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Modeling and Model-based Analysis of a Solid Oxide Fuel Cell Thermal-Electrical Management System with an Air Bypass Valve

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ABSTRACT

For stand-alone solid oxide fuel cell (SOFC) power systems without grid connection, delivering demanded power, maintaining system temperature constraints, and achieving high system efficiency are the key design objectives. A typical SOFC system consists of an SOFC stack and a blower, a heat exchanger, an exhaust-burner as the primary components in its balance of the plant. In this work, a novel SOFC system design with an air bypass valve and a target operating range of 1 to 5 kW is considered. A system dynamic model, which captures the spatial electrical and thermal distributions of stack, is developed and optimal operating points to maintain the maximum steady state system efficiency are explored while enforcing four constraints on temperature and temperature gradient. Furthermore, the effects of the control variables, namely the bypass valve opening ratio (BP), voltage (U), fuel utilization (FU), and air excess ratio (AR) in improving system performance and expanding feasible operating range are quantified. In addition, the open-loop optimal operation strategy is obtained. The analysis demonstrates that the design of the stand-alone SOFC system is feasible and the bypass valve plays an important role in improving the overall system performance and operation ability.

1. Introduction

Solid oxide fuel cells (SOFCs) generate electrical power directly from hydrocarbon fuels with a number of advantages, such as high electrical efficiency, fuel flexibility, low emissions and quiet operation. They are also a complement to conventional power generation technologies (such as gas turbines), and therefore can be used very effectively in hybrid energy systems if properly integrated. As such, SOFC power systems are emerging as a promising alternative and practical solution for domestic, commercial and industrial sectors.

Since 1990s, SOFC technology has advanced considerably thanks to innovations in materials and design, especially in single cell and seal materials, cell fabrication, stack design, control and system integration [1]. The efficiency and life cycle performance have been improved dramatically as a result of relatively balanced technical development in all these technical fields [2]. However, high performance and stability of SOFCs are demonstrated mostly on test platforms, where they depend on the stable temperature environment of furnaces to provide necessary thermal operating conditions.

To fully capitalize its high efficiency benefit, the SOFC must have a relatively large envelope of transient operation (changes in power demand) for load following. This transient capability requirement, coupled with the high system efficiency and high fuel utilization considerations, poses major challenges when the SOFC is removed from the test platform to a self-sustained set-up supported by the balance of plant (BOP). Thermal stresses during transient operation can cause failure and degradation of the fuel cell [3–5]. To minimize thermal stresses and ensure system reliability, it is critical to enforce constraints in terms of maximum temperature and spatial temperature variations during transient operation of SOFCs.

For a simple SOFC system that consists of a blower, a heat exchanger, an SOFC stack and an exhaust burner, its degree of freedom for control and dynamic operation is very limited. It has been noted that different system configurations can have major impact on system performances. For example, research has shown that the average temperature of fuel cells can be effectively managed by manipulating the cathode air flow rate [6–9]. Inui et al. [10] have shown that it is possible to minimize the spatial temperature variations of the fuel cell over a large fuel cell

Abbreviations: BOP, Balance of Plant; OOP, Optimal operation point; PEN, Positive electrolyte negative; SOFC, Solid oxide fuel cell.

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Nomenclature

AR	Air excess ratio [-]
BP	Bypass valve opening ratio[-]
C	Specific heat capacity $[kJ \bullet kmol^{-1} \bullet K^{-1}]$
ΔE_0	Standard electrode potential (V)
F	Faraday's constant $[96485C \bullet mol^{-1}]$
FU	Fuel utilization [-]
H	Convective heat transfer coefficient $[kW \bullet m^{-1} \bullet K^{-1}]$
h	Gas enthalpy
I	Current $[A]$
i	Node current density $[A \bullet m^{-2}]$
$i_{0,an}$	Node anode exchange current density $[A \bullet m^{-2}]$
$i_{0,ca}$	Node cathode exchange current density $[A \bullet m^{-2}]$
LHV	low heat value $[kJ]$
M	Species mole fraction
$Max.\vert\Delta T_{PEN}\vert$	Maxmum PEN temperature gradient $[K \bullet cm^{-1}]$
$Max.T_{PEN}$	Maximum PEN temperature $[K]$
N	Control volume mole number $[kmol]$
$\dot{N}$	Molar flow rate $[kmol^{-1} \bullet s^{-1}]$
N_0	Number of fuel cells [-]
p	Pressure $[bar]$
p_j	Partial pressure of gas species j $[bar]$
P	Electrical power $[W]$
$\dot{Q}$	Heat transfer $[kW]$
R	Universal gas constant $[8.314kJ \bullet kmol^{-1} \bullet K^{-1}]$
$\overline{R}$	Input space
R_{ohm}	Ohmic resistance $[\Omega]$
SA	Surface area $[m^2]$
S	Node area $[m^2]$
T	Temperature $[K]$
U	Voltage $[V]$
$\dot{W}$	Work $[W]$
X	Symbol of temperature constraint

