Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Dynamic modeling of solid oxide fuel cell and engine hybrid system for distributed power generation

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HIGHLIGHTS

- Development of a SOFC-Engine hybrid system dynamic model.
- Integrating the component models of SOFC, reformer, heat exchanger, engine, blower.
- Investigating the dynamic behavior of the hybrid system during transients.

ARTICLE INFO

Article history:
Received 11 June 2016
Received in revised form 14 March 2017
Accepted 15 March 2017
Available online xxxx

Keywords:
Hybrid system
Solid oxide fuel cell
Dynamic modeling
Engine
Optimal control strategy

ABSTRACT

Novel hybrid system composed of solid oxide fuel cell (SOFC) and engine has been presented by our previous study. The fuel contents remained in the anode tail gas from the SOFC is reutilized in the engine to improve the system electrical efficiency. Our previous research has confirmed the electrical efficiency of the SOFC-engine hybrid system can be enhanced by about 7.8% compared to the SOFC stand-alone system. Although the hybrid system has higher electrical efficiency than the stand-alone system, higher elaboration for the system operation should be necessary due to higher degree of system complication. The objective of the present study is to develop the dynamic modeling of the SOFC-engine hybrid system. The component dynamic modeling of SOFC, engine, external reformer, air blower, and heat exchanger are developed and integrated into a system using Matlab-Simulink®. Component models of SOFC, external reformer, and engine have been verified by comparison with the experimental data. The dynamic behavior of the hybrid system during transients is investigated. Since the time scale for the engine operation is much shorter than that of the SOFC stack, the power generated by the engine is mainly dependent on the characteristics variation of the anode tail gas. Consequently, the overshoot behavior is appeared in the engine power generation during increase of the demand SOFC power. This model is useful to develop the optimal control strategy for the SOFC-engine hybrid system.

1. Introduction

High temperature fuel cell system has been regarded as a promising power source for the stationary application due to high fuel flexibility, high efficiency, low emission, and high capability for combined heat and power (CHP) [1,2]. Our previous researches have presented the solid oxide fuel cell (SOFC)-homogeneous charge compression ignition (HCCI) engine hybrid system [3]. While SOFC stand-alone system uses the anode tail gas as a fuel for the catalytic combustor to supply the heat for the external reforming reaction, presented hybrid system uses that as a fuel for the engine to generate the additional electrical power. The SOFC-engine hybrid system has the 7.8% and 0.9% enhancement of the system electrical efficiency compared to the SOFC stand-alone system and SOFC-micro gas turbine (MGT) system, respectively. And the SOFC-engine hybrid system achieved respective 12.9% and 7.6% LCOE reduction by comparing the SOFC stand-alone system and SOFC-MGT hybrid system.

Many researchers have been trying to develop the SOFC hybrid system to increase the overall system electrical efficiency. The most common SOFC hybrid system is the SOFC-GT hybrid system [4–7]. The SOFC-GT hybrid system could be designed as several configurations by varying the design parameters of temperature, pressure, fuel type, reforming type, and steam supply [8]. The pressurized SOFC-GT hybrid system is the most common SOFC-GT hybrid system [4,6,9,10]. The conventional pressurized Brayton cycle can be employed for the SOFC-GT hybrid system by replacing the combustor with a SOFC stack [4–6,11]. The air entering the SOFC is heated by system exhaust gas by flowing through the

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http://dx.doi.org/10.1016/j.apenergy.2017.03.077
0306-2619/© 2017 Published by Elsevier Ltd.

Nomenclature

A	active area [m^2]
B	mass transport coefficient [$m\ s^{-1}$]
C	specific heat capacity of solid [$kJ\ kg^{-1}\ K^{-1}$]
C_P	constant pressure gas specific heat capacity [$kJ\ kg^{-1}\ K^{-1}$]
C_V	constant volume gas specific heat capacity [$kJ\ kg^{-1}\ K^{-1}$]
C	molar concentration [$kmol\ m^{-3}$]
D_H	hydraulic diameter [m]
D	diffusion coefficient [$m^2\ s^{-1}$]
ΔE	activation energy [$kJ\ kmol^{-1}$]
F	Faraday's constant [96,485 $C mol^{-1}$]
f	friction factor [–]
ΔG	Gibbs energy [$kJ\ kmol^{-1}$]
h	enthalpy [$kJ\ kmol^{-1}$], or heat transfer coefficient [$kW\ m^{-1}\ K^{-1}$]
ΔH	formation enthalpy [$kJ\ kmol^{-1}$]
i_o	exchange current density [$A\ m^{-2}$]
i	current [A]
i_L	limiting current density [$A\ m^{-2}$]
k_b	Boltzmann's constant
K_e	equilibrium constant of reaction [bar^2]
K	adsorption constant
k	kinetic rate constant [$kmol\ kg^{-1}\ h^{-1}$]
M	molecular Weight [$kg\ kmol^{-1}$]
N	molar capacity, or total number of moles [kmol], or number of fuel cells [–]
$\vec{N}$	species molar capacity [kmol]
$\dot{N}$	molar flow rate [$kmol\ s^{-1}$]
n	electron number [–]
P	pressure [kPa]
$\dot{Q}$	heat transfer rate [kW]
R	external load resistance [ohm], or Universal gas constant [8.3145 $kJ\ kmol^{-1}\ K^{-1}$]
$\dot{r}$	reaction rates [$kmol\ s^{-1}$]
r_p	pore radius [m]
$\vec{\dot{R}}$	reaction rate [$kmol\ s^{-1}$]
Re	Reynolds number [–]
Sh	Sherwood number [–]
T	temperature [K]
t	time [s], or thickness [m]
V	voltage [V], or velocity [$m\ s^{-1}$]
V	volume [m^3]
$\dot{W}$	generated Work
X	species mole fraction [–]

