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Thermal conditions and heat transfer characteristics of high-temperature solid oxide fuel cells investigated by three-dimensional numerical simulations

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ABSTRACT

Elucidating internal thermal conditions of high-temperature solid oxide fuel cell (SOFC) stacks is essential for obtaining a substantial thermal efficiency and reliability for long-term operations prior to their commercialization. To examine simultaneous heat transfer and its generation and their effect on the local thermodynamic state, a high-fidelity physical model that resolves spatially the three-dimensional structure of planar, anode-supported SOFC stacks is used in this study. Results show that thermal conduction through metallic interconnects plays a key role in transferring the heat produced by joule heating and electrochemical reactions and thus determining the internal thermal conditions. The heat generated from the electrolyte and thin reactive electrode layers is transferred to the interconnect predominantly by gaseous convection and conduction through materials in the anode and cathode, respectively. The interconnect subsequently transports this heat conductively towards gas inlets and/or surrounding repeating units, influencing temperature increments, its profile and hot spot formation. Its effect on the internal thermal conditions was further examined by a parametric study with respect to the thermal property and geometry of the interconnect which determine its thermal resistance. They indeed affect significantly heat generation and its transfer within the cell, through its boundaries, between repeating units and to incoming gases.

1. Introduction

To facilitate commercialization of solid oxide fuel cell (SOFC) technologies, its stacks require effective thermal management providing a high thermal efficiency and reliability for long-term operations. Given its scalability, small footprints, and fuel flexibility [1–5], the deployment of SOFC into energy markets has been extensively investigated [6,7]. However, appreciable power losses during scale-up from unit-cells to their stacks and performance degradation during stack operations need to be minimized prior to commercialization. To tackle these issues, a number of factors have been accounted for [8], which includes chemical (i.e., materials incompatibility at their interfaces, impurity poisoning and sealing losses), thermal (i.e., local heating/cooling and heat transfer), and mechanical (i.e., crack formation/propagation and warpage) problems. Among them, the thermal management of SOFC stacks is critical because thermal conditions within the stacks affect temperature increments, its profile, and the formation of hot spots (attributed to local heating and exothermic reactions) or cold spots (driven by local cooling and endothermic reactions). This, in turn, influences electrochemical kinetics, temperature-dependent materials properties, external heat requirements for high-temperature operations, and thermal stresses. All of these determine the thermal efficiency and performance degradation of SOFC stacks [9,10], highlighting needs for effective thermal management by controlling their internal thermal conditions.

The thermal conditions in SOFC stacks can be characterized by heat transfer between/through solid and gas and simultaneous local heat generation. In comparison with batteries, SOFC is an open system which involves thermal interactions with an environment

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via reactive gases, as shown in Fig. 1. Heat transfer pathways in SOFC stacks include conduction through ceramic and metallic materials, gaseous convection inside the porous electrodes, and internal forced convection in gas-channels fabricated in-between the cell and interconnect. Its solid materials undergo heat transfer with gases carrying substantial enthalpy and flowing around cells and interconnects. High-temperature stack operations may require external thermal energy or cooling technique to maintain their operating temperature. In the meantime, heat is generated by joule heating upon charged-species transport through ionic and electronic conductors, irreversible heat dissipation due to activation polarization, and reversible heat generation attributed to the entropy of reactions. These thermal phenomena are interrelated taking place simultaneously, and the heat transfer rate is influenced by the amount of heat generated, and vice versa [11]. As a result, heat generation and its transfer towards gases and interconnects play an important role in determining the local thermodynamic state of SOFC stacks [9]. In this regard, they need to be elucidated by detailed analysis, which can be performed with an aid of multi-dimensional numerical simulations.

