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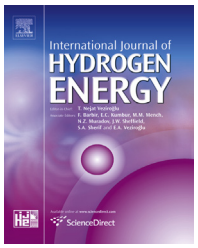

Numerical study on the effects of gas humidity on proton-exchange membrane fuel cell performance

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ABSTRACT

To examine the effects of gas humidity on proton-exchange membrane fuel cells (PEMFCs), three-dimensional multi-phase non-isothermal fuel cell model simulations were performed. Various inlet gas humidity conditions were independently imposed at the inlets of the anode and cathode flow channels. This numerical simulations revealed that fuel cell performance is significantly affected by both anode and cathode humidification. The ohmic loss is influenced by both anode and cathode inlet gas humidity, whereas the concentration loss is mainly affected by the cathode inlet gas humidity. The gas humidity in the flow channel can be controlled by adjusting the bipolar plate temperature. Additional simulations assessed different bipolar temperature distributions. When the temperature of the bipolar plate was increased in the direction of gas flow, the concentration loss decreased, owing to the reduced condensation of liquid water in the catalyst layer. Consequently, fuel cell performance increased, especially in the high current density region.

Introduction

Proton-exchange membrane fuel cells (PEMFCs) are considered a promising technology for various applications since they demonstrate many advantages such as high power density, rapid start-up, and high efficiency. In addition to electrical energy, a PEMFC generates water by the electrochemical reaction of the hydrogen ions that move through the electrolyte with the oxygen supplied through the fuel channel. If the produced water is not properly removed from the fuel cell, a flooding phenomenon occurs and the concentration loss significantly increases because the fuel must be transported through the liquid water to the reaction site [1]. The condensation of liquid water in a PEMFC can be easily prevented by increasing the operating temperature. However, an excessive increase in the operating temperature can cause the electrolyte to dry, and thus, significantly decrease the ion conductivity of the membrane [2]. The relative humidity (RH) is closely related to both liquid water condensation and the water content in the membrane, and thus, exerts a significant effect on fuel cell performance. Therefore, many studies have examined the effects of humidity in PEMFCs because the RH significantly effects changes in fuel cell performance.

In an experiment that maintained a fully humidified anode inlet, Williams et al. [3] reported that cell performance increased as the cathode humidification changed from 0 to 75%, however, a fully humidified cathode inlet resulted in a significant drop in cell performance due to flooding. On the other hand, Yin and Chang [4] tested the effects of the anode

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relative humidity (RHa) under fixed cathode humidifying conditions (RHc = 0 and 100%). They also reported that a high RHa effectively reduced cell performance due to flooding within the cathode gas diffusion layer (GDL) at high current density. Saleh et al. [5] examined the combined effects of the RH of the cathode and anode in both symmetric and asymmetric arrangements on the performance of PEMFCs. They showed that the effects of cell humidification depended on the cell temperature. For the symmetric RH conditions, at T_{cell} = 70 °C under high RH (>60%), the performance was limited by mass transfer resistance, whereas the cell performance increased with the relative humidity to RH = 100% at T_{cell} = 90 °C. In contrast to these studies, Kim and Hong [6] reported that the PEMFC stack performance was more affected by cathode humidity and continued to increase with cathode humidity from RHc = 40%–100%.

Several numerical simulation studies have been also performed to examine the effects of the humidity on PEMFC performance. Using two-dimensional numerical analysis, Wong et al. [7] showed that the anode inlet humidity mainly affected the membrane ionic conductivity, whereas the cathode inlet humidity mainly influenced the level of liquid water saturation, and hence, the cathode active polarization. On the other hand, Jeon et al. [8] tested the effect of the RHc for PEMFCs by performing computational fluid dynamics (CFD) simulations on a 300 cm^2 serpentine flow-field configuration. They reported that a higher RHc gave rise to better cell performance and more uniform distributions of current density and temperature.

