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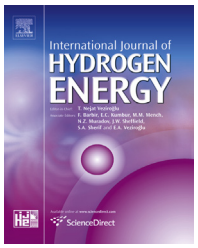

Influence of transient operating parameters on the mechanical behavior of fuel cells

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ABSTRACT

Transient operating parameters of polymer electrolyte membrane fuel (PEM) cells significantly influence their performance and durability by affecting the water content of the membrane. Towards understanding the factors contributing to mechanical degradation, this paper presents numerical simulations on the effects of operating conditions on the stress and strain induced in the membrane constrained by bipolar plates and subjected to changing humidity levels. The fuel cell is subjected to dynamic changes in load to capture the water content values in the membrane using detailed three-dimensional (3D) computational fluid dynamics simulations. Using the information from the three-dimensional simulations, two-dimensional (2D) finite element (FE) analysis is used to predict the mechanical response of the membrane at various planar sections for hygral (water) loading and unloading cycles. The effects of operating parameters (anode and cathode pressure, stoichiometry and relative humidity at cathode inlet) on evolution of stresses and plastic deformations in the membrane are analyzed for cyclic changes in operating load.

Introduction

Polymer electrolyte membrane (PEM) fuel cells are attractive options as energy source for mobile and stationary applications. Faster transient response and low-temperature operation, makes PEM fuel cells a better power source alternative for automotive applications compared to other types of fuel cells. Improving the durability of membranes such as to meet the operational life of 5000 h (150,000 miles equivalent) is one of the vital considerations for fuel cells to become a more viable option as power source in automotive applications [1–4].

A PEM fuel cell is composed of membrane electrode assembly (MEA), sandwiched between porous gas diffusion layers (GDL) on either side. Humidified stream of hydrogen (H_2) and oxygen (O_2) or air are transported, through anode and cathode flow channels, respectively. The reactants flow through the gas diffusion layers to react at the catalyst layers of the MEA. Water is produced at the cathode catalyst layer as result of combination of hydrogen cations, oxygen and electrons. The performance of a fuel cell is critically related to the membrane hydration as it affects the proton conductivity through membrane—a greater water content (number of water molecules per sulfonic acid group) in the membrane ensures higher conductivity. The chemical and mechanical

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Nomenclature

A	superficial electrode area, m^2
C_k	molar concentration of species, mol/m^3
D	mass diffusivity of species, m^2/s
E_{cell}	cell potential or voltage, V
EW	equivalent weight of dry membrane, kg/mol
F	Faraday constant, 96,487 C/equivalent
j	transfer current, A/m^3
K	permeability, m^2
n_d	electro-osmotic drag coefficient, H_2O/H^+
p	pressure, bar
R	gas constant, 8.314 J/mol K
RH	relative humidity
S	source term in transport equations
T	temperature, K
$\vec{u}$	velocity vector
v	displacement

Greek letters

α	transfer coefficient
ε	porosity; strain
η	surface overpotential, V
λ	membrane water content; proportionality scalar
μ	viscosity, kg/m s
ρ	density, kg/m^3
σ	electronic conductivity, S/m; stress
τ	shear stress, N/m^2; time constant; tortuosity
φ	phase potential, V

Superscripts and subscripts

a	anode
c	cathode
$cell$	single fuel cell
e	electrolyte
el	elastic
eff	effective value
eq	equivalent
g	gas phase
in	inlet
k	species
m	membrane phase
max	maximum
0	t = 0 s, initial state
pl	plastic
ref	reference value
s	electronic phase
S	swelling
sat	saturated value
SS	steady state
t	time > 0 s
w	water

degradation processes significantly affect the life and performance of fuel cell over the period of operation. Catalyst layer and membrane poisoning owing to the impurities in the feed, loss of effective activation area due to agglomeration and migration of platinum, corrosion of electrodes and flooding of electrodes are the most common mechanisms responsible for electrochemical degradation of the fuel cells. On the other hand, mechanical degradation is caused by mechanical stresses due to swelling and shrinking of membranes, uneven compression of the layers by bipolar plates, thermal stresses and hotspots, and shocks and vibrations during the operation [5–7]. Mechanical stresses arise as membrane swells (hydrates) or shrinks (dehydrates) as a function of moisture content during the transient process, requiring careful examination. These stresses may exceed the yield-limit causing the membrane to deform plastically, which, in turn, induces residual stresses, causes opening and propagation of cracks, and formation of pin-holes in the membrane or delamination between the membrane and the GDL, causing degradation [5–13]. The operating conditions play an important role in determining the membrane water content for given external load changes thus affecting the performance and durability of fuel cells.

Numerical studies have been carried out by several researchers focusing on the degradation mechanisms and mechanical behavior. One of the first numerical studies incorporating the effects of mechanical stresses on fuel cell was performed by Weber and Newman [10]. The model presented a one-dimensional analysis of a fuel cell and did not incorporate the property changes across layers of the fuel cell. Tang et al. [11] investigated the effects of stresses induced by swelling and thermal expansion on a uniformly hydrated membrane for different clamping methods, and suggested that the contribution by in-plane stresses are more significant than others. Kusoglu et al. [12,13] incorporated plastic deformation and anisotropy to demonstrate the residual stresses induced as the membrane is cycled through various uniformly distributed humidity loads. The above approaches [11–13] have been limited to either using uniform membrane hydration or simplistic water content profiles that do not take in to account the complex water distribution across length and thickness for realistic load changes. Kusoglu et al. [14] later incorporated the effects of non-uniform distribution of water in membrane, by specifying the water volume fraction at the membrane boundaries and solving for diffusion of water across the membrane. Kleeman et al. [15] characterized the local compression distributions in GDL and the associated effect on electrical material resistance. Zhou et al. [16] analyzed the effects of assembly pressure and operating temperature and humidity on PEM fuel cell stack deformation, contact resistance, overall performance and current distribution. Serincan and Pasaogullari [17] studied the effects of humidity, and operating voltage on the mechanical stresses induced due to thermal and hygral loading, suggesting that thermal stresses are typically a fraction of the hygral stresses in a typical PEMFC operation. Taymaz and Benli [18] studied the effect of assembly pressure on the performance of PEM fuel cells. Wang et al. [19] conducted endurance experiments to emphasize the impact of in-cell water management techniques on the degradation. In our previous study [20], we have presented a model to predict the mechanical stresses induced in membrane due change in loads for specified inlet humidification value of cathode feed for two different sections along the length of fuel cell.