The thermal environment of SOFC stacks has been investigated by using multi-dimensional physical models. Xenos et al. proposed a quasi-three-dimensional model which enables transient thermal simulation of planar SOFCs [12]. They investigated internal temperature distribution when assuming various transient operations such as start-up, load change or change of gas inlet temperatures. Iwai et al. also developed a quasi-three-dimensional numerical model and argued that internal reforming taking place in the vicinity of fuel inlet reduces the local temperature, resulting in a highly non-uniform temperature field [13]. They discussed that heat losses through side walls produce non-uniformity of temperature as well. Amedi et al. formulated a three-dimensional physical model in order to approximate state variables during operations by employing advanced numerical technique [14]. They also compared the internal temperature fields observed from concurrent and countercurrent flows. The effect of flow-pattern (i.e., flow directions of air and fuel) on the temperature profile and its increment was also elucidated by Zhang et al., which shows that a co-flow arrangement results in the highest gas temperature [15]. Wei et al. estimated the local thermodynamic state such as species molar fractions, current density and temperature using their three-dimensional model and relate them to the distribution of principal stresses [16]. Hosseini et al. developed a three-dimensional model to investigate the effect of microstructure parameters such as porosity, pore size, and electrode-layer thickness on the temperature field and thermo-electrochemical reactions [17]. They discussed that the parameters affect gas and materials temperatures through reforming reactions. Andersson et al. examined how pre-reformed fuel compositions, especially methane concentration, influence the cell temperature using their three-dimensional model [18]. They also studied the effect of design parameters including gas-channel geometry and cathode support layer on the temperature of the cell and surrounding metallic interconnects, and argued that the cathode support layer plays a key role in reducing the cell temperature [19]. He et al. correlated their three-dimensional model to two-dimensional one to predict the cell temperature assuming local temperature equilibrium between gas and solid in porous electrodes [20]. Although these studies provided good insights into the temperature field developed along the SOFC, none of them investigated heat transfer characteristics or mechanism coupled with local heat generation and their relationship with the internal thermal conditions. Furthermore, key constituents of SOFC stacks other than the cell, such as metallic interconnect and current collecting materials were frequently neglected, and their influence on heat transfer was not elucidated in detail.

In this study, thermal conditions and heat transfer characteristics of SOFC stacks were elucidated by using a high-fidelity three-dimensional model. The numerical model resolves spatially the three-dimensional structure of a SOFC stack repeating unit which consists of a planar anode-supported SOFC, current collecting materials, and metallic interconnects. The physical model incorporates thermal energy transport assuming local thermal equilibrium between gas and solid phases in porous structures and using volume-averaged effective transport parameters. Assuming galvanostatic operations, heat generation and its transfer mechanism was discussed in order to elucidate the internal thermal conditions. Then, a parametric study with respect to key parameters determining thermal resistance such as the thermal conductivity and cross-sectional area of interconnects was conducted to examine their effect on heat transfer characteristics.

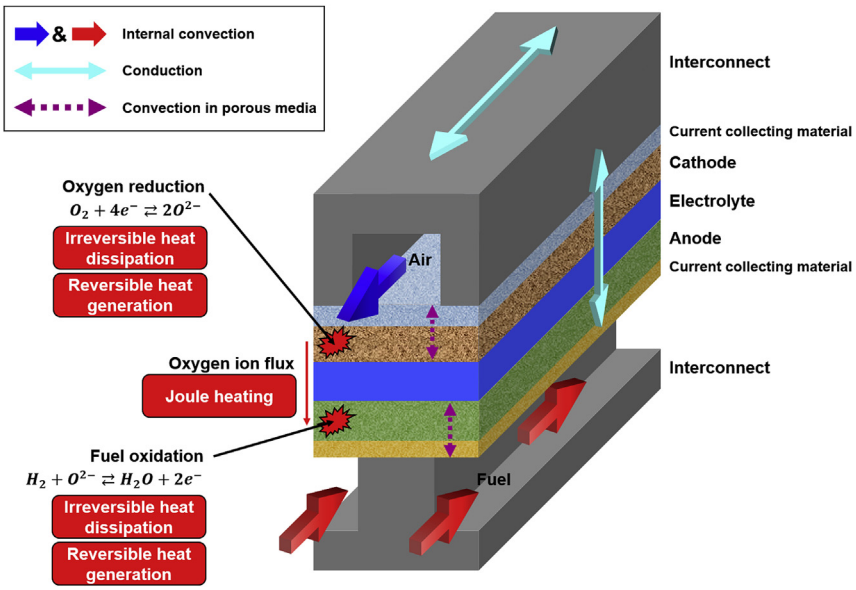

Fig. 1. Thermal conditions in SOFC stacks attributed to simultaneous heat transfer and its generation.

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