Applied Energy 205 (2017) 822–833

Contents lists available at ScienceDirect

Applied Energy

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

Development of a highly efficient solid oxide fuel cell system

Kanghun Lee, Sanggyu Kang*, Kook-Young Ahn

Korea Institute of Machinery and Materials, Daejeon 34103, Republic of Korea

HIGHLIGHTS

- Development of a novel highly efficient SOFC stand-alone system.
- Performance comparison of the proposed system with two other SOFC systems.
- Sensitivity analysis for the three systems.

ARTICLE INFO

Keywords:
Solid oxide fuel cell
Anode off gas
Ejector
Turbocharger
Optimization

ABSTRACT

The overall efficiency of a high-temperature fuel cell system can be enhanced by reuse of the unreacted fuel and the thermal energy from the system exhaust gas. Much of the steam in the anode off gas (AOG) can also be used for the methane steam reforming (MSR) reaction. In this study, a novel SOFC system has been developed. An ejector instead of a regenerative blower has been selected as a recirculation device for the AOG. The cathode air blower has been replaced with a turbocharger. To verify the efficiency enhancement of the proposed system, two other reference systems are presented, and their efficiencies are compared using Aspen Plus®. To estimate the system performance more accurately, a lumped electrochemical SOFC model and a one-dimensional ejector model are incorporated into the system model, using a Fortran® subroutine. To determine the optimal operating schemes for the presented system, its performance has been compared with that of two other reference systems by varying the operating parameters, such as the external reforming (ER) ratio, the fuel utilization, and the steam to carbon (S/C) ratio. Sensitivity analysis for the three systems has been conducted to determine the dominant operating parameters related to the system efficiency.

1. Introduction

The solid oxide fuel cell (SOFC) system has received attention as a strong candidate for stationary power generation because of its high fuel flexibility, high efficiency, low emission, and high capability [1,2]. The fuel contents and the thermal energy of the anode off gas (AOG) can be utilized to improve the system electrical efficiency in the SOFC system. The AOG of the SOFC also includes a large amount of steam for the methane steam reforming (MSR) reaction. Therefore, in the SOFC system the steam generator for the MSR reaction can be eliminated by AOG recirculation (AOGR). Although the AOG does not include a high enough amount of steam to satisfy the designed steam to carbon (S/C) ratio, the power consumption for the steam generation can be decreased. The AOGR can also decrease the amount of fuel input by reusing the fuel content based on the H_2 and CO, which can increase the system electrical efficiency. Lisbona et al. conducted a numerical study on a SOFC system with AOGR for the steam supply for the MSR reaction [3]. The system performance has been evaluated by varying the operating parameters. Schimanke et al. demonstrated and evaluated a two-stage serial connection system consisting of 30 cells stack with catalytic partial oxidation (CPOX) and 60 cells stack with MSR [4]. The AOG from the first stack is mixed with additional fuel and enters into the MSR and second stack, which increased the system efficiency. They confirmed the efficiency enhancement of the SOFC with AOGR by using this system configuration. The small scale SOFC system with propane fuel has been demonstrated by Dietrich et al. [5]. The hot-gas injector has been implemented for the AOGR. The experimental results presented the efficiency gain of the SOFC system with AOGR. Eveloy conducted the numerical analysis of an internal methane reforming SOFC with fuel recycling [6]. They concluded that the partial recycling of the anode exhaust mitigates the risk of carbon deposit, which could extend operational range of direct internal reforming SOFC. The numerical study on the diesel auto-thermal reforming for SOFC systems with AOGR has been performed by Walluk et al. [7]. They presented that the optimum AOGR ratio for attaining the maximum syngas production is 45% at the fuel utilization of 65%. The sensitivity analysis of

---

* Corresponding author.
E-mail address: kyu2613@kimm.re.kr (S. Kang).

http://dx.doi.org/10.1016/j.apenergy.2017.08.070
Received 4 April 2017; Received in revised form 10 August 2017; Accepted 11 August 2017

