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Current collector design for closed-plenum polymer electrolyte membrane fuel cells

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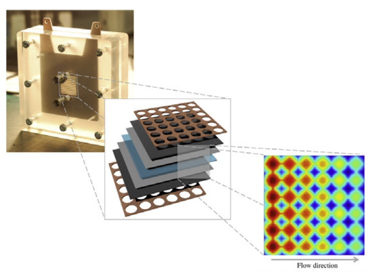
HIGHLIGHTS

- A 3D model of a whole planar PEMFC with a closed-plenum flow field is presented.
- Effect of printed circuit board current collector design on transport investigated.
- Parallel channels outperform circular channels with best species distribution.
- Study completed on channel size, current collector material, feed humidification.
- Model predicts key inhibitors of successful operation are flooding and overheating.

GRAPHICAL ABSTRACT



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ABSTRACT

This work presents a non-isothermal, single-phase, three-dimensional model of the effects of current collector geometry in a 5 cm^2 closed-plenum polymer electrolyte membrane (PEM) fuel cell constructed using printed circuit boards (PCBs). Two geometries were considered in this study: parallel slot and circular hole designs. A computational fluid dynamics (CFD) package was used to account for species, momentum, charge and membrane water distribution within the cell for each design. The model shows that the cell can reach high current densities in the range of 0.8 A cm^{-2}–1.2 A cm^{-2} at 0.45 V for both designs. The results indicate that the transport phenomena are significantly governed by the flow field plate design. A sensitivity analysis on the channel opening ratio shows that the parallel slot design with a 50% opening ratio shows the most promising performance due to better species, heat and charge distribution. Modelling and experimental analysis confirm that flooding inhibits performance, but the risk can be minimised by reducing the relative humidity of the cathode feed to 50%. Moreover, overheating is a potential problem due to the insulating effect of the PCB base layer and as such strategies should be implemented to combat its adverse effects.

1. Introduction

Polymer electrolyte membrane fuel cells (PEMFCs) are an attractive alternative for electrical power generation. Their low operating temperature makes them versatile in that they can be used in a variety of applications (e.g. portable, automotive). PEMFCs operate by converting the chemical energy in fuel (of which

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hydrogen is a particularly good fuel) into electrical power by electrochemically reacting the fuel with oxygen (air); this is associated with the production of water and heat (which can be usefully harvested in certain applications). The core of a PEMFC consists of a membrane electrode assembly (MEA) made of a proton conducting electrolyte (e.g. a perfluorosulfonic acid membrane such as Nafion) sandwiched between two electrodes containing a suitable electrocatalyst. These electrodes are covered with a carbon-based gas diffusion layer (GDL) that facilitates the conduction of electrons and distribution of reactants and products across the electrodes. In conventional fuel cell designs, each MEA is placed between two bipolar plates, which allow for the conduction of current from the MEA to the load and the distribution of the reactants and products to and from the MEA. The bipolar plates also provide the necessary structural stability required by each cell in the stack [1,2].

Given the complexity of the construction and operation of a fuel cell, it is desirable to fully understand the transport phenomena within a given arrangement. Computational tools can be used to determine the need for appropriate reactant transport, water management and heat management through accurate design and operation. Various models can be found in literature for fuel cell operation [3–15], water management [8,16–21], heat management [16,22–25] and bipolar plate design [26–51]. Notable works include the one-dimensional models of Bernardi and Verbrugge, and Springer et al. that were among the first to supply a comprehensive view of steady-state fuel cell operation through coupling of the various transport phenomena [3,10]. Berning et al. presented a three-dimensional model of a PEMFC channel as part of a serpentine flow field design, followed by a parametric study that indicated that contact resistance is a performance limiting factor [4,52].

Understanding the effect of bipolar plate design (flow fields) on fuel cell operation is highly important. The bipolar plate contributes to the majority of the mass of a typical stack and it is known to be costly to fabricate. Optimisation of the flow field is imperative as it has a significant impact on the fuel cell stack performance, geometry, weight and cost. A variety of models exist in literature that investigate the influence of traditional flow field plates such as the serpentine, parallel and pin channel designs [26,27,29,34–46]. Wang et al. have been particularly active in this area [35–45]. They have demonstrated that by altering the channel height within a single serpentine flow field design, sub-rib convection velocities can be achieved that are comparable in magnitude to those in the channel, which results in increased oxygen transportation to the cathode and effective removal of excess water [44]. Further work has shown that through the use of a three-dimensional, two-phase model, serpentine and interdigitated flow fields provide better access of gases to the porous electrodes, which minimises reactant depletion and flooding [41].

