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Quasi-three-dimensional numerical simulation of a solid oxide fuel cell short stack: Effects of flow configurations including air-flow alternation

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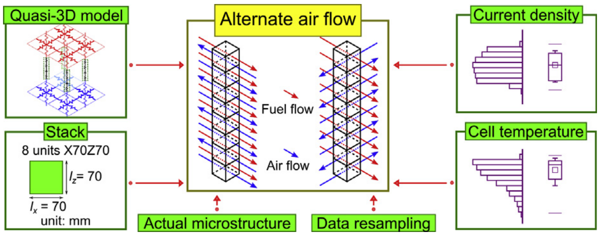
HIGHLIGHTS

- Effect of flow configurations in an SOFC short stack is numerically investigated.
- The distributions in the short stacks are discussed statistically.
- Alternating the air-flow direction helps to improve cell efficiency.
- Local fuel depletion can be avoided by suitable flow configuration design.

GRAPHICAL ABSTRACT



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ABSTRACT

The effects of flow configuration in solid oxide fuel cell (SOFC) stacks are investigated using a quasi-three-dimensional numerical model. Flow configurations with alternated air flows in parallel and perpendicular to the fuel flows are considered in addition to the conventional co-, counter-, and cross-flow configurations. The stacks have eight cells with unity aspect ratio and an active area of 4900 mm^2 and are compared at fuel utilization of 0.193, 0.386, 0.579, and 0.772. The numerical model is capable of analyzing both the streamwise and spanwise directions of the cells. Although the counter-flow stack achieves the highest voltage efficiency among the stacks with the conventional flow configurations, it has the highest dispersion of the current density distribution on the cells. Air-flow alternation is effective to achieve uniform and high cell temperature and hence low dispersion of the current density. Alternate air flows parallel to the fuel flows achieve the highest voltage efficiency of 0.797 at a fuel utilization of 0.772, while alternate air flows perpendicular to the fuel flows reduce the risk of local fuel depletion as compared with the cross-flow stacks. Appropriate selection of the air-flow configuration within stacks allows operation at higher efficiency without fuel depletion.

1. Introduction

A fuel cell is a device that harvests electrical energy from chemical energy within the supplied fuel through electrochemical reactions. Among the various types of fuel cells, the solid oxide fuel cell (SOFC) is one of the most outstanding types of fuel cells and has the highest electrical efficiency. SOFCs are operated at high temperatures of between 873 and 1273 K depending on the materials used for the electrolyte and electrodes. Basically, high operation temperatures are preferable for SOFCs to reduce the ohmic losses and activation overpotentials to achieve high cell efficiency. Conversely, a high operation temperature results in high thermal stress among the SOFC components owing to the difference in the thermal expansion coefficients among the cell components. A single repeating unit of an SOFC consists of porous electrodes, a dense solid electrolyte, flow channels, and separators. Such single repeating units can be stacked together to form an SOFC

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stack to provide the required electrical output. In such a case, the difficulty of thermal management of the SOFC stack is increased as the total heat released from the stack is multiplied.

The flow channels on the cathode side of an SOFC are responsible not only for supplying oxygen to the cell but also for removing excess heat that is generated from electrochemical reactions. Co-, counter-, and cross-flow configurations of the air flow relative to the fuel flow are among the conventional flow configurations for a planar SOFC or an SOFC stack. There have been extensive studies on the effect of these flow configurations at the cell level. These SOFC cells were supplied with either humidified hydrogen [1–3] or internally reformed methane [4–6]. All of these flow configurations have advantages and disadvantages. A counter-flow with a high average cell temperature is capable of maximizing the performance of a cell but has the major drawback of an inhomogeneous temperature distribution [4]. Furthermore, Nakajo et al. [7] reported that a counter-flow could extend the lifespan of a cell operated with a partially reformed methane fuel as compared with a co-flow. A cross-flow is preferred by SOFC manufacturers owing to the simplicity of the manifold design [8]. However, local fuel depletion during operation at high fuel utilization is more likely to occur under a cross-flow configuration than the other flow configurations [2]. Furthermore, Fardadi et al. [9] reported that cross-flow has the highest peak temperature and the largest temperature gradient, which can lead to high thermal fatigue and short lifespan of cell/stack as compared to the co- and counter-flow. A co-flow tends to have homogeneous distributions of current density [10] and cell temperature [11]. Therefore, the selection of the flow configuration for an SOFC cell and stack affects not only their performance but also their durability. There is still the possibility of constructing new flow configurations in a stack assembly. The alternation for both fuel- and air-flows within the ribs of each cell was proposed by Fardadi et al. [9] to overcome the high peak temperature and large temperature gradient in the cross-flow. However, such design required an extremely complex manifold design due to a large number of ribs per cell. Such complexity can be reduced by the alternation of the air flows in every other cell of a stack by either parallel (streamwise) or perpendicular (spanwise) direction to the fuel flow.

