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Parametric study of an external coolant system for a high temperature polymer electrolyte membrane fuel cell

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HIGHLIGHTS

- Heat transfer model for a stack taking account of segments of individual cells.
- Flow, heat transfer and electrochemical coupling.
- Temperature and current density mapping over individual cell segments.
- Optimization for high efficiency and specific power density.

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ABSTRACT

Considerable heat is generated in a high temperature polymer electrolyte membrane fuel cell (HT-PEMFC) at high current densities which poses a challenge in the cooling of stack, especially in automobile applications which require high power densities. In the present study, we investigate the effectiveness of an external coolant system using a multiscale, stack heat transfer model on a commercially available computational fluid dynamics (CFD) computer code which takes account of the convective and conductive heat transfer occurring through various layers of the cell and stack elements of an HT-PEMFC operating at 473 K (200 °C). The model accounts for the coupling between the local cell temperature, the local current density and the local overpotential through an empirical polarization curve appropriate for the cell. Results from the simulations show that temperature variations within the stack can be kept to within 10 K by an optimal choice of the number of coolant plates, the coolant flow rate and the temperature at which it enters the stack. Specific power densities of up to 690 W kg^{-1} (based on the active volume of the fuel cell) have been obtained for a 1 kWe stack with graphite cooling plates located one for four cells.

1. Introduction

High temperature proton exchange member fuel cells (HT-PEMFCs) operate in the temperature range of 373–473 K (100–200 °C) and offer several advantages compared to low temperature fuel cells proton exchange member fuel cells (LT-PEMFCs) which operate at temperatures below 353 K (80 °C) [1–3]. HT-PEMFCs do not require humidification of the reactants during the operation because of the lower sensitivity of the proton conductivity of the electrolyte to humidification. They also have high carbon monoxide (CO) tolerance and allow use of a wider range of fuels. However, they have low efficiency at low current densities and their efficiency increases significantly as the current density and the operating temperature increase. Therefore, proper thermal management of the HT-PEMFCs stack is required to ensure that the cell temperature is neither too low (which would lead to low cell efficiency) nor too high (which would damage the materials of the stack). The local heat generated in the interior of a cell must be effectively removed without creating any hot or cold spots.

The cooling of the fuel cell stack can be achieved through a number ways including: (1) active cooling with air or liquid coolants, (2) passive cooling with cooling fins and high thermal conductivity heat spreaders, (3) evaporative cooling or cooling with phase change liquids and (4) cooling with a separate air flow [4–7]. Passive cooling methods in which heat is removed by using heat spreaders are also known as edge cooling methods. They have the limitation that they cannot be used alone, i.e., without using an air blower, when the stack size is greater than 50 W because of the

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limited surface area available within the cell and the low temperature difference between the PEMFCs and the ambient. As a result, natural convection is not effective in maintaining a sufficiently uniform cell temperature. This can however be achieved by using forced air ventilation over the stack [7]. Active cooling methods, in which the coolant fluid (either air or water) is pumped through cooling passages within the stack, are capable of greater heat removal from the stack. LT-PEMFCs and flow field configurations have been developed to minimize pressure drop and to maximize temperature uniformity within the stack [8–11]. It is also possible to remove the heat through evaporation and condensation of water inside the LT-PEMFC stack; in such cases, the liquid saturation along the length of the coolant path influences the cell temperature gradient [12].

Thermal management of HT-PEMFC stacks has also been reported in the literature. Andreasen et al. [13] developed a dynamic air-cooled HT-PEMFC stack model for a hybrid electrical vehicle using air as coolant. Andreasen et al. [14] later developed a model for heating strategies for a HT-PEMFC stack and concluded that the startup time can be reduced by sending pre-heated cathode air. Direct electrical heating of the fuel cell can take up to 50 min during the startup of the stack which can be reduced by sending pre-heated air to the cathode. Scholta et al. [15] developed a 5-cell HT-PEMFC stack which was cooled using air or a liquid coolant. Scholta et al. [16] also developed a model for a 10-cell HT-PEMFC stack which was cooled using heat pipes. In both cases, they did not consider the electrochemical reaction and assumed a constant heat source term. They reported that the temperature variation from the center to the edge was around 56 K at a cell operating temperature of 433 K and an inlet cooling oil temperature of 373 K. Song et al. [17] developed a prototype model of a natural circulation-driven water cooling system for an HT-PEMFC stack operating at and exit temperature of 423 K. In this concept, water was used as the coolant and the buoyant force caused by the density difference between vapor and liquid was utilized to circulate the coolant between the stack and the cooling device. The coolant water circulated through the stack goes to the cooling device where the excess heat is transferred to a secondary cooling stream. The stack temperatures were found to be sensitive to the secondary coolant and it needed additional control attention.

