Journal of Power Sources 384 (2018) 223–231

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Fuel composition effect on cathode airflow control in fuel cell gas turbine hybrid systems

Nana Zhou[a,b,*], Valentina Zaccaria[c], David Tucker[c]

[a] State Key Laboratory of Mechanical Transmissions, Chongqing University, Chongqing 400030, China
[b] Postdoctoral Station of Mechanical Engineering, Chongqing University, Chongqing 400030, China
[c] US. Department of Energy, National Energy Technology Laboratory, Morgantown, WV 26507, USA

HIGHLIGHTS

- Cathode airflow transients were analyzed in an SOFC-GT hybrid system.
- Transfer functions were developed for key variable.
- The impact of fuel composition on cathode airflow control was evaluated.
- Controller response could become unstable with different composition.
- A single set of controller gains is insufficient for cathode airflow control.

ARTICLE INFO

Keywords:
Solid oxide fuel cell
Gas turbine
Hybrid system
Cathode airflow
Fuel composition
Robust control

ABSTRACT

Cathode airflow regulation is considered an effective means for thermal management in solid oxide fuel cell gas turbine (SOFC-GT) hybrid system. However, performance and controllability are observed to vary significantly with different fuel compositions. Because a complete system characterization with any possible fuel composition is not feasible, the need arises for robust controllers. The sufficiency of robust control is dictated by the effective change of operating state given the new composition used. It is possible that controller response could become unstable without a change in the gains from one state to the other.

In this paper, cathode airflow transients are analyzed in a SOFC-GT system using syngas as fuel composition, comparing with previous work which used humidified hydrogen. Transfer functions are developed to map the relationship between the airflow bypass and several key variables. The impact of fuel composition on system control is quantified by evaluating the difference between gains and poles in transfer functions. Significant variations in the gains and the poles, more than 20% in most cases, are found in turbine rotational speed and cathode airflow. The results of this work provide a guideline for the development of future control strategies to face fuel composition changes.

1. Introduction

The extremely high efficiency of solid oxide fuel cell (SOFC) technology draws significant interest regarding its applications in energy production, despite cost and reliability issues. The hybridization of an SOFC and a gas turbine has been proven to enhance the system electrical efficiency at both full- and part-load [1–4]. Because system performance is fairly independent from system size, and because of their large turn-down ratio, Solid Oxide Fuel Cell Gas Turbine (SOFC-GT) hybrid systems are considered a promising solution for distributed generation and micro-grid applications [5]. It is believed that SOFC based systems will play a pivotal role in sustainable energy production at distributed level, once durability and cost issues are assessed [6,7]. To explore the dynamic performance and develop control systems, the National Energy Technology Laboratory (NETL) designed and built a SOFC-GT hybrid emulation, as the Hybrid Performance (Hyper), by coupling a physical gas turbine with the cyber-physical system (CPS) of SOFC stack [8].

Another interesting aspect of SOFC technology stems from flexibility in terms of feeding fuel, due to the high operating temperature (600–900 °C) and the consequent capability to internally reform methane or other hydrocarbons [9,10]. Thus, the fuel is not limited to hydrogen, but includes natural gas, biogas and syngas. This flexibility can lead to significant advantages in micro-grid and poly-generation

---

[*] Corresponding author. State Key Laboratory of Mechanical Transmissions, Chongqing University, Chongqing 400030, China.
E-mail address: zhounana@cqu.edu.cn (N. Zhou).

https://doi.org/10.1016/j.jpowsour.2018.01.026
Received 5 September 2017; Received in revised form 3 January 2018; Accepted 9 January 2018

systems applications [11–13].

In the literature, SOFC performance with various fuel compositions were analyzed by many authors at both cell and system levels [14–16]. Yi et al. observed that thermal management of the fuel cell could not be the same if the fuel composition changed, and it was especially influenced by the presence of methane [17]. In an integrated gasifier SOFC gas turbine hybrid, fluctuations in biomass-derived syngas composition were shown to impact on the system power output and to cause detrimental temperature variations when an adequate control system was not used [18]. The effect of fuel composition change on the performance of an SOFC gas turbine hybrid system was also studied by Harun et al. switching from a coal-derived syngas to a high methane content fuel using Hyper facility [19,20]. Hence, hybrid system performance and safe operations need to be guaranteed for different fuel compositions.