All the computational works by previous researchers had the common difficulty of the high computational cost of the fully three-dimensional (3D) models [12–14] used to analyze the cross-flow configurations. Therefore, works have been limited to the cell level. Some researchers strategically reduce the computational cost. For example, Yuan [15] developed a two-dimensional (2D) numerical model in the streamwise and spanwise directions of flows to solve electrochemical reaction, mass balance, and energy balance equations. The conservation of energy in interconnect was derived by considering the heat exchange between interconnect and working fluids as well as interconnect and neighboring cells. He et al. [16] implemented Monte Carlo simulation of a 2D spatially-smoothed non-isothermal model in a 3D planar SOFC stack to allow fast computation. The model is claimed to have the capability of solving a stack consists of hundreds of cells without a prohibitive computational cost. However, this 2D spatially-smoothed non-isothermal model is limited for the co- and counter-flow configurations. Lai et al. [11] proposed a quasi-two-dimensional model that is capable of analyzing an SOFC stack with up to 96 cells, although the model was limited to co- and counter-flows. The model was validated using that of Recknagle et al. [2] and was capable of reproducing the effect of the flow configuration (co- or counter-flow) under single-cell operation. However, no further work on the effect of the flow configuration was conducted for the stack operation. As a new approach to overcoming the difficulty associated with stack-level simulations, we have developed a quasi-3D model. It was previously applied to study the effect of the cell aspect ratio on the cell performance for a co-flow configuration by the authors' group [17]; the developed model implementing actual microstructure information of the electrodes successfully reproduced experiments conducted using a six-cell stack. Note that the quasi-3D model is capable of analyzing flows not only in the streamwise direction but also in the spanwise direction of a cell/stack, making it applicable to a wide variety of flow configurations as well as the conventional co-, counter-, and cross-flow configurations.

As an important application of the quasi-3D model, the present work aims to study the effects flow configuration in an eight-cell SOFC stack on the stack performance, the distribution of the current density, and the distribution of the cell temperature using the previously developed quasi-3D numerical model. Flow configurations with alternated air flows in parallel and perpendicular to the fuel flows are considered in addition to the conventional co-, counter-, and cross-flow configurations. In this study, the distributions of both the current density and cell temperature are discussed statistically regarding the overall dispersion and its interquartile range. This approach aims to provide both qualitative and quantitative measurements for distributions, which is a novel feature of this study.

2. Numerical modeling

This study is conducted on an eight-cell stack. Each cell unit, consisting of top and bottom separators, fuel, and air channels, and a positive-electrolyte-negative assembly (PEN), is modeled as shown in Fig. 1. The PEN is treated as a dense solid layer. Both the fuel and air channels are filled with metal foam as a current collector. Fig. 1(a)–(c) correspond to the conventional co-, counter-, and cross-flow configurations, while Fig. 1(d) and (e) show the cases with an alternate air

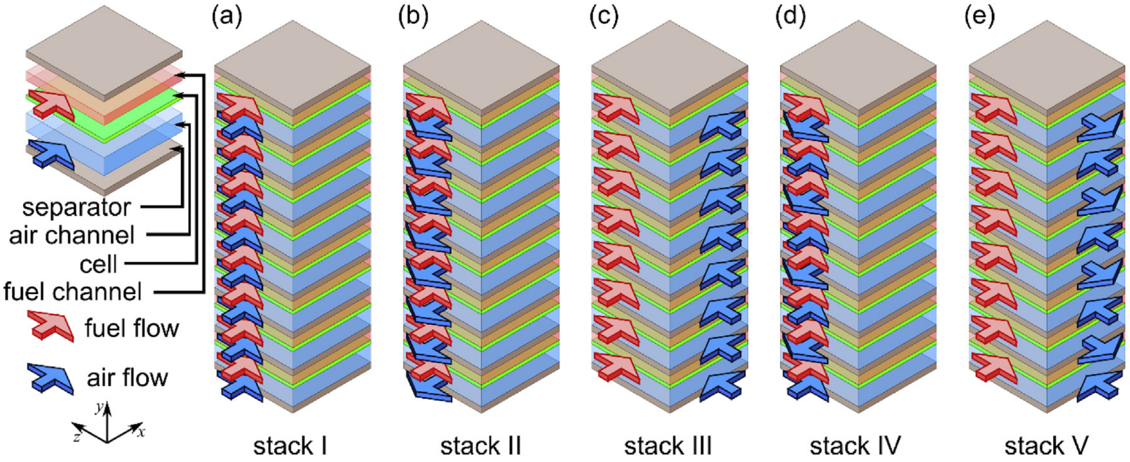

Fig. 1. Flow configurations in an eight-cell stack. (a) co-flow, (b) counter-flow, (c) cross-flow, (d) alternate air flow in the parallel direction to the fuel flow, and (e) alternate air flow in the perpendicular direction to the fuel flow.