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Feasibility of solid oxide fuel cell dynamic hydrogen coproduction to meet building demand

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HIGHLIGHTS

- A dynamic internal reforming-solid oxide fuel cell system model is developed.
- Electricity and hydrogen coproduction to meet dynamic building demand is modeled.
- The co-producing system well follows the measured building electric load dynamics.
- Dynamic operation of an SOFC system for co-producing hydrogen is demonstrated.
- Thermal and tank filling responses to dynamic operation are presented.

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ABSTRACT

A dynamic internal reforming-solid oxide fuel cell system model is developed and used to simulate the coproduction of electricity and hydrogen while meeting the measured dynamic load of a typical southern California commercial building. The simulated direct internal reforming-solid oxide fuel cell (DIR-SOFC) system is controlled to become an electrical load following device that well follows the measured building load data (3-s resolution). The feasibility of the DIR-SOFC system to meet the dynamic building demand while co-producing hydrogen is demonstrated. The resulting thermal responses of the system to the electrical load dynamics as well as those dynamics associated with the filling of a hydrogen collection tank are investigated. The DIR-SOFC system model also allows for resolution of the fuel cell species and temperature distributions during these dynamics since thermal gradients are a concern for DIR-SOFC.

1. Introduction

The concept of co-producing hydrogen and electricity using a high temperature fuel cell operating on natural gas is driven by the possibility that hydrogen is more valuable than heat and will become increasingly valuable with the emergence of hydrogen fuel cell vehicles and the required infrastructure for their refueling. Some researchers suggest that this concept will be responsible for 15% of the hydrogen production in 2030 [1]. The term coproduction (sometimes referred to as poly-generation or tri-generation) generally implies increased efficiencies through the production of co-products using one system. The specific case of using a high temperature fuel cell operating on natural gas to produce electricity and hydrogen has been demonstrated to produce the co-products with high efficiencies [2–5]. Using a solid oxide fuel cell to coproduce hydrogen provides two major benefits: higher cell voltages that lead to higher electrochemical efficiency and the ability to variably produce the co-products – electricity and hydrogen – to meet market demands. Given these possible benefits, it is important to study these systems. In addition, such systems could locally produce hydrogen to avert the emissions and energy penalties associated with distribution of hydrogen to refueling stations. Given these attributes and the likely deployment of hydrogen vehicles in 2015, it is important to study these high temperature fuel cell hydrogen coproduction systems.

Vollmar et al. performed thermodynamic design calculations examining different operating modes of a solid oxide fuel cell (SOFC) hydrogen coproduction system and different overall system

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configurations, e.g., some included a proton exchange membrane fuel cell that would operate on the coproduced hydrogen [2]. They showed that high efficiencies could be achieved in a solid oxide fuel cell coproduction system [2]. Leal and Brouwer investigated several solid oxide fuel cell hydrogen coproduction system configurations using thermodynamic analyses [3]. Their results showed that the direct internal reformation (DIR) configuration provided the highest electrical efficiencies and the most hydrogen per unit input of natural gas. Hemmes et al. studied three different operation modes in a direct internal reformation solid oxide fuel cell (DIR-SOFC) hydrogen coproduction system. These researchers concluded that the maximum total efficiency occurs at low fuel utilization regardless of the operating mode selected [4]. Margalef et al. also evaluated several different configurations of a solid oxide fuel cell hydrogen coproduction system using newly developed efficiency definitions [5,6]. Their results were found to be in agreement with Leal and Brouwer [3] in that the DIR (on anode) configuration yielded the highest overall efficiency.

Although previous studies have focused on the optimization of the system configuration and the steady state operation of the system, the study of the dynamic responses of these solid oxide fuel cell hydrogen coproduction systems to various possible perturbations has not yet been performed. The present study will investigate these dynamic system responses by examining the extreme case of a load following DIR-SOFC hydrogen coproduction system servicing the measured demand of a commercial building while storing coproduced hydrogen for later use, e.g., in fuel cell vehicles, industrial processes, or in a stationary proton exchange membrane fuel cell for dynamic dispatch or assistance in load following. Although high temperature fuel cells have yet to be proven as load following devices, some researchers have proposed that solid oxide fuel cells do have inherent transient capabilities that are afforded to them by their electrochemical nature [7].