In the present study, three-dimensional multi-phase non-isothermal fuel cell model simulations were performed to examine the effects of gas humidity conditions on PEMFCs. Various values of inlet gas humidities were tested, which were independently imposed at the inlets of both the anode and cathode flow channels. The ohmic and activation polarizations were analyzed to examine the changes in cell performance due to cell humidification. The water content in the membrane and the liquid water saturation in the cathode catalyst were affected by the inlet gas humidity. Finally, the effects of varying the temperature of the bipolar plate on cell performance were examined, because cell humidification can be also controlled by adjusting this temperature parameter.

Computational details

In the present study, a series of three-dimensional multi-phase non-isothermal fuel cell model simulations were performed. For the numerical simulations, the commercial software ANSYS FLUENT (ANSYS, Inc., Canonsburg, PA, USA) was utilized in conjunction with the PEMFC module. The module includes the conservation of mass, momentum, and energy as well as electric and protonic charges. In addition to the conservation equations, the model solves the species transport equations with source terms corresponding to the electrochemical reactions. The PEMFC module assumes that the reactants are ideal gases and the flow in the channel is laminar. Liquid condensation was taken into account by solving for the liquid water saturation in porous media. Note that the liquid water saturation in the gas channel is negligible because the liquid water in the gas flow channel is assumed to be in a mist state and it can be instantaneously removed by the bulk flow. More details on the FLUENT fuel cell module can be found in Ref. [9].

A simple straight-channel configuration was considered, as shown in Fig. 1. The structural parameters of the present model and operating conditions are listed in Table 1. The operating temperature and pressure were 80 °C and 1.5 atm, respectively. The stoichiometric ratios, defined at a reference current density (J^{ref}) of 1 A cm^{-2}, were 1.5 and 1.8 at the anode and cathode, respectively. The RH of the inlet gas was independently varied from 0 to 100% for both anode and cathode sides.

The mass flow rates of the gas mixtures are given by their stoichiometric ratios ξ as

$$\dot{m}_a = \frac{\rho_g \xi_a J^{ref} A}{2FC_{H_2}} \tag{1}$$

$$\dot{m}_c = \frac{\rho_g \xi_c J^{ref} A}{4FC_{O_2}} \tag{2}$$

where ρ_g is the density of gas mixture, A is the active area and F is Faraday's constant (96,487 C/mol). The fuel concentrations at the inlet are calculated as:

$$C_{H_2} = \frac{(P_a - RH_a P^{sat})}{RT_0} \tag{3}$$

$$C_{O_2} = \frac{0.21(P_c - RH_c P^{sat})}{RT_0} \tag{4}$$

where T_0 and P are the temperature and pressure at the inlet, and the subscripts 'a' and 'c' denote the anode and cathode, respectively. The saturation pressure P^{sat} is calculated, in terms of atm, as,

$$\log_{10} P^{sat} = -2.1794 + 0.02953(T - 273.17) - 9.1837 \times 10^{-5}(T - 273.17)^2 + 1.4454 \times 10^{-7}(T - 273.17)^3 \tag{5}$$

Results and discussion

First, the changes in the polarization curve due to different inlet gas humidification levels were examined. Fig. 2 shows

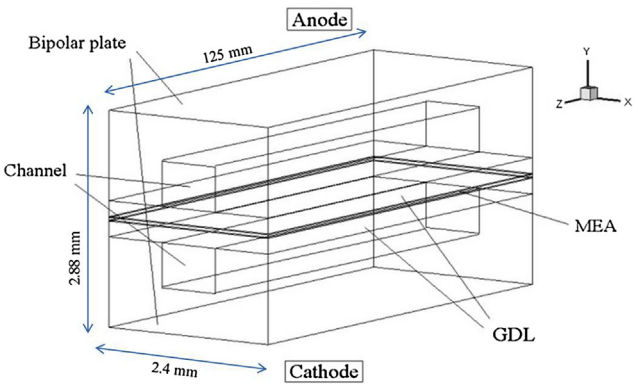

Fig. 1 – Computational domain.