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Thermo-electrochemical and thermal stress analysis for an anode-supported SOFC cell

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ABSTRACT

The main objective of this paper is to evaluate the fuel/oxidant gas distributions as well as thermal stresses of an anode-supported solid oxide fuel cell (SOFC) test cell under different operating conditions. In this study, the commercial computational fluid dynamics (CFD) code Star-CD with es-sofc module is employed to simulate the current–voltage (*I–V*) characteristics and to provide the temperature field of the cell to the commercial code MARC for further thermal stress analysis. Structural and fluid elements are built by preprocessing codes PATRAN and GRIDGEN, respectively. The simulation results indicate that the cells experience higher principal stresses at lower cell voltages due to a higher local current density and a higher temperature gradient.

1. Introduction

A solid oxide fuel cell (SOFC) is a device that converts chemical energy into electric power through electrochemical reactions at elevated temperatures. The SOFCs operating at high temperatures have many advantages, such as preserving higher oxide-ionic conductivity and kinetic activity, utilizing carbon monoxide as fuels rather than poison, and recovering of the exhausted heat. Meanwhile, they also involve some problematic issues to be resolved, such as, high-temperature gradient, high degradation rates, and substantial thermo-stresses at interfaces because of mismatch of the thermal expansion coefficients between components, etc.

Many experimental and numerical simulation techniques have been developed to analyze the SOFC cell performance [1–8]. Of which, computational fluid dynamics simulation codes, such as FLUENT, CFD-RC and Star-CD, are widely used to evaluate the cell performance at different conditions, such as, high oxygen utilization rates, low R_{MIX} ratios (methane-to-oxygen ratio), and different compositions of fuel, etc. Autissier et al. [9] provided subroutines to the commercial software, FLUENT, to calculate reaction rates, and distributions of current density, gas flow, temperature and fuel concentration in cells. In their study, electrochemical behavior was experimentally fitted on small cells and then applied to complex geometries. Recknagle et al. [10] used Star-CD to investigate the effects of different cell flow patterns, including co-flow, cross-flow and counter-flow. With similar fuel utilizations and average cell temperatures, they concluded that the co-flow design would have a smaller temperature gradient. Through a simplified electrochemical model, Yakabe et al. [11] adopted a commercial computational fluid dynamics tool, Star-CD, to calculate the fuel concentrations, temperature and current density distributions. Its thermal stress distribution was then evaluated by the commercial code ABAQUS. The results showed a co-flow pattern is advantageous to mitigate the temperature differences and hence it has lower internal stresses. In Yakabe and Sakurai's model [12], the electromotive force counterbalance with the oxygen ions was used to calculate the electric current flow in the cell channel. The effects of variations of channel to rib width ratios were investigated. It was found that, attributed to a smaller contact area between interconnect and electrode, the current density and contact resistance at the interfaces increased for a higher channel to rib width ratio. Selimovic et al. [13] utilized an in-house tool to assess the electrochemical and thermal performance of a bipolar planar cell; the input temperature profiles were generated by the finite element analysis (FEA) commercial code, FEMLAB to calculate thermal stresses. Lin et al. [14] analyzed the thermal stress distribution of a multiple-cell SOFC stack at different stages, where the temperature profiles were provided by an integrated thermo-electrochemical approach [15].

In this study, simulation of the *I–V* characteristics versus the experimental data from the cell performance tests is carried out. A 3D numerical model is set up to analyze an anode-supported cell. Effects of different operating voltages, temperature gradients and different thermal expansion coefficients between components are evaluated.