None of the above HT-PEMFC stack models consider the effect of local current density on the variation of the cell temperature and the performance of the stack. Kvesic et al. [18,19] developed a multi-scale, 3D model of an HT-PEMFC stack containing one cooling channel in each bipolar plate. In this model, the stack manifolds were considered separately from the body of the stack and a porous medium approach was used for the resolution of cell-level phenomena. The porous medium included the anode and the cathode flow fields, the land area of the channel and the gas diffusion layer (GDL); all these were combined to form a homogeneous porous domain. The membrane-electrode assembly (MEA) consisting of the anode catalyst layer, the membrane and the cathode layer, was treated as a separate volume in which the catalyst layers were modeled as two–dimensional planes. The anode and the cathode side volumes of the MEA were coupled through adjacent mesh sites and source and sink term were defined by a Tafel equation for the cell. While their earlier work [18] considered the case of a hydrogen-fed PEM fuel cell, their later work [19] considered the case of a reformate gas using their earlier work [18,20] to characterize the corresponding electrochemical performance of the cell. Their studies showed that, if the reactants and the coolant were preheated, then the cell temperature variations would be in the range of 3–6 K within the cell for a hydrogen-fed case and about 9–10 K for a reformate gas case. A significant variation of the local current density, in the range of 0.5–0.8 A cm^{-2} for an average cell current density of 0.6 A cm^{-2}, was predicted and this was found to be in agreement with their own experimental results. In a recent paper, Supra et al. [21] have reported measurement of cell temperatures in a 1 kWe, liquid-cooled HT-PEMFC stack with one cooling plate for every three cells. The fuel for the cell was reformate gas and the liquid coolant entered the stack at 433 K. The measured temperature variations in the cells in between the cooling plates showed a temperature variation of the order of 6–8 K with a maximum variation of 8.3 K. Data of local cell voltage obtained under constant current mode of operation showed that the voltage varied by about 5–10% and that the variation correlated well with that of the cell temperature. These experimental data are thus a confirmation of the effect of liquid coolant on the temperature variation within the stack and of the resulting effect on the electrochemistry of the cell.

In previous work by the present authors [22], the possibility of using cathode air as a coolant for a 1 kWe HT-PEMFC stack was investigated through simulations using a multiscale CFD model of the stack. Here, the fine details of heat and fluid flow through the stack consisting of thin layers of the MEA, the GDL, the flow fields and the coolant channel were resolved. The electrochemistry was included in the form of empirical V–I curves reported in the literature [2,23] and a coupling between the local temperature and the local current density was created to account for the effect of cell temperature on the V–I curve. It was shown that through a combination of excess stoichiometric factor of cathode air and forced draft (which would be relevant for transport applications), the temperature variation within the cell could be restricted to about 20 K over most of the cell and up to 50 K in isolated spots for a cell operating at a maximum permissible temperature of 473 K anywhere. The predicted local current density showed a variation of ±15% from its mean value. In the present study, we extend this methodology of multiscale calculation to the study of stack thermal management using a separate coolant. In contrast to previous studies of a similar type [15,16,18,19], the present problem formulation allows the local heat source to vary spatially as per the current density; an explicit linkage between the local temperature and the electrochemistry has also been included. Details of the model and the results obtained are discussed below.

2. Calculation methodology

2.1. Geometric model of HT-PEMFC stack

The present HT-PEMFC stack model is based on the polybenzimidazole (PBI) membrane doped with phosphoric acid. It contains multiple cells connected in series to develop the required voltage. Each cell consists of a membrane for ion conduction, two catalyst layers for electrochemical reactions, two gas diffusion layers and two bipolar plates for the electron conduction and flow distribution. The gas diffusion layers and the bipolar plates are the same as those for an LT-PEMFC. Typical platinum loadings for HT-PEMFCs are in the range of 0.2–0.4 mg cm^{-2} [24] which is slightly higher than that for LT-PEMFCs. The HT-PEMFC membrane is entirely different from the LT-PEMFC membrane, because the LT-PEMFCs generally feature a Nafion® membrane which is not suitable for temperatures above 80 °C. The HT-PEMFC membrane is made of phosphoric acid-doped PBI which has fairly high protonic conductivity even without humidification [1].

The fuel cell stack under consideration has a design power output of 1 kWe. When operated at a voltage of 0.6 V per cell at an average current density of 0.42 A cm^{-2} [23], the stack is made up of 40 cells connected in series and generates an overall voltage of 24 V. Each cell has an active area of 100 cm^2 and the bipolar plates have 50 parallel channels of a length of 100 mm and a cross-section of