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Short communication

The dynamic and steady state behavior of a PEM fuel cell as an electric energy source

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Abstract

The main objective of this work is to extract information on the internal behavior of three small polymer electrolyte membrane fuel cells under static and dynamic load conditions. A computational model was developed using Scilab [SCILAB 4, Scilab—a free scientific software package, http://www.scilab.org/, INRIA, France, December, 2005] to simulate the static and dynamic performance [J.M. Correa, A.F. Farret, L.N. Canha, An analysis of the dynamic performance of proton exchange membrane fuel cells using an electrochemical model, in: 27th Annual Conference of IEEE Industrial Electronics Society, 2001, pp. 141–146] of this particular type of fuel cell. This dynamic model is based on electrochemical equations and takes into consideration most of the chemical and physical characteristics of the device in order to generate electric power. The model takes into consideration the operating, design parameters and physical material properties. The results show the internal losses and concentration effects behavior, which are of interest for power engineers and researchers.

Keywords: Alternative energy; Dynamic studies; Proton exchange; Polymer electrolyte; Steady state; Scilab

1. Introduction

In the last decade, a group of researchers [5,6] published a series of papers on electrochemical problems relating to PEM fuel cells, from modeling to the problems of poisoning of the cell, their work aimed at the need for a model based on electrochemical equations to correctly model this new electrical power source. Almost 10 years later another group of researchers has focused on electrochemical reaction modeling [4], but like previous publications, their model is based on the assembling of a prototype fuel cell and laboratory experiments.

More recent work by Souza and Gonzales [15] has presented a mathematical model for the PEM Fuel Cell, and their modeling has allowed detailed studies. They discussed the electrocatalysis of the reactions and the design of water-management schemes to cope with membrane dehydration. Mishra, Yang and Pitchumani [18], did a detailed numerical investigation of the transport and electrochemical phenomena involved in the operation of a single proton exchange membrane (PEM) fuel cell with reformate feeding with a view to developing optimal design and operating conditions.

Along with a large number of methodologies, Cheddie and Munroe [16] did a review of recent literature on proton exchange membrane fuel cell modeling, and they have categorized them as analytical, semi-empirical or mechanistic. Mechanistic modeling has received the most attention in the literature. In mechanistic modeling, differential and algebraic equations are derived based on the physics and electrochemistry governing the phenomena internal to the cell.

Mehta and Cooper [17] did an extensive review and analysis of PEM fuel cell designs and manufacturing. Their work had an important influence on the work we present here, Goveli-oglu and Stenger [19] developed research on computational fluid dynamics modeling of PEM fuel cells. They used a finite element method to solve the transport model coupled with flowing

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Nomenclature

A	anode (or cathode) area/cell useful area (cm^2)
$c^*_{H_2}$	hydrogen concentration in the interface electrode membrane ($mol\,cm^{-3}$)
$C_{ion,m}$	membrane ionic concentration ($mol\,cm^{-3}$)
E^0	open circuit voltage (V)
F	Faraday constant ($96487\,C\,mol^{-1}$)
ΔFE_a	anode reaction activation energy ($J\,mol^{-1}$)
ΔFE_c	cathode reaction activation energy ($J\,mol^{-1}$)
ΔG	Gibbs free energy variation (−237.165 J)
ΔH	variation of enthalpy (−285.823 J)
i_{op}	operational cell current
i_L	electrode current limit
$i_{L,a}$	electrode current limit in the anode
$i_{L,c}$	electrode current limit in the cathode
I_{op}	operational electrical current (A)
j_{op}	cell operation current density ($A\,cm^{-2}$)
j_0	exchange current density in the electrode ($A\,cm^{-2}$)
k^0	reaction degree intrinsic constant ($cm\,s^{-1}$)
l	membrane thickness (cm)
m_{air}	mass flow of air (dimensionless)
m_{H_2}	mass flow of hydrogen (dimensionless)
m_{O_2}	mass flow of oxygen (dimensionless)
n	number of moles involved in a reaction for each mol of H_2 (dimensionless)
n_a	number of moles of reagent in the anode
n_c	number of moles of reagent in the cathode
P_{H_2}	partial pressure feeding for hydrogen (atm)
P_{O_2}	partial pressure feeding for oxygen (atm)
R	universal constant of gases ($8314\,J\,K\,mol^{-1}$)
R_{cj}	resistance of gas spreaders and separating plates (Ω)
R_m	resistance of the electrodes (Ω)
ΔS	variation of entropy ($-163.2\,J\,K^{-1}$)
T_{op}	operational temperature (K)
T_{ref}	reference temperature ($298.15\,K^{-1}$)
V_{atv}	activation voltage drop (V)
V_{con}	concentration voltage drop (V)
V_{ohm}	Ohmic voltage drop (V)
V_{op}	operational voltage (V)

Greek letters

α	electronic transference current (around 0.4 for the cathode and 1.0 for the anode)
α_c	cathode load transference coefficient (dimensionless)
α_a	anode load transference coefficient (dimensionless)
γ	membrane ionic conductance ($S\,cm^2\,mol^{-1}$)
δ_c	cathode Nernst diffusion layer thickness (cm)
δ_a	anode Nernst diffusion layer thickness (cm)
λ_{air}	stoichiometry of air (dimensionless)
λ_{H_2}	stoichiometry of hydrogen (dimensionless)
λ_{O_2}	stoichiometry of oxygen (dimensionless)
ρ_m	electrical resistivity of the membrane (Ω cm)
ϕ_{H_2}	relative humidity of hydrogen (%)
ϕ_{O_2}	relative humidity of oxygen (%)

in a porous medium, charge balance, electrochemical kinetics, and a rigorous water balance in the membrane.

These papers have contributed greatly to comprehension of the global electrochemical processes in a fuel cell, but did not improve understanding of the fuel cell as an electrical energy source, and that is our proposal in this work, i.e. to make a model [1] suitable for use with power electronics hardware.

The basic physical structure of a fuel cell used in the computer model consists of an electrolyte and a polymeric membrane, with a typical thickness of between 12 and 210 μm, which separates the porous anode and cathode from each other; they have a thickness of between 5 and 15 μm. The porous and slender electrodes, make it possible to assemble a membrane electrode assembly (MEA). In a typical fuel cell, a flux of fuel which is rich in hydrogen (liquid or gaseous) is fed continuously through channels that keep it in contact with the anode and, simultaneously, a flux of an oxidant (in general the oxygen in the air) are also fed through different and separate channels, which make the contact with the cathode [2]. The layers in between are responsible for the gas diffusion process in the electrodes, with a thickness between 300 and 400 μm, they are made of an electrical conducting material, like porous carbon paper, a carbon based fabric with a Teflon® layer that prevents water adherence and make possible the fast diffusion of gases [3].

The process that takes place is a natural reaction, however due to its slow speed it is necessary to use a catalyst for the reaction to be efficient, the element used as catalyst at the present is platinum. The other two important elements in the fuel cell are, firstly the separating plates, to give mechanical stiffness and to direct the flow of gas through the cell, and secondly the cooling elements that have the function of extracting heat from the exothermal reactions, the ratio used for interspersing the cooling elements are used in a proportion that varies from 1:1 to 1:5 [5].

2. Mathematical modeling of the PEM fuel cell

A mathematical model that presents the correct answers for the fuel cell is of paramount importance, since it allows the development of electronic systems for feeding and control of fuel cells without the need for a great number of experimental prototypes. Electrically speaking, a fuel cell works basically as a current source. The voltage response for the cell will be studied from the current variation required by the load. The main operational parameters are: the operational electrical current, temperature, and the characteristics of gas transportation.