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A high dynamic PEM fuel cell model with temperature effects☆

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Abstract

Safe and reliable operation of a fuel cell requires proper management of the water and heat that are produced as by-products. Most of the current models for the cell used for an analysis of the fuel cell system are based on the empirical polarization curve and neglect the dynamic effects of water concentration, temperature and reactant distribution on the characteristics. The new model proposed in this paper is constructed upon the layers of a cell, taking into account the following factors: (1) dynamics in temperature gradient across the fuel cell; (2) dynamics in water concentration redistribution in the membrane; (3) dynamics in proton concentration in the cathode catalyst layer; (4) dynamics in reactant concentration redistribution in the cathode GDL. Simulations have been performed to analyze the effects of load currents on the behaviors of the fuel cell. In the future, the fuel cell model will be extended to a stack model and integrated with system models. All of the models will be implemented on a real time system that optimizes the computation time by a parallelization of solvers, which provides an environment to analyze the performance and optimize design parameters of the PEM fuel cell system and components.

Keywords: PEMFC; Dynamic; Temperature; Water; Efficiency; Startup

1. Introduction

The PEM fuel cell is a strong candidate for use as an alternative power source in future vehicle and power conditioning applications. The effects of electric loads on temperature, water in the stack and reactants are crucial issues that must be considered for the optimum design of fuel cell powered systems. Currently, fuel cell stack models are being employed to analyze these effects. However, the simulation results do not incorporate either the dynamic or transient aspects of the fuel cell system in operating environments.

As a matter of fact, the dynamic power output and efficiency profile of a PEMFC is strongly influenced by the variation of the temperature, reactant and product transfer in the fuel cell caused by a current load.

Firstly, the temperature significantly affects the performance of a fuel cell by influencing the water removal and reactants activity, etc. A current proposed model assumes a constant working temperature [1], which does not incorporate the reality that this working temperature dynamically varies at different load currents, as well as during startup and shut-down of the fuel cell system. Some authors proposed improved models, with Amphlett et al. [2] using the first empirical thermal model, and Gurski et al. [3] considering the reactant flows and coolant control based upon the previous model. Others proposed models calculating the temperature variation of the stack, cell [4–10] or two electrodes and MEA [11,12]. B. Wetton et al. [13] proposed an explicit thermal model to analyze the temperature gradient of different layers in the fuel cell stack considering the stack asymmetric effects, which does not include dynamics. Recently, M. Sundaresan published the most detailed 1D thermal dynamic model [14]. However, the flow of species at the inlet must be the same as that at the outlet. Thus, no fluid dynamics is considered in the model.

Secondly, the proton transport in the membrane and its associated ohmic losses mainly determine the characteristics

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Nomenclature

Alphabets

a	species activity
A	area (m^2)
C	mass concentration ($kg\,m^{-3}$)
D	diffusion coefficient ($m^2\,s^{-1}$)
F	faraday number
G	gibbs free energy ($J\,mol^{-1}$)
H	enthalpy ($J\,mol^{-1}$)
i	current density ($A\,m^{-2}$)
j	exchange current density ($A\,m^{-2}$)
l	thickness (m)
m	mass (kg)
M	mole mass ($kg\,mol^{-1}$)
n_d	electro-osmotic drag coefficient
N	mole flux ($mol\,s^{-1}\,m^{-2}$)
P	pressure (partial pressure) (Pa)
R	universal gas constant
R_{mem}	proton transfer resistance (Ω)
R_{ab}	electrical resistance (Ω)
S	entropy ($J\,mol^{-1}\,K^{-1}$)
T	temperature (K)
W	mass flux ($kg\,s^{-1}\,m^{-2}$)

Greek symbols

ε	porosity
λ	water uptake coefficient
ρ	density ($kg\,m^{-3}$)
τ	tortuosity

Superscripts and subscripts

an	anode
ca	cathode
cv	control volume
d	gas diffusion layer
g	gas
i	index
l	liquid
mem	membrane layer
ref	reference value
sat	saturation
sou	source

of ohmic polarization. The proton conductivity has been regarded as constant, temperature dependent [1] or temperature and water concentration dependent variables [15]. Recently, Pukrushpan et al. [16] proposed the most comprehensive model that considers the dependence of the proton conductivity on the water concentration and temperature. However, the water concentration of the membrane is obtained from the membrane relative humidity (RH) on an average of the anode and cathode RH. In fact, the RH in the anode and cathode varies rapidly, while the RH in the membrane does slowly because the amount of water residing in both sides is relatively less than in the membrane [15].

Thirdly, the oxygen concentration in the GDL on the cathode side is continuously changing in operating environments and significantly affects the performance of the cell. Therefore, plenty of models considering multi-phase multi-species have been employed to investigate the transport phenomena in the GDL. However, those models do not consider the dynamics. Recently, Pukrushpan et al. proposed a dynamic model with lumped parameters to predict the gas dynamics in a cathode electrode, which does not consider the effects in the GDL [16]. In this paper, we use a 1D single-phase model to represent the dynamics present in the GDL.

2. Model setup and assumptions

The model has been developed on the basis of layers in a cell that consist of a MEA, two gas diffusion layers and two gas channels sandwiched by two coolant channels, as shown in Fig. 1. The input variables for the model are current load, mass flow rate, the gas components fraction, temperature, pressure and relative humidity of reactants as well as the temperature and velocity of coolants at the inlets.

The main assumptions made for the new model are as follows:

1. Reactants are ideal gases.
2. There is no pressure gradient between the anode and cathode side; it means no convection but only diffusion for gas transport is considered.
3. There is no gas pressure drop from the inlet to the outlet of the gas channel.
4. The temperature gradient is linear across the layers in a fuel cell.
5. The thermal conductivity for the materials in a fuel cell is constant.
6. There is no contact resistance.
7. Anodic over-potential is negligible.

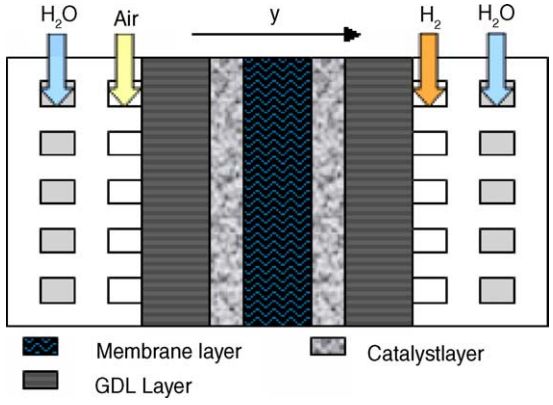

Fig. 1. Schematic simulation domain.