Biomimetic flow designs have been proposed as a way to optimise reactant distribution. Wang et al. used computational fluid dynamics to present two different biomimetric designs that showed high flow uniformity and reduced pressure drop across the cell, while maintaining good oxygen distribution and water removal [33]. Advanced flow plate designs have been proposed and demonstrated by Kjelstrup et al. using a nature inspired chemical engineering (NICE) approach that adopts a fractal structure inspired by the human lung [53]. Yi and Nguyen were one of the first research groups to promote the use of an interdigitated design to increase the transportation of reactants in the electrodes under the rib areas [47]. Lobato et al. [28] also demonstrated the use of a three dimensional model on the cathode side for comparison of the parallel, pin and serpentine flow fields in a high temperature fuel cell; the serpentine design gave the best performance due to a more uniform distribution of oxygen and current density across the active area; however, the model neglects to take into account the problems that are associated with low-temperature PEMFCs [28].

1.1. Self-breathing and closed-plenum fuel cells

The flow fields described above have the common feature of having active advection supply of reactant to the channels such that the channels are enclosed, with flow occurring along their length. However, other geometries exist that have the flow entering above the channel, as shown in Fig. 1.

The self-breathing, also commonly known as the air-breathing, PEMFC has an exposed cathode that is supplied with an oxidant via natural convection (Fig. 1). This configuration is particularly

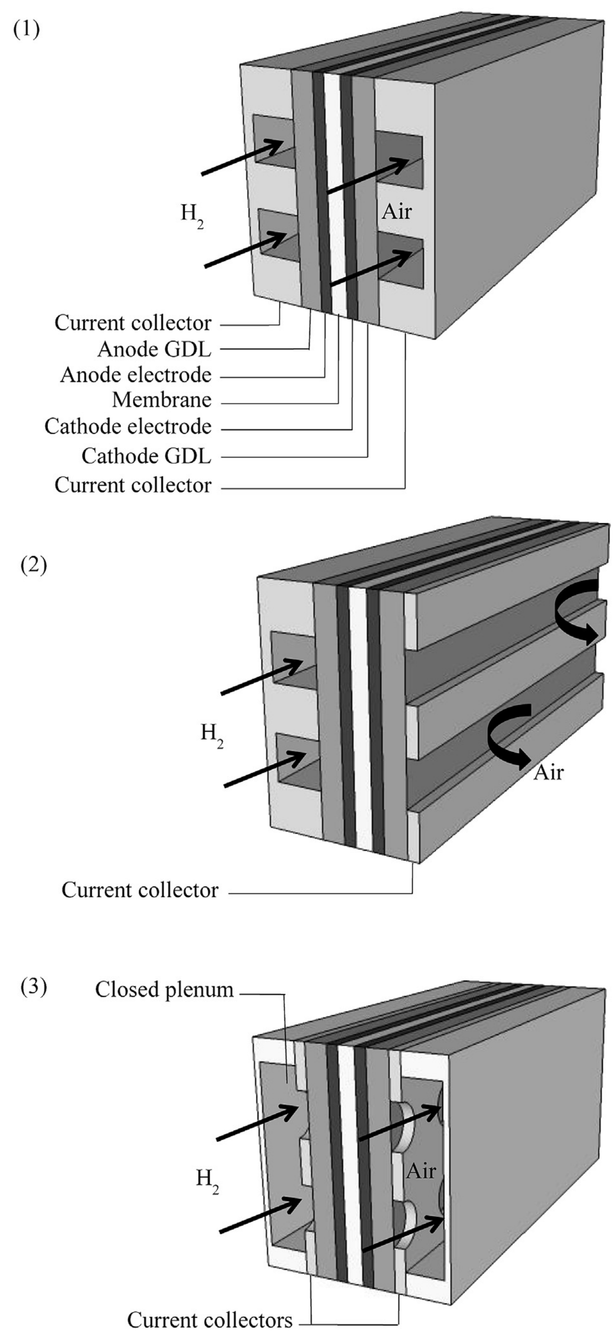

Fig. 1. Three-dimensional representations of: (1) conventional forced-convection, (2) air-breathing and (3) closed-plenum PEMFCs.