Nomenclature

A	area [m^2]
A^*	critical area at sonic point [m^2]
C_P	constant pressure gas specific heat capacity [$kJ\ kg^{-1}\ K^{-1}$]
CH_4	methane
C_2H_6	ethane
C_3H_8	propane
C_4H_{10}	butane
CO	carbon monoxide
CO_2	carbon dioxide
F	Faraday's constant [96,485 $C mol^{-1}$]
ΔG	Gibbs Energy [$kJ\ kmol^{-1}$]
ΔH	formation enthalpy [$kJ\ kmol^{-1}$]
H_2	hydrogen
i_o	exchange current density [Am^{-2}]
i	current [A]
i_L	limiting current density [Am^{-2}]
M	Molecular Weight [$kg\ kmol^{-1}$] or Mach number [–]
$\dot{m}$	mass flow rate [kg/s]
$\dot{N}$	molar flow rate [$kmol\ s^{-1}$]
N_2	nitrogen
O_2	oxygen
P	pressure [Bar]
R	universal gas constant [8.3145 $kJ\ kmol^{-1}\ K^{-1}$]
T	temperature [K]
t	thickness [m]
V	voltage [V]
v	velocity [ms^{-1}]
$\dot{W}$	generated Work

Greek letters

α	tuning coefficient of activation overpotential [–]
γ	specific heat ratio [–]
ρ	density [$kg\ m^{-3}$]
η	efficiency [–]

Subscripts

0	standard condition
2	position of nozzle outlet
3	position of diffuser inlet
A	anode
act	activation
air	air
b	mechanical
blower	blower
C	cathode
c	position of ejector outlet or Cold part
con	concentration
f	fuel
g	gas
h	hot part
H_2O	water
is	isentropic
in	in to control volume
LMTD	log mean temperature difference
MEA	membrane
Nernst	nernst
Net	net
m	position of fluids mixing
ohm	ohmic
out	out of control volume
p	primary flow
Pump	pump
s	secondary flow
sh	position of a normal shock wave
y	position of hypothetical throat

a SOFC system with a dynamic quasi-two dimensional model has been performed by Wahl et al. [8]. They concluded that system net electrical efficiency can be increased up to 65% from 57% by AOGR. Those studies did not specify the physical device for AOGR and its power consumption. This caused the overestimation for determining the system net efficiency.

The regenerative blower is mostly used to recirculate the AOG. The regenerative blower has a higher controllability compared to the ejector. However, the regenerative blower requires the parasitic power consumption to recirculate the AOG, which decreases the system electrical efficiency. And the temperature of the AOG is cooled down to 500 °C before flowing into the blower due to its durability. This could decrease the system thermal efficiency. The Powell et al. demonstrated the SOFC system with AOGR by regenerative blower [9]. The methane and AOG enters to the adiabatic steam reformer for the MSR reaction. Half of the methane can be converted into H_2 and CO by only the sensible enthalpy of the AOG. Performance and cost analysis of a 5 kW SOFC system with AOGR has been conducted by Toril et al. [10]. They presented that higher recirculation ratio increases net fuel utilization and net system electrical efficiency. Carre et al. developed the feed-forward control strategy of a SOFC system with AOGR [11]. In order to secure the optimal operating conditions, the respective flow rate of the fuel, air, and the AOG has been controlled by manipulating respective blowers. The efficiency of the hydrogen-fueled SOFC system with and without AOGR has been compared by Peters et al. [12]. AOG is flowing into the condenser to remove the water contents and recirculated to the SOFC stack by regenerative blower. The authors found that AOGR including steam condensation improves electrical efficiency by up to 11.9% compared to the SOFC system without AOGR.

The AOG could also be fed to the ejector without temperature decrease, because the ejector has higher robustness compared to the blower. When the high pressure of the primary flow is ensured in the system, the AOG could be entrained to the secondary flow in the ejector without additional power consumption. Marsano et al. captured the on-design and off-design performance evaluation of an anodic recirculation system for SOFC hybrid system [13]. Two different ejectors that have the constant pressure mixing section and constant area mixing section have been designed and integrated with the SOFC hybrid system model. They investigated the effect of the ejector part-load operation on the performance of the SOFC hybrid system. Kazempoor et al. presented and evaluated the characteristics of the hydrogen and methane-fuelled SOFC systems with numerical analysis [14]. In both of two systems, the cathode-off gas is recirculated by the ejector. The AOG is recirculated by the ejector for the MSR reaction in the methane-fuelled SOFC system, whereas the hydrogen-fuelled SOFC system does not recirculate the AOG. Zhu et al. developed the one-dimensional model of the fuel ejector for the AOGR of the SOFC system [15,16,17]. In those studies, they presented the optimal geometric design and control strategy of the fuel ejector with the proposed numerical model. Liu et al. investigated the effect of the anode recirculation on the carbon deposition and nickel oxidation of the SOFC system fed with gasification syngas [18]. They concluded that the net system electrical efficiency could be enhanced by 160% with the AOGR. Vincenzo et al. presented a novel detailed procedure for the ejector designing and validated the methodology by comparing with the experimental results [19]. They found that the fuel inlet temperature and the diameter of the mixing chamber largely affect