Greek letters

α	tuning coefficient of activation overpotential [–]
ε	electrode mean porosity [–]
Φ	diffusion flux through electrode [$kmol\ s^{-1}$]
Ψ_{ref}	refoming reaction rates [$kmol\ s^{-1}$]
τ	tortuosity [–], or timing, or torque [Nm]
σ	mean characteristic length [XX]
Ω	dimensionless diffusion collision [–]
ρ	density [$kg\ m^{-3}$]
η	efficiency [–]
λ	air stoichiometric ratio [–]
ω	rotational speed [$rad\ s^{-1}$]

Subscripts

A	anode
act	activation
b	burned
C	cathode
c	cylinder, or isentropic
CO	carbon monoxide
CO_2	carbon monoxide
$cell$	fuel cell
con	concentration
eff	effective
$elec\_anode$	anode electrode
$elec\_cathode$	cathode electrode
f	fuel
hr	heat release rate
H_2	hydrogen
ign	ignition
in	in to control volume
L	limiting
LHV	low heating value
$local$	local section
$Nernst$	Nernst
0	standard condition
O_2	oxygen
ohm	ohmic
out	out of control volume
p	pore
ref	reference condition, or reforming reaction
s	solid phase
tr	transfer

recuperator [5]. Ambient air is compressed up to the SOFC operating pressure. McLarty et al. investigated the steady-state and dynamic performance of the pressurized SOFC and GT hybrid system [12,13]. In the steady-state and dynamic study, they compared the system efficiency among various fuel cell hybrid system and investigated the dynamic performance with proposed system control logic, respectively. Ferrari presented the novel advanced control strategy consists of the feed-forward and proportional integral techniques for the SOFC hybrid system [14]. Since the SOFC-GT hybrid system used the natural gas as a fuel, the hydrocarbon fuel should be reformed to be used for electrochemical reaction. The hybrid systems with the internal reforming configuration can decrease the system cost and complexity because no external fuel processor is necessary [4–6,15–19]. In case of the direct internal reforming (DIR), the natural gas is reformed in the anode electrode of the SOFC. DIR has a system simplicity and low capital cost. However, the carbon deposition and the temperature gradient through the cell could be increased [4–6,20]. Indirect internal reforming [IIR] separated the reforming channel and the anode electrode to mitigate the issues of the DIR configuration. However, IIR configuration has a higher system complexity and capital costs [21,22]. In order to attain the internal reforming reaction, adequate amount of steam should be supplied [21–23]. The steam could be generated by the heat recovery steam generator (HRSG) driven by system exhaust gas [11,24,25]. The steam could also be supplied by recirculating the anode tail gas from the SOFC stack [23]. Even though the advantage of the internal reforming, certain systems equipped the external reformer for converting more complex types of fuels (biogas, syngas, and liquids) [4,6,26,27]. Yang et al. compared the internally and externally SOFC-GT hybrid system [28]. They concluded that the external reforming configuration has a penalty such as a more complex thermal management, which may require fuel addition to achieve the desire SOFC and turbine inlet temperatures. Other researchers studied on the integration of the SOFC, GT, and Steam Turbine (ST) in single combined cycle [29]. Arsalis presented a numerical study on the SOFC-GT-steam turbine (ST) hybrid system ranging from 1.5 to 10 MWe [29]. They concluded that the hybrid SOFC-GT-ST con-

Please cite this article in press as: Kang S, Ahn K-Y. Dynamic modeling of solid oxide fuel cell and engine hybrid system for distributed power generation. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.03.077