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Modeling and experimental performance of an intermediate temperature reversible solid oxide cell for high-efficiency, distributed-scale electrical energy storage

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HIGHLIGHTS

- LSGM-electrolyte cell achieves area specific resistance <0.20 Ωcm^2 at 650 °C.
- Calibrated cell modeling analysis integrates materials and system development.
- Model calculations with careful parameter selection simulate roundtrip operation.
- Current density, reactant composition, and flow configuration are analyzed.
- Stack roundtrip performance is evaluated for efficiency and thermal management.

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ABSTRACT

Electrical energy storage is expected to be a critical component of the future world energy system, performing load-leveling operations to enable increased penetration of renewable and distributed generation. Reversible solid oxide cells, operating sequentially between power-producing fuel cell mode and fuel-producing electrolysis mode, have the capability to provide highly efficient, scalable electricity storage. However, challenges ranging from cell performance and durability to system integration must be addressed before widespread adoption. One central challenge of the system design is establishing effective thermal management in the two distinct operating modes. This work leverages an operating strategy to use carbonaceous reactant species and operate at intermediate stack temperature (650 °C) to promote exothermic fuel-synthesis reactions that thermally self-sustain the electrolysis process. We present performance of a doped lanthanum-gallate (LSGM) electrolyte solid oxide cell that shows high efficiency in both operating modes at 650 °C. A physically based electrochemical model is calibrated to represent the cell performance and used to simulate roundtrip operation for conditions unique to these reversible systems. Design decisions related to system operation are evaluated using the cell model including current density, fuel and oxidant reactant compositions, and flow configuration. The analysis reveals tradeoffs between electrical efficiency, thermal management, energy density, and durability.

1. Introduction

Reversible solid oxide cells (ReSOC) are a promising technology for electrical energy storage, performing energy management services including energy-time shifting, peak shaving, and renewables integration [1,2]. The U.S. Department of Energy (DOE) published long-term performance targets for electrical energy storage of 80% roundtrip efficiency, 10 ¢/kWh-cycle levelized cost, and 150 $/kWh capital cost [3]. Recent cell-level advances focusing on durability, cyclability, and intermediate temperature operation suggests that ReSOCs are capable of meeting these targets [4–8]. To complement improvements in cell performance, it is imperative to also consider the design and operation of ReSOC stacks and

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systems, and evaluate whether the high energy conversion efficiencies achieved under laboratory conditions can be maintained for a system implementation.

Few ReSOC system studies have been published to date [9], and many questions remain regarding system configurations and operating conditions best suited for effective implementation. This paper presents current-voltage performance and reports electrochemical impedance spectroscopy data from intermediate temperature ReSOCs constructed with a strontium- and magnesium-doped lanthanum gallate (LSGM) electrolyte. The experimental results are used to calibrate a physically based electrochemical model to simulate roundtrip energy storage. Performance metrics describing the electrical efficiency, thermal management, durability, and energy density are evaluated using the calibrated model for varied operating conditions.

A ReSOC is an operationally flexible energy conversion device which can operate in both power producing (solid oxide fuel cell, SOFC) and fuel producing (solid oxide electrolysis cell, SOEC) modes. Fig. 1 shows a simplified schematic of a stand-alone energy storage system with reversible solid oxide cells. The system operates sequentially between discharging (SOFC mode) and charging (SOEC mode). During discharging operation, a fuel-rich gas mixture flows out of a "fuel" storage tank to the ReSOC stack. In the stack, the fuel species are electrochemically oxidized generating electric power and exhaust species – primarily H_2O and CO_2 with some unused fuel. The exhaust species are stored in a different tank for use in charging mode. In charging mode, the stack is operated as an electrolyzer. Reactant and product flows reverse direction to supply the stack with a gas mixture from the "exhaust" tank. Excess electricity from, for example, a renewable or distributed energy resource, is used to reduce the "exhaust" species within the stack and re-fill the "fuel" tank.

Oxygen, typically from air, is consumed within the stack in SOFC mode by the electrochemical oxidation reactions (see Fig. 2a). In SOEC mode, oxygen is a product, and electrical performance is enhanced by flowing air as a sweep-gas through the stack to reduce the concentration of generated oxygen. The oxidant/sweep-gas flow is also necessary as a heat sink to maintain a desired stack temperature under exothermic operating conditions.

Progressing from the simple concept presented in Fig. 1 to design and implementation of a realizable ReSOC energy storage system requires addressing several design challenges, many of which are unique to reversible systems. One central challenge is that the discharging (SOFC) mode is highly exothermic under typical operating conditions, while the charging (SOEC) mode is typically endothermic or near thermo-neutral.