Cathode airflow regulation has been considered an effective means to control fuel cell temperature in both standalone SOFC system and SOFC-GT hybrid system [21–23]. In a hybrid system, the management of cathode airflow can be accomplished by manipulating a bypass valve. In previous work, the effect of cathode airflow variation on the hybrid system performance and dynamics was experimentally evaluated, in which hydrogen-fueled SOFC was used [24]. The dynamic response of the system parameters was characterized for a step change in cathode airflow to develop transfer functions, mapping the response at the nominal operating state [25]. Using humidified H_2 as the anode fuel was to research the baseline operation of the cathode airflow transients and system control. As mentioned above, fuel composition had a huge impact on fuel cell temperature and thermal management, which would be challengeable without appropriate control systems. Therefore, to validate the transfer functions and the control method of cathode airflow shown in Ref. [25], another experiment under different fuel composition was needed. Thus, a comparison experiment was designed via the same bypass valve in Hyper facility using syngas as the fuel composition in the fuel cell anode. The employed fuel composition can well represent a reformed fuel after the complete conversion of methane to CO and H_2, as well as a typical coal-derived syngas.

The dynamic responses and transfer functions from the above experiment are presented in this paper, comparing with the results obtained in Refs. [24,25]. The aim of the present work is to compare the baseline hydrogen operation with syngas operation during airflow transients. If a different fuel composition leads to substantial difference in system dynamics, traditional controllers may not be adequate for fuel cell thermal management. The results support the design of robust controllers to deal with various fuel operations, with the final goal of increasing the system flexibility and improving the economic viability. If the transfer function parameters vary significantly, then even robust control may be inadequate, and an adaptive or multivariable approach must be taken.

Nomenclature

K	equilibrium constant	*Acronyms*	
G	Gibbs free energy	SOFC-GT	solid oxide fuel cell gas turbine
p	pressure, kPag	Hyper	hybrid performance
F	Faraday's constant, Coulombs mol^{-1}	CPS	cyber-physical system
η	losses	LHV	lower heating value, kJ m^{-3}
i	current density, A cm^{-2}	WGS	water gas shift
i_0	exchange current density, A cm^{-2}	HA	hot air bypass
T	temperature, K		
V	voltage, V		
θ	dead time, s	*Subscripts and superscripts*	
τ	time constant, s	*act*	activiation
k	transfer function gain	*cell*	fuel cell
y	output	*dif*	diffusion
u	input	an	anode
$\triangle$	difference/variation	ca	cathode
$\dot{Q}$	thermal effluent from fuel cell, kW		

2. Facility description and SOFC model

The experiment was conducted using Hyper facility located in NETL. The facility was designed to represent a pilot-scale topping cycle SOFC gas turbine hybrid system. To avoid damage of the extremely expensive SOFC stack, Hyper uses a cyber-physical system to emulate a physical SOFC stack. The layout of the Hyper facility with the SOFC cyber-physical system is depicted in Fig. 1.

The CPS included a cyber aspect, a physical aspect, and the connections and communications between these two levels, or middleware. A 1-D distributed real time model was built on the cyber level to simulate the electrochemistry and thermodynamics in the SOFC stack. On the physical level, two pressurized vessels and a post-combustor were used to emulate the physical existence of the SOFC stack, including the enthalpy change and the residence time associated with pressure dynamics. The first vessel, V-301, was used to represent the SOFC cathode volume, including the cathode channels, flow volume, and associated manifold volume. A natural gas combustor, V-302, was located after the volume to mimic the heat generated in the SOFC system. A second vessel in between combustor and turbine, V-304, was used to represent the post-combustor volume in the SOFC system. During operations, the airflow coming from the compressor fed the physical volumes: V-301, V-302, and V-304, in order. The live measurements of airflow parameters at V-301 inlet were sent to the cyber level as cathode inputs. Meanwhile, the natural gas mass flow in the physical system was controlled by the thermal output of the fuel cell in real time with a feed-forward controller, to emulate the thermal power from the SOFC model [26].

Hyper integrated the SOFC cyber-physical system with a physical 120 kW Garrett and two parallel heat exchangers for exhaust heat recover. After going through the SOFC cyber-physical system, the air expanded in the turbine, which was connected to a generator and a resistive load bank.

Three bypass valves were used in the system for control purposes. A bleed valve blew air into the atmosphere to mitigate compressor surge effects or to regulate turbine speed; a cold bypass diverted air from compressor exit to turbine inlet, bypassing heat exchangers and the SOFC simulators; a third valve bypassed the SOFC system, referred to as the hot air bypass, or shortened to HA in this paper. The HA bypass was mainly used to control cathode airflow.

2.1. Measurements

Multiple sensors were located in the plant to measure mass flows, temperatures, pressures and turbine speed. Details of measurements are presented in Table 1. In particular, measurements from FT-380 (cathode inlet mass flow), PT-305 (cathode inlet pressure) and TE-326 (cathode inlet temperature) were sent to the fuel cell model in real-time (i.e. every 80 ms) for numerical simulations.

2.2. SOFC real-time model

Since the SOFC hardware simulators are controlled by the thermal output from the cyber level, electrochemistry and thermodynamics of a planar, co-flow, anode-supported SOFC are modeled in MATLAB-Simulink using a real-time, distributed model. This model was previously built and validated with experimental data. Details about the model and its validation can be found in previous publication [27].