational fuel cells [20–23]. Thermal imaging is a technique which utilises emitted infrared radiation in order to accurately measure the surface temperature of devices, often using a semiconducting detector. Unlike traditional thermocouple measurements, which provide only limited information on the temperature in PEFCs, infrared imaging enables a highly resolved spatial measurement. In addition, thermal imaging offers a non-invasive measurement with sufficient temporal resolution to capture a wide range of dynamics associated with fuel cell operation. Thermal imaging has previously been demonstrated on a range of electrochemical devices [1,21,23,24]; however, due to the fact that it requires optical access to the sample, modifications must often be made to the design of cells and stacks in order to image the regions of interest, typically the electrodes. Infrared imaging has also been used in the validation of a range of models. Matian et al. used thermal imaging in order to validate a heat transfer model on a single-cell and two-cell stack showing a strong correlation between the analytical results and modelling [25]. Noorkami et al. examined the effect of temperature uncertainty on PEFC performance; identifying a 'polarisation area' as a more effective way of describing performance due to the uncertainty in controlling and knowing the temperature of a stack [26].

In conventional fuel cells, thermal imaging of electrodes would require the use of an IR transparent window made from materials such as zinc selenide, barium fluoride or sapphire, which all have high transmissions in the infrared range. The open-cathode self-breathing design has the advantage of allowing direct access without the need of optical windows. Such a design enables surface temperature measurements of the 'open' gas diffusion layer/electrode and the 'land' current collector regions.

Water management in PEFCs

While water is required within the fuel cell to enhance proton conductivity of the electrolyte, excess liquid water accumulating in the GDL and flow fields leads to mass transport limitations [27]. An important function of the GDL is to facilitate removal of liquid water from the electrode. Liquid water produced in the cathode catalyst layer must overcome capillary forces to penetrate through the GDL into the flow fields, both under the lands and the open channels [27–29]. Straubhaar et al. [30] studied the mechanisms of water transport in GDL on the cathode side using pore network simulations and results shows that temperature gradients leads to the possibility of condensation because of the existence of colder zones within the GDL. Li et al. [31] studied the role of cathode structure and properties on water management and electrochemical performance of a PEM fuel cell; results revealed that a hydrophobic cathode catalyst layer is effective in preventing cathode flooding and ensuring membrane hydration.