The current load following analysis was selected to investigate SOFC system transient capabilities for the highly dynamic case of load following a measured building demand, focusing upon the possible dynamic thermal gradients that may be observed in such a system. This highly dynamic case analysis is especially important in a DIR-SOFC hydrogen coproduction system where although the DIR allows high efficiencies and high hydrogen production amounts [3,5] it also results in large thermal gradients within the SOFC. In addition coke formation may occur if high steam to carbon ratios are not dynamically maintained during transient operation [8,9]. Given these issues with DIR operation of SOFCs, it is important to resolve the temperature and species distributions across the SOFC. However, this can require detailed and highly spatially resolved physical modeling which may not be compatible with dynamic system simulation and controls development.

This work describes how a quasi-2-D DIR-SOFC model, which still allows resolution of the temperature and species distributions across the fuel cell, is integrated into a hydrogen coproduction system model, and demonstrates the feasibility of this integrated system's capability to meet the dynamic electrical load of a commercial building while also dynamically producing hydrogen on site for later use or sale (e.g., for vehicles).

2. Approach

This paper aims to investigate the dynamic capabilities of a DIR-SOFC H_2 coproduction system for implementation at a commercial building site. This investigation is accomplished by simulating the DIR-SOFC system as it follows measured building load data for a 24 h period with 3-s resolution. In addition to electrical load dynamics, the system dynamics associated with the hydrogen collector tank are examined. The dynamic electrical data were measured at a commercial building in the University Research Park near the University of California, Irvine campus on November 8, 2004 [10]. For the purposes of this work, the data were scaled so that a 1 MW SOFC system could continuously follow the building demand.

The hydrogen coproduction system is forced to meet the building load demand completely on its own with the exception of the fuel cell system blower demand. The blower power never exceeded 33 kW during the dynamics of the day (i.e., 3.3% of the maximum power of the system).

3. DIR-SOFC H_2 coproduction system model

The DIR-SOFC H_2 coproduction system model consists of three heat exchangers, a blower, a hydrogen separator, a collection tank, a catalytic burner, and the DIR-SOFC itself (see Fig. 1). The catalytic burner, blower, and hydrogen separator were modeled as single control volumes (bulk models) while the DIR-SOFC and heat exchangers are discretized into multiple control volumes (CV), which allows resolution of spatial distributions of temperature and species concentrations across these components. The system model was constructed in the MATLAB Simulink environment, and the system of ordinary differential equations (ODEs) resulting from the various single control volume system components and the discretization of the DIR-SOFC and the heat exchangers (method of lines) was solved using the numerical ODE solver package, ode15s. See Table 1 for the full specifications of the system.

3.1. Conserved quantities: mass and energy

Pressure is assumed to be constant throughout the system leaving only the conservation equations of energy and mass to be solved for in each control volume, which allows a substantial reduction in computational intensity. This is a reasonable assumption due to low Reynolds number flows and low pressure drops, which previous work has shown to minimally affect model fidelity [11]. With regard to the conservation of mass/species, the following equation is utilized

$$\frac{\mathrm{d}}{\mathrm{d}t}(NX_{\mathrm{out}}) = \dot{N}_{\mathrm{in}}X_{\mathrm{in}} + R - \dot{N}_{\mathrm{out}}X_{\mathrm{out}} \tag{1}$$

The conservation of energy equation is shown below

$$\frac{\mathrm{d}U}{\mathrm{d}t} = \dot{H}_{\mathrm{in}} + \dot{H} - \dot{H}_{\mathrm{out}} + \dot{E}_{\mathrm{gen}} + \sum \dot{Q} \tag{2}$$

The above equations will be solved simultaneously and dynamically for temperature and species concentrations.

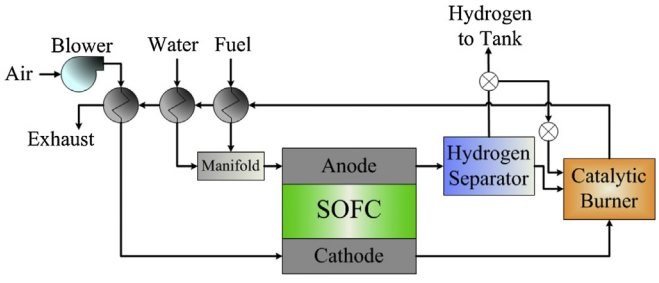

Fig. 1. DIR-SOFC hydrogen coproduction system schematic.