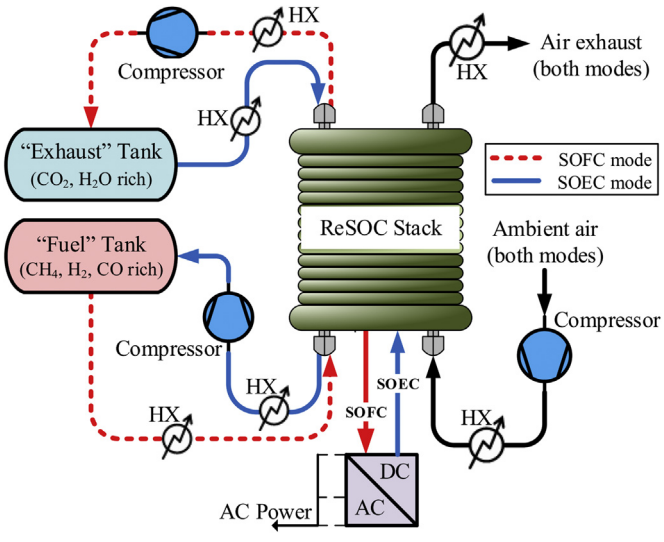

Fig. 1. Simplified schematic of a reversible solid oxide cell system for stand-alone electrical energy storage.

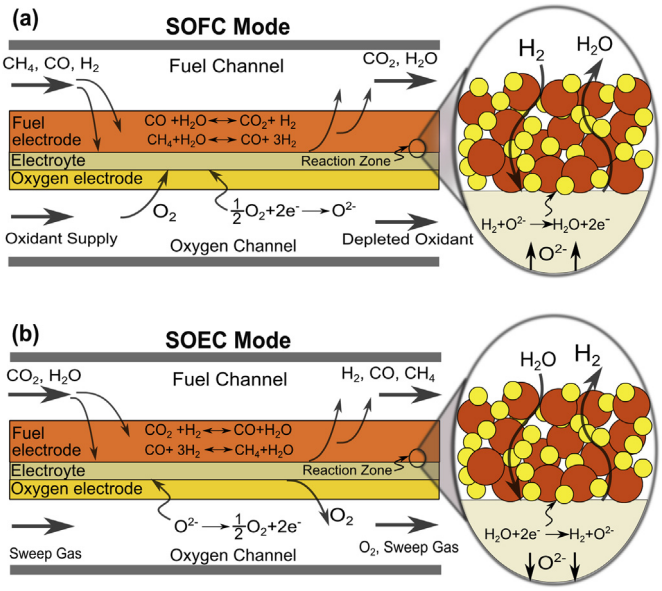

Fig. 2. ReSOC schematic showing gas flow channels, PEN structure, species diffusion, and reaction chemistry in (a) SOFC and (b) SOEC modes.

This work leverages a stack thermal management strategy that mitigates the thermal imbalance between operating modes. By using carbonaceous reactant species and intentionally selecting stack operating conditions, the overall electrochemical conversion process is mildly exothermic in both modes. Specifically, by operating the ReSOC at intermediate temperature and/or elevated pressure, methanation – an exothermic reaction – occurs within the stack during SOEC mode. The exothermic methanation offsets endothermic electrolysis reactions, thereby allowing an efficient, net exothermic process. This approach has been previously studied through thermodynamic analysis with expected beneficial ReSOC operating conditions of 600 °C and/or 10 bar [10], and modeling of grid-scale systems (>10 MWh) with expected roundtrip efficiency over 70% at optimal stack operating conditions of 675 °C and 20 bar [9,11].

The present study considers ReSOC stack operation to inform design decisions for a distributed scale system (<1 MWh). Pressurized ReSOC-based systems are considered more challenging to realize commercially at the distributed scale due to increased capital cost, durability, and concern over stack failure due to operating pressure excursions (i.e., cathode-to-anode pressure imbalance) so this study focuses on near-ambient pressure operation at intermediate temperature. At the intermediate temperatures required for the proposed thermal management strategy (<700 °C), resistance of yttria stabilized zirconia (YSZ)-electrolytes is too high for competitive performance. We instead utilize a promising intermediate temperature material set based on an LSGM-electrolyte with a strontium-doped lanthanum titanate support (SLT), which has shown ASR < 0.2 Ωcm^2 and power density > 1.5 W/cm^2 at 650 °C in fuel cell mode [7,12] (equivalent to performance of a state-of-the-art YSZ-cell at 850 °C).

In the present paper, button cell (0.5 cm^2 active area) performance with this novel material set is reported and used to calibrate an electrochemical model for both fuel cell and electrolysis modes.