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Cell level modeling of the hygrothermal characteristics of open cathode polymer electrolyte membrane fuel cells

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ABSTRACT

Open cathode designs that utilize ambient air for both cooling and oxygen supply are a useful feature for low- to medium-power polymer electrolyte membrane fuel cell (PEMFC) stacks. Elimination of balance-of-plant subsystems greatly reduces the complexity, parasitic power, and cost of the overall system, and therefore increases the appeal of open cathodes. The present research addresses the key challenges of open-cathode PEMFCs related to thermal management and membrane hydration, two highly coupled phenomena. Accurate knowledge of the temperature and relative humidity (RH) distributions in the cell is essential in order to optimize heat removal by suitable strategies. In the present work, a three-dimensional numerical model is developed that can predict the hygrothermal characteristics in a complete open-cathode cell. The model is validated using experimental data obtained with Ballard Power Systems' FCgen®-1020ACS stack under a range of operating conditions. The model is then used to analyze the key flow conditions and properties that control the hygrothermal behavior of open-cathode stacks. Based on the obtained results, flow conditions can affect temperature and RH distributions significantly; in-plane plate thermal conductivity can provide a uniform temperature distribution while adversely reducing the RH; and edge cooling can increase temperature and RH gradients in the cell. Recommendations for hygrothermal design and operation of open cathode stacks are provided.

Introduction

Fuel cells are considered as the "21st century energy-conversion devices for mobile, stationary, and portable power" [1]. An open cathode fuel cell that utilizes natural or forced convection of ambient air as the main oxygen supply is an emerging type of polymer electrolyte membrane fuel cell (PEMFC) technology which has certain advantages and challenges when compared to the more commonly employed

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humidified and liquid-cooled PEMFC. The open cathode fuel cell type is simple in terms of system design and maintenance, but complex in terms of hygrothermal management. Elimination of balance of plant subsystems such as liquid coolant loop and gas humidifier reduces the system complexity and cost which is important for commercialization. Ballard Power Systems, as one of the leading fuel cell companies in the world, recognized the importance of open-cathode PEMFCs and pioneered the product development in this area. As a result, an open cathode air-cooled PEMFC stack is currently manufactured by Ballard with the FCgen®-1020ACS product designation (*cf*., Fig. 1(a)). This stack can operate in various ambient conditions and the output power is scalable from 300 W to 3 kW.

In order to unlock the far-reaching potential of PEMFC technology, a wide variety of research and development activities are currently underway in both industry and academia. Major advances in this field often rely on modeling to guide experimental and development work. Common modeling approaches in fuel cell science and technology were recently reviewed by Wang [1]. Fuel cell modeling is a complex process, because it deals with multi-scale geometries, electrochemical reactions, mass and heat transfer, and deformation phenomena. A comprehensive fuel cell model should include the transport equations from the nano- and micro-scale catalyst layers, gas diffusion layers, and membrane to mini-scale channels and large-scale stacks with multiple cells with consideration of solid, ionomer, gas, and liquid phases. However, considering the available computational resources, it is not possible to include all the details in such models. Hence, depending upon the fuel cell conditions, the required accuracy, and the aim of the research, different modeling scenarios may emerge. Many research activities to date considered macroscopic modeling [2–7] while others focused on pore scale modeling of different fuel cell components [8–10]. The recent trends in macroscopic fuel cell modeling of relevance for open-cathode designs were directed towards thermal management, flow field design, and water management. The issues related to the water and thermal management are particularly important when dealing with the open cathode air-cooled PEMFCs. This is attributed to the low humidity operating conditions and limited cooling effectiveness. Most established fuel cell models assume fully hydrated membranes and isothermal conditions [11–13] which are generally acceptable for liquid-cooled fuel cells operating under well-humidified conditions. However, such assumptions are not valid for open cathode designs, known to operate under low humidity conditions and have significant temperature gradients [14].

Thermal management is a necessity for PEMFCs, especially for the air-cooled stacks. Heat generation inside the cells and its distribution could result in different thermal behavior of the stack. Ju et al. [15] examined different heat generation mechanisms in a single channel PEMFC. Their model was accurate in predicting the thermal behavior on the single-channel level; however, it could not capture the temperature or RH gradients on the cell level. Bapat and Thynell [16] studied the effects of anisotropic thermal properties and contact resistance on the temperature distribution using a two-dimensional single-phase model based on a single channel domain, but did not investigate the effects of those properties on the RH distribution. Several useful thermal management strategies have been developed for PEMFCs. Installation of separate liquid cooling channels in the bipolar plate is the most common strategy to avoid high temperatures. This approach was experimentally examined by Matian et al. [17]. Wider cooling channels were shown to enhance the rate of heat transfer from the stack with the tradeoffs of reduced mechanical stability and increased complexity of plate design and manufacturing. The Ballard Nexa stack pioneered the use of air cooling through a separate flow field configuration [18]. However, due to their complexity, the Nexa stack was replaced with the modern Ballard FCgen®-1020ACS stack with combined cathode air supply and cooling channels. Alternative strategies are also available in the literature that may increase the complexity of the stack design and operation under transient conditions [19,20].

Another important phenomenon in low humidity air-cooled stacks is membrane dehydration. Membrane water content, which is a function of water activity, will directly affect proton conductivity [12] and consequently ohmic losses. It is shown in Ref. [21] that low humidity operation will reduce the overall fuel cell performance. Therefore, self-humidifying MEAs should be utilized to avoid membrane dehydration. A vast amount of research is focused on water transport modeling and water management in PEMFCs. These investigations are mostly directed towards resolving the flooding issues under high humidity conditions [22,23] in

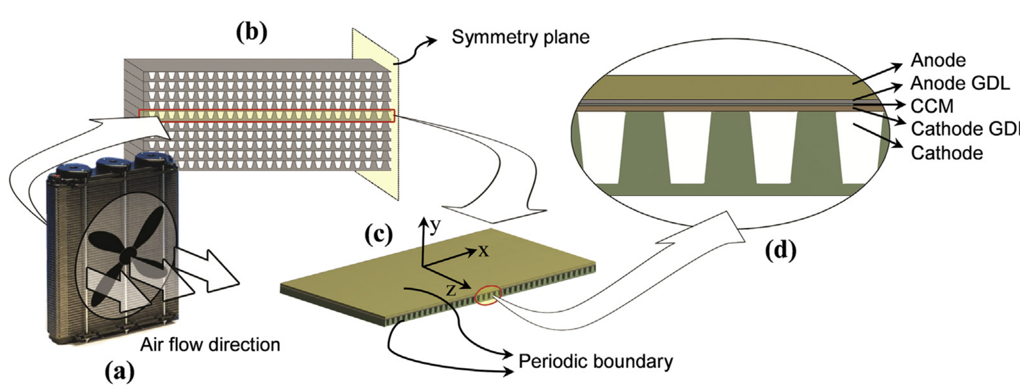

Fig. 1 – Model geometry, cell components, and boundary conditions.