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Water and pressure effects on a single PEM fuel cell

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Abstract

A fuel cell is a promising energy conversion system that will eventually become the first-choice for producing power because of its clean or zero-emission nature. A steady-state, two-dimensional mathematical model with pressure and phase change effects for a single PEM fuel cell was developed to illustrate the inlet humidification and pressure effects on proton exchange membrane (PEM) fuel cell performance. This model considers the transport of species along the channel as well as water transfer through the membrane. It can be used to predict trends of the following parameters along the fuel cell channels: mole number of liquid water and water vapor, pressure, temperature, density, viscosity, velocity, saturation pressure, pressure drop, vapor mole fraction, volume flow rate, required pumping power and current density.

Keywords: PEM fuel cell; Water and thermal management; Mathematical model; Humidification; Pressure drop

1. Introduction

Proton exchange membrane (PEM) fuel cells, using hydrogen as fuel, emitting water and operating at low temperature for quick startup, have been widely recognized as the most promising candidates for replacing the internal combustion engine in automobiles, and for replacing batteries in portable and micro applications. In recent years, research and development on fuel cells have accelerated and the PEM fuel cell technology has been successfully demonstrated. But many key challenges affecting PEM fuel cell performance still exist, and much more efforts on improving the performance of PEM fuel cell become even more crucial than ever before. Useful mathematical models can provide powerful tools for the analysis and optimization of fuel cell performance.

Costamagna and Srinivasan [1] gave a very good review regarding fuel cell science and technology up to the year 2000. Another recent review made by Yao et al. [2] presented both empirical performance models and theoretical models. In the early 1990s, the pioneering work on PEM fuel cell model development was done by Bernardi and Verbrugge [3,4], and Springer et al. [5] who formulated one-dimensional and isothermal models for the gas-diffusion layer, active catalyst layer and ion-exchange membrane. Only the direction perpendicular to the membrane was considered. The model employed water diffusion coefficient, electro-osmotic drag coefficients and membrane conductivities to predict the change of membrane resistance with current density. The temperature was assumed to be constant and these models were unable to simulate the flow behavior along the channels.

Compared with one-dimensional model, a two-dimensional mathematical model is preferred for water and heat management analysis, as the temperature, pressure and water varies along the channel as well as across the membrane. Fuller and Newman [6] developed a non-isothermal model by including material balances in the channel, concentration and temperature gradients along the channel as well as across the membrane surface. In the model developed by Nguyen and White [7], the focus was on the transport and reaction in the MEA and heat balances in the gas channels. Subsequently, an improved model was developed by Yi and Nguyen [8] to compare different fuel

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Nomenclature

a	water vapor activity in stream
A_{cross}	the cross-section area of channel (cm^2)
A_{stack}	the heat transfer area in a control volume (cm^2)
c_{MW}	concentration of water at interface of the membrane ($mol\,cm^{-3}$)
$C_{p,i}$	heat capacity of species i ($J\,mol^{-1}\,k^{-1}$)
d	channel height (cm)
D	hydraulic diameter of channel (cm)
D°	a parameter used in the expression for diffusion coefficient of water ($cm^2\,s^{-1}$)
D_{MW}	diffusion coefficient of water ($cm^2\,s^{-1}$)
$f(x)$	friction factor
F	Faraday constant, 96487 C equivalent^{-1}
h	channel width (cm)
I	current (A)
$I(x)$	current density ($A\,cm^{-2}$)
I°	exchange current density for the oxygen reaction ($A\,cm^{-2}$)
k_c	condensation rate constant (s^{-1})
k_p	hydraulic permeability of water in the membrane (cm^2)
L	length of channel (cm)
M_i	molecular weight of species i ($g\,mol^{-1}$)
$M_{m,dry}$	equivalent weight of a dry membrane ($g\,mol^{-1}$)
n_d	electro-osmotic drag coefficient
n_e	the mole number of electrons needed per second for 1 A of current ($mol\,s^{-1}\,A^{-1}$)
N	mole number of species in the stream ($mol\,s^{-1}$)
NE	number of electrons ($A^{-1}\,s^{-1}$)
N_{ch}	number of channel (s)
p	local pressure (Pa)
p_i	partial pressure of species i (Pa)
dp	pressure drop (Pa)
P_{pump}	pumping power (W)
Q	volume flowrate ($m^3\,s^{-1}$)
Re	Reynolds number
R_u	universal ideal gas constant ($8.3144\,J\,mol^{-1}\,K^{-1}$)
RH	relative humidity
T	temperature of stream (K)
T_s	temperature of stack (K)
U	overall heat-transfer coefficient ($J\,s^{-1}\,cm^{-2}\,^{\circ}C^{-1}$)
V	flow velocity ($m\,s^{-1}$)
V_{cell}	cell voltage (V)
x	direction along the channel length
y	direction normal to the channel length

Greek letters

α	excess coefficient
α_{area}	reaction area coefficient
β_{O_2}	mole fraction of oxygen in air (20.9%)
β_{H_2}	mole fraction of hydrogen
η	overpotential for the oxygen reaction (V)
μ	dynamic viscosity ($N\,s\,m^{-2}$)
ρ	density ($kg\,m^{-3}$)
$\rho_{m,dry}$	density of a dry membrane ($g\,cm^{-3}$)
ϕ	water content in stream
σ_m	membrane conductivity ($\Omega^{-1}\,cm^{-1}$)

Subscripts

1A	per ampere
air	dry air
avg	average
A	anode
C	cathode
cell	single fuel cell
concentration	concentration of species in the streams
drag	electro-osmotic drag
e	electron
H_2	hydrogen
H_2O	produced water
in	inlet of channel
MW	water in membrane
N_2	nitrogen
O_2	oxygen
oc	open circuit
pressure	partial pressure in streams
pump	pump
s	stack
sat	saturation
vapor	water vapor
liquid	liquid water
water	all water including vapor and liquid
#	cathode or anode

cell designs with coflow and counterflow heat exchangers. A number of researchers have been conducting fuel cell modeling for many years and made very impressive progress on single cell modeling [9–15]. These models emphasized important characteristics of the membrane and electrode as well as a detailed description of the water content in the membrane. To the authors' knowledge, most of those models assume that there is no temperature and pressure drop along the channel. Most results reported were at high and constant stack temperature (e.g. 90–100 °C), high and constant pressure (e.g. 3 atm) and without considering phase-change effects. But in practical engineering, the PEM fuel cell is usually operated at varying low temperature (e.g. 65–75 °C) and varying low pressure (e.g. about 1.3 atm for 1 kW portable applications), with water phase-change inside the fuel cell flow channels.

In order to meet these challenges, in the present study, a steady-state, two-dimensional mathematical model with pressure effects, water phase-change effects and detailed