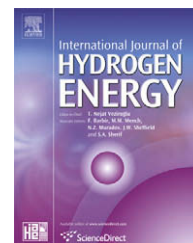


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Numerical analysis of start-up operation of a tubular solid oxide fuel cell

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ABSTRACT

The purpose of the current study is to numerically predict the start up behavior of a tubular solid oxide fuel cell (SOFC) using a 2-D transient model. The developed model provides the transient response of the start-up mode as well as the steady state operation of the SOFC. A code based on finite volume method is utilized to solve the transient nonlinear transport equations of the cell (momentum, species and energy equations). To account for the Ohmic losses and Joule heating of the current that passes through the cell body, a discretized network circuit is adopted. The local electrochemical parameters are calculated based on the local pressure, temperature, and concentrations of the species. At each time step an iterative procedure is used to solve the electrochemical, electrical and transport equations simultaneously. The model predicts the cell output voltage, the local EMF and the state variables (pressure, temperature and species concentration) during the start up. It also predicts the cell heat-up rate for hot input gases as well as the start up time of the SOFC. The results show that the gases mass flow rate and temperature affect the heat-up rate. Also during the start-up, the cell electrical response is about 2.5 times quicker than the cell temperature response. The start-up time for the cell output voltage is about 50 min.

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1. Introduction

Current Solid Oxide Fuel Cell (SOFC) technology demonstrates viable manufacture, feasible power generation and wide application ranges. This has been accompanied by development of new cell and stack designs, advanced and cost effective processing methods and novel materials. SOFC employs a solid-state electrolyte (usually yttrium-stabilized zirconium (YSZ)) and works at a high temperature, in the range of 700–1000 °C (depending on cell material technology) to reach the required high electrolyte ionic conductivity [1]. Considerable amounts of research work have been conducted to SOFC, making the SOFC close to the stationary or portable commercial applications [2–4]. One of the main SOFC application challenges is its relatively

slow response to the input parameters. In addition, the rapid start-up of SOFC is difficult due to its high operating temperature and intense dependency of electrical and electrochemical parameters on the temperature [5]. Various studies with different levels of sophistication and approximation on transient modeling of the SOFCs have been published [6–12]. Achenbach [6,7] analyzed the dynamic operation of a planar solid oxide fuel cell. He examined the transient cell voltage performance due to temperature and current density changes with lumped assumption for the cell temperature distribution. Hall and Colclaser [8] also developed a thermodynamic model for prediction of transient operation of the Tubular SOFC. Sedghisigarchi and Feliachi [9] combined heat transfer dynamics and species dynamics to form a new dynamic model. Also Xue

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Nomenclature			
A	Surface area (m ²)	v	Radial velocity (m s ⁻¹)
C_p	Specific heat capacity (J kg ⁻¹ K ⁻¹)	V	Voltage (volt)
$D_{j,m}$	Diffusion coefficient of jth species into the left gases of a mixture (m ² s ⁻¹)	X_j	jth species mol fraction
E	Cell ideal voltage (volt)	Y_j	jth species mass fraction
E_a	Activation energy of anode (J mol ⁻¹)	<i>Greek symbols</i>	
E_c	Activation energy of cathode (J mol ⁻¹)	η	Electrical losses (volt)
F	Faraday's constant (C mol ⁻¹)	δ	Thickness of layers (anode, cathode and electrolyte) (m)
G	Gibbs function (J kg ⁻¹)	ρ_p	Electrodes and electrolyte electrical resistivity in node p (Ω m)
G^0	Standard Gibbs function (J kg ⁻¹)	θ	Cell peripheral angel (rad)
T	Temperature (K)	ρ	Density (kg m ⁻³)
I	Current (A)	μ	Viscosity (pa s)
i	Current density (A m ⁻²)	λ	Thermal conductivity (W m ⁻¹ K ⁻¹)
k	Pre-exponential factor (A m ⁻²)	ΔH	Hydrogen heat value (J mol ⁻¹)
\dot{m}	Mass flux (kg m ⁻² s ⁻¹)	\Re	Universal gas constant (J mol ⁻¹ K ⁻¹)
M	Molecular mass (g mol ⁻¹)	ΔV	Volume of an element in the electrodes or electrolyte (m ³)
n_e	Number of electrons participating in electrochemical reaction	<i>Subscripts</i>	
P	Pressure (pa)	a	Anode
\dot{Q}	Volumetric heat source (W m ⁻³)	c	Cathode
\dot{q}	heat source (W)	e	Electrolyte
r	Radius (m)	act	Related to Activation loss
R	Electrical resistance (Ω)	p	Node p in the network circuit
U	Utilization percentage (0–1)	Ω	Related to Ohmic loss
u	Axial velocity (m s ⁻¹)		

et al. [10], considered a one-dimensional transient model for heat and mass transfer simulation assuming an electrical circuit include the Ohmic resistances and capacitors for the energy storage mode of operation. Iora et al. [11] considered the internal reforming/shifting reactions in fuel channel in their study.

Following the last studies on the cell dynamic modeling, Qi et al. [12,13] developed a quasi 2-D transient model of a tubular SOFC using the control volume (CV) approach. In their model, the cell length is divided to several serial segments. Each segments included five control volumes: air tube, air channels, cell body (electrolyte and electrodes) and fuel channel. The study obtained a non-linear set of differential equations for the heat and mass transfer as well as the electrical and electrochemical variables and calculated the cell time response with respect to the load change. None of the developed models has considered the cell second dimension effects (r -direction) on the dynamic operation of the tubular SOFC.

To date as important as it is, very limited studies of SOFC start-up operation have been conducted [14]. Apfel et al. [15] analyzed the start-up behavior of a 5 kW planar SOFC stack in a cycle with the reformer, heat exchanger and catalytic burner components. They investigated different system thermal management strategies for the start-up and shut-down periods with parameters: heat-up energy consumption, cell start-up time, material thermal shock and the cell temperature gradients. They concentrated on the cell heat-up and shut-down process. However, the cell internal interchanges after the electrical load connection was not analyzed. In another study, Lin et al. [16] simulated a GT-SOFC system start-up by an overall thermodynamic model for the stack and

system components. They predicted the system start-up time of 1.3 h (up to 200 kW nominal powers for the SOFC and 50 kW for the Gas turbine). They showed that the most important factor that affects the system start-up time is the response of the SOFC stack temperature. In their model, mainly the overall system start-up was studied and the stack was simulated by a simple thermodynamic model, as a system component.

The purpose of the current study is to predict the detailed start up behavior of a tubular SOFC using a 2-D transient numerical model. The goal is to numerically investigate the different start up processes up to the cell nominal power. During the start up, the cell load current is constant while the output voltage varies with time.

2. The cold start-up process of the SOFCs

Fig. 1 depicts the flowchart of the solid oxide fuel cells start up process. Initially, the cell is assumed to be at the ambient temperature. Then, the cell is heated up to a minimum operating temperature (600–900 °C). Based on the cell design and the materials used, the SOFC stack can operate within a distinct temperature range in which the upper limit is given by the material properties and the lower limit by the ionic conductivity of the electrolyte.

The cell heat-up is usually done by an external heat source (i.e., furnace, the hot input gases, etc.). The following issues during the heat-up must be considered [5]:

- Temperature increasing rate and thermal shock
- Temperature gradient in the cell

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