Energy Conversion and Management 148 (2017) 1382–1390

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Application of cascading thermoelectric generator and cooler for waste heat recovery from solid oxide fuel cells

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ARTICLE INFO

Article history:
Received 19 February 2017
Received in revised form 3 June 2017
Accepted 30 June 2017

Keywords:
Solid oxide fuel cell
Thermoelectric generator
Thermoelectric cooler
Waste heat recovery
Parametric study

ABSTRACT

Besides electricity generation, solid oxide fuel cells (SOFCs) produce a significant amount of waste heat, which needs to be immediately removed to ensure the normal operation of SOFCs. If the waste heat is recovered through bottoming thermal devices, the global efficiency of SOFCs can be improved. In this study, a new hybrid system mainly consisting of a thermoelectric generator, a thermoelectric cooler and an SOFC is proposed to recover the waste heat from SOFC for performance enhancement. The thermodynamic and electrochemical irreversible losses in each component are fully considered. An analytical relationship between the SOFC operating current density and the thermoelectric devices dimensionless electric current is derived, from which the range of SOFC operating current density that permits the thermoelectric devices to effectively work is determined. The equivalent power output and efficiency for the hybrid system are specified under different operating current density regions. The feasibility and effectiveness are illustrated by comparing the proposed hybrid system with the stand-alone SOFC. It is found that the power density and efficiency of the proposed system allow 2.3% and 4.6% larger than that of the stand-alone SOFC, respectively. Finally, various parametric analyses are performed to discuss the effects of some design and operation parameters on the hybrid system performance.

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1. Introduction

The worldwide energy and environment crisis raise a strong demand for development of efficient and clean energy technologies [1]. Fuel cells are promising power sources as they can efficiently and environmental-friendly convert the fuel chemical energy into electricity without intermediary complicated energy conversion processes [2]. Among various fuel cells, SOFCs have attracted considerable interests due to their low emissions, fuel flexibility, inexpensive metal catalyst and high electrochemical reaction rate [3–5]. In literatures, a great number of studies have focused attention on aspects such as new electrode material fabrication [6,7], lowering operating temperature [8,9], durability improvement [10,11], new cell prototype development [12,13], and single cell theoretical modeling [14–16].

The high operating temperature of SOFCs also produces substantial amounts of high-grade heat that are capable of powering a wide range of bottoming thermodynamic devices [17–21]. By developing cogeneration or trigeneration systems, the energy and exergy efficiencies of SOFC-based hybrid systems could reach 80% and 60%, respectively [22–24]. Extensive studies have been conducted on SOFC-based hybrid systems fueled with various kinds of fuels [25–27] and integrated with different bottom cycles [28–32] by means of various analysis approaches [33–35]. Liao et al. proposed thermophotovoltaic cells to efficiently exploit the waste heat from SOFCs and compared the proposed hybrid system with some other SOFC based hybrid systems [28]. Mehrpooya et al. [29] introduced a combined system containing SOFC-GT (SOFC-gas turbine) system, steam Rankine cycle and absorption refrigeration system. They used energy and exergy as well as economic factors to discriminate optimum operation points of the combined system. Ma et al. [30] carried out thermodynamic analyses of a trigeneration system by employing an ammonia-water mixture thermodynamic cycle to harvest the waste heat from a natural gas fueled SOFC-GT. They examined the dependence of system performance on several important thermodynamic parameters. Ebrahimi et al. [31] proposed a novel cycle combining SOFC, micro gas turbine (MGT), and organic Rankine cycle (ORC) for power production. They evaluated the

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http://dx.doi.org/10.1016/j.enconman.2017.06.089
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Nomenclature

