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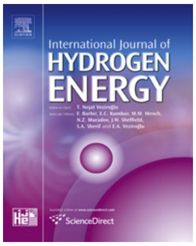

Effect of channel and rib width on transport phenomena within the cathode of a proton exchange membrane fuel cell

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ABSTRACT

A two-phase, half cell, non-isothermal model of a proton exchange membrane fuel cell has been developed. The model geometry includes a gas diffusion layer, a micro-porous layer and a catalyst layer along with the interfaces for channel, land and membrane. The effect of channel and rib width on transport phenomena has been examined. The model was run with saturated gas feed at different operating current densities and cell temperatures. The results show that increasing the channel to rib width ratio does not have any effect on the total amount of liquid saturation, however, its distribution is significantly affected under the channel and rib region within the porous layers. The degree of supersaturation and undersaturation extends, but, the supersaturation region shrinks and the undersaturation region extends with increase in channel to rib width ratio. It is concluded that the transport mechanism within the cathode is a highly coupled phenomena which interlinks local distribution of temperature, liquid saturation and the relative humidity.

1. Introduction

The transport phenomena in a proton exchange membrane fuel cell (PEMFC) are very complex and include multiphysics environments, such as, electro-physicochemical and thermal transport to be taken into account [1]. It has been widely accepted that the thermal and water management are the key issues in controlling the PEMFC performance [2–5]. Unlike, solid oxide fuel cells, in which the transport remains in a single gaseous phase, it becomes complicated in PEMFCs due to two-phase effects. The two-phase transport, especially on the cathode side is believed to be the limiting factor in PEMFC performance [4]. Under-humidified (i.e. relative humidity less than 100%) gas feed may result in membrane dehydration, whereas, fully or over-saturated reactant feed may cause flooding of the cathode. In either case, the performance of a PEMFC drops either due to insufficient proton conductivity (dehydration) or due to pore blocking effect via excessive liquid water within the porous layers (flooding). Therefore, a model that can predict liquid water saturation within the porous layers is of great importance. It should be noted that calculating liquid water saturation in a PEMFC is not a trivial task. The liquid water saturation is highly coupled to the thermal management within the cell. If, on one hand, operating temperature is increased while keeping the inlet relative humidity constant, the liquid water saturation will drop due to evaporation effect. On the other hand, if the operating temperature is decreased, while fixing the inlet relative humidity as constant, the liquid water saturation may rise due to condensation effect. Furthermore, it is not only the change of operating temperature that causes the change in liquid water saturation, the operating current density could also have some effect. For example, increasing the operating current density to a certain level will increase liquid water

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production due to electrochemical effect, beyond that level, liquid water saturation may drop because of evaporation effect, mainly due to high amount of heat generation. From the above discussion it is clear that liquid water saturation within the PEMFC cathode is a highly coupled phenomena that interlinks temperature, current density and relative humidity. It has been reported that the liquid water saturation within the porous layers may change because of the heat pipe effect. In a heat pipe effect, heat is transferred from a relatively hotter zone to the cooler zone via thermal diffusion, as a result, a non-equilibrium phase change effect may take place that could alter the liquid water saturation within the porous region [6]. Furthermore, it has also been observed that the areas under the rib region are relatively cold due to inaccessibility of the reactants. In such cases, the effect of geometrical configuration of the bipolar plates may play an important role in determining the liquid water saturation profiles, especially near the rib and channel region.

There are several studies available in the open literature on two-phase transport in PEMFCs [1–22]. To the authors' knowledge, only few of them have stressed the importance of non-equilibrium phase change effects [2–5,7–9]. For example, Meng [2] developed a two-phase non-isothermal model for a PEMFC using two-fluid approach. His results indicate that with under-humidified reactant, a condensation/evaporation zone appears in the porous layers and its location changes with the inlet value of the relative humidity. He also pointed out the appearance of dry region directly under the gas channel and a relatively wet region near the current collecting land owing to phase change effects.

Dalasm et al. [3] developed a three-dimensional, two-phase, non-isothermal model for the cathode side of a PEMFC with emphasis on interfacial mass transfer-phase change by implementing a non-equilibrium evaporation–condensation phase change term. They carried out a parametric study to investigate the effect of operating conditions such as, inlet humidity, cell operating temperature and inlet mass flow rate. They concluded that the maximum evaporation rate zone coincides with the maximum temperature and lowest saturation zones. On the other hand, the maximum condensation zone was seen at the lowest temperature and correspondingly higher saturation.

In another study, Dalasm et al. [4] studied transient phase change in the cathode side of a PEMFC. They developed a three-dimensional, transient, two-phase, non-isothermal model. With the help of non-equilibrium interfacial phase change rate, their model allows to predict the supersaturation and undersaturation phenomena within the porous layers. They observed that when the dominant phase change mechanism is condensation, the transient time decreases and the steady state can be achieved in a shorter time. Furthermore, they also predicted that the transient behavior of the phase change significantly affected the transient cell response.

Basu et al. [5] developed a three-dimensional, non-isothermal model to study the phase change effects in a PEMFC using mixture model approach. They quantified the locations of condensation and evaporation and reported that the relative humidity of the inlet gases and thermal conductivity of the gas diffusion layer have major influence on the phase change effect. In order to reduce the condensation and to alleviate the liquid water build-up under the rib region, they suggested the use of lower inlet humidity gas feed and a higher thermal conductivity of the gas diffusion layer.

Berning et al. [7] extended their previously developed model [21] to include phase change kinetics and compared the results for interdigitated and conventional straight channels. They concluded that by choosing an appropriate diffusion media with high in-plane permeability, the pressure drop in the interdigitated flow field can be substantially reduced. They also noted that in case of interdigitated design more water can be exhausted in vapor form compared to the straight channels, therefore, making them more favorable for liquid water management. Furthermore, interdigitated design offers more waste heat in the form of latent heat which reduces load on the coolant.

Min et al. [8] developed a three-dimensional, two-phase, non-isothermal model of a PEMFC using two-fluid approach. In their model, the interaction between reactant fluid and solid matrix temperatures was made to take into account various losses and phase change effect. The local difference between the reactant fluid and solid matrix temperatures causes different phase change rates within the porous medium. Due to electrochemical production of water at the cathode side, they recommended a lower cathode humidity to avoid flooding on the cathode side.

Wang et al. [9] reported a multidimensional model for comparing numerical predictions with the neutron radiography data. Their work was focused on the through-plane water distribution, mainly through the membrane electrode assembly including the gas diffusion layer. They concluded that the liquid water saturation was lower at higher cell temperatures mainly due to greater water evaporation and increased heat pipe effect. They also examined the role of thermal conductivity of the gas diffusion layer and observed that the two-phase region shrinks with decrease in thermal conductivity of the gas diffusion layer.

As discussed earlier, the effect of geometrical configuration of the bipolar plates such as the channel to rib width ratio on the liquid water saturation profiles and the corresponding phase change phenomena could provide useful insights about the heat pipe effect. To the authors' knowledge, this area has been given less attention, especially in the context of non-equilibrium phase change. Therefore, the objective of this study is to explore the effect of geometrical configuration on transport parameters with emphasis on phase change effects.

2. The mathematical model

The model geometry consists of a gas diffusion layer, a microporous layer and a catalyst layer as shown in Fig. 1. It should be noted that the gas channels are excluded from the current geometry to only focus on the transport phenomena within the porous layers. The liquid water transport within the PEMFC channels has been separately reported by the authors in [23]. The half-cell dimensions are listed in Table 1. The two-phase flow of liquid water/gaseous oxygen along with the heat transport is implemented using the methodology described below.