Greek letter

γ	Specific heat ratio
ζ	Efficiency

Subscript

amb	Ambient
act	Activation
B	Burner
bl	Blower
by	Bypass
con	Concentration
dl	Diagonal line
$diff$	The difference of stack inlet gas temperatures
i,k,m	Number
j	Species
In	Inlet
Out	Outlet
net	System net output power
req	Required output power for system
s	Stack
set	setpoint
v	Volume

operating envelope by optimally manipulating both the fuel cell air flow and air inlet temperature. Xi [11] has analyzed the system steady-state performance at half-load and full-load operation modes by considering two temperature constraints of maximum cell temperature gradient and maximum positive-electrolyte-negative (PEN) operating temperature. These results are crucial for safe and stable operation of the SOFC system with high system efficiency. Fardadi [12] has optimized system steady-state performance and developed a feedback controller to maintain the cell spatial temperature deviations during load following by adjusting the cathode inlet gas temperature using a bypass valve (BP). The simulation results indicated that the SOFC system can be designed and controlled to contain the spatial temperature distribution deviation within a small range so that thermal stress problems can be mitigated. In their work, the overall effect of the BP on the system thermal management and system efficiency under various output power conditions has not been analyzed.

There are some limitations for the work reported in [11,12] nevertheless. The SOFC systems considered in their studies are simplified without the complete BOP subsystem, which should at least consist of a blower, an exhaust-burner and heat exchangers. In Xi's work [11], the key BOP components were neglected and constant inlet gas temperature (1023 K) was assumed. Moreover, the coupled relations among fuel utilization, burner temperature and stack inlet gas temperature cannot be reflected. The same approach is taken in Fardadi's work [12]. Consequently, the analysis of [11,12] is incomplete and warrants revisit.

In this work, we first develop a pure hydrogen SOFC system model in Matlab/Simulink based on physical and electro-chemical laws to perform control-oriented system analysis. Then a reduction Based on the quasi-dimensional SOFC system model which includes a bypass valve in the BOP subsystem we investigate the sensitivity of the system performance to control input variables (i.e., voltage/current, bypass valve opening ratio, air excess ratio and fuel utilization). The optimal operation points (OOPs) for different load power conditions are then obtained by analyzing the system efficiency subject to four temperature constraints on the cell temperature gradient, cell operating temperature, stack inlet gas temperature difference, and burner temperature. Based on the OOPs, the effect of BP to system efficiency is investigated and the open-loop steady-state optimal control strategy is obtained, which is significant for the optimal management of SOFC thermo-electric coupled system.

This paper is organized as follows We present a dynamic model of a 5 kW co-flow, anode supported, intermediate temperature, and hydrogen fueled planar SOFC system with a bypass valve in Section 2. Analysis methodology for deriving the OOPs is established based on the model and presented in Section 3. In Section 4, the effects of operation variables on system steady-state performance are discussed in detail with the consideration of four temperature constraints. Based on the analysis results, an operation strategy for maintaining the maximum system efficiency is proposed. Finally, the conclusions are drawn in Section 5.

2. SOFC model development

Modeling of the SOFC system has been pursued by many research groups and different SOFC models can be found in the literature. For example, Achenbach [13] modeled the temperature distribution of a planar SOFC stack in three dimensions. Ota et al. [14] considered the temperature dynamics of a tubular SOFC in one dimension, where conduction, convection and radiation were all included. Qi et al. [15] modeled the temperature dynamics for a tubular SOFC to investigate the influence mechanisms, which