A	effective polar plate area of an SOFC (m^2)
A_L	heat-transfer area between the SOFC and the environment (m^2)
A_{re}	heat-transfer area of the regenerator (m^2)
$C^0_{O_2}$	O_2 molar concentration at the cathode surface ($mol\ m^{-3}$)
$C_{T,c}$	total gas molar concentration in the cathode ($mol\ m^{-3}$)
c_1, c_2	composite parameters in Eq. (23) ($W\ m^{-2}\ K^{-1}$)
D_p	pore size (m)
D_s	grain size (m)
$D^{eff}_{O_2}$	effective diffusion coefficient for O_2 ($m^2\ s^{-1}$)
E	equilibrium potential of an SOFC (V)
E_{act}	activation energy level ($J\ mol^{-1}$)
F	Faraday's constant ($C\ mol^{-1}$)
$(-\Delta\dot{H})$	total energies supplied to the hybrid system per unit time ($J\ s^{-1}$)
Δh	molar enthalpy change of the electrochemical reactions ($J\ mol^{-1}$)
I	operating electric current through SOFC (A)
I_g	electrical current flowing through TEG (A)
i	dimensionless electric current flowing through TEG
i_1	lower bound dimensionless electric current of TEG
i_2	upper bound dimensionless electric current of TEG
j	operating current density of SOFC ($A\ m^{-2}$)
j_1	lower bound operating current density of the SOFC ($A\ m^{-2}$)
j_2	allowable maximum current density of the SOFC ($A\ m^{-2}$)
j_P	operating current density at P^*_{max} ($A\ m^{-2}$)
j_S	stagnation operating current density of the SOFC ($A\ m^{-2}$)
$j_{fc,P}$	operating current density at $P^*_{SOFC,max}$ ($A\ m^{-2}$)
j_{lH_2}	limiting current densities of H_2 mass transfers ($A\ m^{-2}$)
j_{lH_2O}	limiting current densities of H_2O mass transfers ($A\ m^{-2}$)
$j_{td,P}$	operating current densities at $P^*_{td,max}$ ($A\ m^{-2}$)
j_0	exchange current density ($A\ m^{-2}$)
$j_{td,\eta}$	operating current densities at $\eta_{td,max}$ ($A\ m^{-2}$)
Δj	effective operating current density interval ($A\ m^{-2}$)
K	thermal conductance of a thermoelectric element ($W\ K^{-1}\ m^{-1}$)
K_L	heat leakage coefficient ($J\ m^{-2}\ K^{-1}\ s^{-1}$)
K_{re}	heat-transfer coefficient ($J\ m^{-2}\ K^{-1}\ s^{-1}$)
L	thickness for the components (i.e., anode, cathode or electrolyte) of SOFC (m)
m	number of pairs thermoelectric elements in the TEG
n	number of pairs thermoelectric elements in the TEC
P	power output of the hybrid system (W)
P^*	power density ($W\ m^{-2}$)
P^*_{max}	maximum power density ($W\ m^{-2}$)
P_{H_2}	partial pressures H_2 (atm)
P_{O_2}	partial pressures O_2 (atm)
P_{H_2O}	partial pressures H_2O (atm)
P_{ref}	reference pressure (atm)
p	operating pressure (atm)
Q_C	heat-transfer rate from the cooled space to the environment ($J\ s^{-1}$)
Q_H	heat-transfer rate from the SOFC to the TEG ($J\ s^{-1}$)
Q_R	heat-loss rate of the regenerator ($J\ s^{-1}$)
Q_1	heat-transfer rates between the TEG and the environment ($J\ s^{-1}$)
Q_2	heat-transfer rates between the environment and the TEC ($J\ s^{-1}$)
R	universal gas constant ($J\ mol^{-1}\ K^{-1}$)
R_{te}	internal electrical resistance of a thermoelectric element (Ω)
S	cross-sectional areas of semiconductor arms (m^2)
T	operating temperature of SOFC (K)
T_C	temperatures of the cooled space (K)
T_0	temperature of the environment (K)
V	output voltage of an SOFC (V)
V_{act}	activation overpotential (V)
V_{con}	concentration overpotential (V)
V_{ohm}	ohmic overpotential (V)
X	ratio of the length of the grain contact neck to the grain size
x	ratio of thermoelectric element numbers between the TEG and the TEC
Z	figure of merit of a thermoelectric element (K^{-1})

Greek symbols

α	seebeck coefficient
β	effectiveness of the regenerator
γ	exchange current density pre-exponential factor
ε	electrode porosity
η	efficiency
η_P	hybrid system efficiency at P^*_{max}
σ	electrical conductivity of the components of SOFC ($\Omega^{-1}\ m^{-1}$)
ϕ	cooling rate of the thermoelectric device ($J\ s^{-1}$)
ψ	coefficient of performance of the thermoelectric device

Subscripts

a; c; e	anode; cathode; electrolyte
max	maximum
N	N-type semiconductor material
ohm	ohmic
opt	optimum
P	P-type semiconductor material
SOFC	solid oxide fuel cell
TEG	thermoelectric generator
TEC	thermoelectric cooler
td	thermoelectric device

cycle behavior and investigated the effects of ten design parameters on the overall cycle electrical efficiency. Eveloy et al. [32] integrated a hybrid SOFC-GT system and a reverse osmosis plant to enhance power generation and desalinate seawater. Compared with existing standard gas turbine cycle, the proposed system could improve the exergy efficiency by approximately 29% and simultaneously produce additional 494 m^3/h fresh water. Rokni et al. [33] performed thermodynamic and thermoeconomic analyses of a biomass gasified SOFC/Stirling heat engine hybrid system. It was found that a thermal efficiency of 0.424 LHV and a net electric capacity of 120 kW_e were obtained when the feedstock was 89.4 kg/h. Lee et al. [34] evaluated the environmental impacts associated with a SOFC-based combined heat and power (CHP) generation system. It was showed that in the total environmental impact of manufacturing, the SOFC stack accounted for 72% and the remaining balance-of-plant were responsible for the rest 28%. Aminyavari et al. [35] implemented exergetic, economic and environmental analyses on an internal-reforming SOFC-GT hybrid system integrated with a steam Rankine cycle. After multi-objective optimization procedures, the final optimum results demonstrated that the exergy efficiency and total cost rate were 65.11% and 0.1374 €/s, respectively.

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