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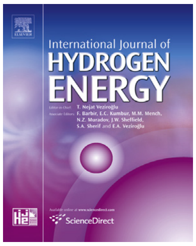

Development of open-cathode polymer electrolyte fuel cells using printed circuit board flow-field plates: Flow geometry characterisation

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ABSTRACT

Open-cathode air-breathing fuel cells have the advantage of reduced system complexity and simplified operation, as oxygen is taken directly from ambient air without the need for blowers/compressors. In this study, printed circuit boards (PCBs) are used as flow-field plates. The use of PCBs offers the potential for significant cost reduction due to their well-established manufacturing processing and low materials cost. This study investigates the effect of varying the cathode geometry (parallel and circular) and opening ratios (43%, 53% and 63%) on fuel cell performance using polarisation curves, electrochemical impedance spectroscopy (EIS) and thermal imaging. The results obtained indicate that circular openings afford lower Ohmic resistance than parallel flow-field designs, which helps improve contact between the gas diffusion layer and flow-field plate. However, flow-field plates with circular openings suffer from greater mass transport limitation effects. Likewise, greater opening ratios offer better mass transport but increased Ohmic resistance as a result of the reduced area of lands/ribs. The thermal imaging results reveal lower temperature in the middle of the fuel cell due to "bowing" of the printed circuit board flow field plates which reduces the local current density. A trade-off between these factors results in a design with a maximum area specific power density of 250 mW cm^{-2}.

Introduction

Polymer electrolyte fuel cells (PEFCs) are a promising alternative for portable power applications due to their high energy conversion efficiency, low temperature operation, power density and the high energy content of fuels used, so giving the technology certain advantages over batteries [1].

A key component of the PEFC are the flow-field plates (FFP) which have the dual role of ensuring effective current collection and distribution of reactant across the extent of the respective electrodes [2]. The FFP is the major source of weight

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and volume for the fuel cell stack, as well as an appreciable cost factor. The need for compact design and cost reduction has resulted in the need for innovative solutions in order to maximize power density and for ease of system integration. The use of alternative cell and stack designs, such as open-cathode configurations, or materials – such as printed circuit board (PCB) fuel cells, offer routes to low-cost and design flexibility [3].

PCBs are used extensively in various applications in the electronics industry. They are made up of a thin layer of copper placed upon a support layer, usually FR4 (made of epoxy resin and glass fibre). They are known for their adaptability, durability and manufacturability, which make them advantageous for use in fuel cell stacks, where strong and lightweight design is desired. They can also be used to produce planar stacks instead of the conventional vertical stack configuration by etching the copper layer to create a lateral connection between membrane electrode assemblies (MEAs), thereby connecting cells in electrical series which can help to further reduce the overall volume of the stack [3]. The use of PCB technology has the potential to significantly reduce stack volume (when unitised eliminating the need for thick end plates and most other peripheral parts), weight and cost (due to low material and fabrication cost as a result of its well-established manufacturing process). O'Hayre et al. [3] developed a 16 V unitised fuel cell assembly and recorded a volumetric power density of 400 mW cm^{-3} which makes the use of PCB technology an interesting platform for portable applications below 1 kW [3]. Consequently, fuel cell stacks that utilise multiple PCBs as fluid flow plates could benefit from the huge manufacturing base and economies of scale of PCB fabrication.

However, new designs and ways of making cells and stacks require a robust way of characterising their performance and a systematic approach to optimization. Previous experimental research on the characterisation and optimization of air-breathing fuel cell performance has focussed most analysis on polarization data [4–6]. In this study, electrochemical impedance spectroscopy (EIS) and thermal imaging are used, alongside polarisation results, to characterise the effect of cathode current collector geometry and opening ratios on the loss mechanisms that contribute to the overall fuel cell performance.

Air-breathing fuel cells

Air-breathing PEFCs are attractive for portable power applications, as they do not require active convection of air to the cathodes, so 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 [7,8]. The performance of this type of fuel cell is lower than for forced-convection fuel cells. The cathode performance is usually the major source of voltage loss as a result of the relatively weak mass transport mechanism of natural convection of air; this leads to significant concentration over-potentials [5,9]. They are also susceptible to flooding, as water removal is mainly due to evaporation [10–12]. Despite these challenges, air breathing designs have the advantages of design simplicity, no parasitic loads associated with pumps or compressors, lower cost, less noise and a potentially smaller system.

Schmitz et al. [13] presented one of the earliest experimental demonstrations of air-breathing PEFCs. They experimentally validated the modelling work of Ziegler et al. [14] which predicted rapid depletion of oxygen under the land ribs and inadequate water removal from the gas diffusion layer (GDL). Schmitz et al. [13] found that thicker GDLs (greater than 1 mm) help compensate for the likely bowing effect that increases contact resistances when operating with PCB current collectors. The influence of channel openings on self-breathing PEFCs has also been investigated by Ying et al. [4], with their findings agreeing with those of Schmitz et al. [13] and also demonstrating its effect on the heat and mass transfer properties within the cell. Jeong et al. [7] further examined the influence of both opening ratios and relative humidity on the performance of open-cathode fuel cells with their results indicating that at lower current densities, an increase in the opening ratio led to a decrease in cell performance. This was attributed to both higher activation and Ohmic losses, which resulted from rapid water evaporation and higher in-plane electrical resistance, respectively [7]. Williamson et al. [6] investigated the influence of temperature on self-breathing fuel cell performance. Their results showed that increase in cell temperature improved the cell performance at high current densities because the heated (more buoyant) air surrounding the system allowed for more air flow over the MEA. However, at lower current densities an increase in temperature led to decrease in cell performance due to higher resistance as a result of membrane dry out.

Besides channel openings, the cathode geometry design and orientation have been shown to have an impact on Ohmic resistance and mass transport limitations [5,8,15–18]. Fabian et al. [19] investigated the role of ambient conditions on the performance of a planar air-breathing system. Their results showed ambient conditions affected all three main electrochemical loss mechanisms, with activation losses the largest component. O'Hayre et al. [20] developed an engineering model to predict the performance of planar self-breathing fuel cells. The model indicated that thermal runaway caused by inadequate heat rejection limits fuel cell performance more than oxygen depletion.

Electrochemical impedance spectroscopy (EIS)

Electrochemical impedance spectroscopy (EIS) is a powerful diagnostic tool that can characterise the various losses in a fuel cell [21–23]. The main advantage of EIS is that it is non-destructive and provides information about fuel cell performance without (substantially) perturbing the system from equilibrium [24]. For example, EIS has been applied in fuel cell research to decouple anode and cathode operation, optimise MEA fabrication and fuel cell operating conditions [24], examine the effect of cell compression [25], water management [26] and flooding effects [27]. In this study, EIS is used to deconvolute the effect of different current collector/flow field geometries on the various performance loss mechanisms.