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Nomenclature

A_i	pre-exponential factor
c_p	constant-pressure specific heat
$\bar{c}$	mean constant-volume specific heat
d	thickness
D	mass diffusivity (m^2/s)
$[D]$	elasticity matrix
E	Young's modulus
E_{act}	activation energy
F	Faraday constant, 96487 (C/mol)
F_h	diffusional energy flux
F_m	diffusional flux
h	static enthalpy
H	heat of formation
i	current density (A/m^2)
i_0	exchange current density (A/m^2)
k	electrochemical reaction rate constant
$[k]$	stiffness matrix
M	molecular weight (g)
P	pressure (Pa)
R	universal gas constant (8.314 J/(mol K))
R_i	resistance
R_m	the rate of mass production or consumption
T	temperature
V	operating voltage (V)
$\dot{V}$	gas flow rate (ml/min)
Y	mass fraction

Greek symbols

ρ	density (kg/cm^3)
τ	stress tensor
$[\sigma]$	stress vector
$[\varepsilon]$	strain vector
ε	porosity

Subscripts

a	anode
c	cathode
H_2	hydrogen
O_2	oxygen
eff	effective
m	mth composition of fuel reactant

2. Experimental

A single-cell test station to investigate the electrochemical characteristics of a planar type SOFC cell has been set up at the Institute of Nuclear Energy Research (INER), Taiwan. The schematic diagram of the cell test station is shown in Fig. 1. The test station consists of a gas manifold system, an electronic load module and a single-cell test housing enclosed in a furnace. Hydrogen fuel gas is humidified and supplied to the anode compartment, and oxygen gas or air is directed to the cathode side as the oxidant gas. A circular cell with a diameter of 5 cm is settled between anode and cathode sides.

The oxidant and hydrogen gases are separately flowed into the center of the cell electrodes and radically distributed across the cell surfaces. Effective electrode area of test cell is about 20 cm^2. The anode is gradually reduced in situ during the heating-up process with a heating rate of 1 °C/min and a fuel gas composition of 10%H_2/90%N_2. As the temperature reaches the preset point, the H_2 concentration is then gradually increased to 100% at a step of 10% per 30 min. The cell performance test is carried out at different fuel compositions and flow rates.

Fig. 2 illustrates the *I–V* and *I–P* curves for the SOFC test cell operating at 800 °C with gas flow rates of 300 and 500 ml/min, respectively. It indicates that in the high cell voltage region, only slight difference of current density is observed for two different gas flow rates and the difference increases as cell voltage decreases. For a gas flow rate of 500 ml/min, the peak power density is 610 mW/cm^2, which is about 15% higher than that of 300 ml/min condition. These test data of *I–V* curves are used to validate the Star-CD simulation.

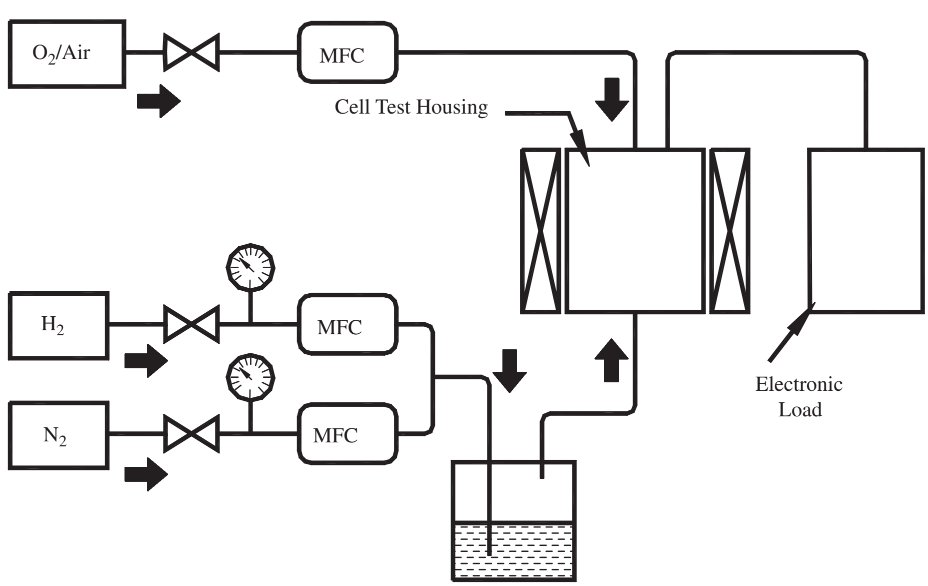

Fig. 1. Schematic diagram of the test cell station.