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Numerical modeling of a cogeneration system based on a direct carbon solid oxide fuel cell and a thermophotovoltaic cell

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ABSTRACT

A new combined system model is proposed to numerically assess the feasibility and effectiveness of using a thermophotovoltaic cell (TPVC) for waste heat recovery from a direct carbon solid oxide fuel cell (DC-SOFC). The system model mainly consists of an irreversible TPVC model and a 2D tubular DC-SOFC model considering the ionic/electronic charge transport, mass transport, momentum transport, and chemical/electrochemical reactions. Mathematical expressions of the power density and efficiency for the proposed system are derived and the performance characteristics of the combined system are revealed. The impacts of operation conditions and designing parameters including the operating temperature of the DC-SOFC, distance between the carbon layer and anode, and band-gap energy of the TPVC on the combined system performance are examined. It is found that the TPVC can efficiently harvest the waste heat from the DC-SOFC. The maximum power density of the combined system is approximately 56.2% larger than that of the stand-alone DC-SOFC. Moreover, a higher operating temperature of the DC-SOFC and a smaller distance between the carbon layer and the anode are beneficial to the performance enhancement of the combined system. The power density of the combined system can be further improved through designing the TPVC with an optimum band gap.

1. Introduction

With the increasing fossil fuels depletion and energy demand, considerable efforts have been devoted to exploring renewable energy sources such as solar energy, wind energy, and fuel cells [1]. Compared with solar and wind energy, fuel cells are capable of directly converting the chemical energy of fuel into electricity and are efficient, reliable, and durable [2–4]. Most kinds of fuel cells use hydrogen as fuel but the large-scale hydrogen production suffers from some technological hurdles [5].

Different from hydrogen-fueled fuel cells, direct carbon fuel cells (DCFCs) use solid carbon fuel for power generation at high temperatures (typically ~800 °C) [6,7]. According to the types of electrolyte, DCFCs can be classified into three kinds: molten carbonate, molten hydroxide, and solid oxide DCFCs. Thereinto, the direct carbon solid oxide fuel cells (DC-SOFCs) are more suitable DCFCs because of their all-solid structure and non-noble metal catalysts [6]. It has been revealed that the performance of the DC-SOFC closely relies on the operation conditions and design parameters. Johnson et al. [8] analyzed the impacts of the design parameters including the tube spacing, carbon bed height, and cell voltage on the power density and efficiency of a solid oxide-based tubular air carbon fuel cell using the finite element method. It was found that the power density increases while the efficiency decreases with the increase of the bed height or tube spacing. Moreover, the DC-SOFC performance is also significantly affected by the carbon gasification kinetics [9]. Li et al. [10] experimentally studied the impacts of various catalysts on the performance of the DC-SOFC. Among K, Ni and Ca, K shows the best catalytic effect for carbon black gasification, while Ca exhibits the poorest catalytic effect for carbon black gasification. The effects of various kinds of carbon on the performance of the DC-SOFC were also found to be different. Jewulski et al. [11] investigated the lignite and char derived from lignite as fuel for the DC-SOFC. It was found that the DC-SOFC performance using char as fuel is better than that using lignite as fuel. Furthermore, the DC-SOFC usually operates at high temperatures so that the mass transport and thermal effect inside the cell should be also considered. Xu et al. developed a multi-physics model considering the electrochemical reaction, chemical reactions, ionic/electronic charge transport, mass transport and momentum transport to investigate the performance characteristics [12] and thermal effect [13] of a tubular DC-

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Nomenclature

B_0	permeability coefficient, m^2
c	speed of light, ms^{-1}
D_i	total effective diffusion coefficient component i, m^2s^{-1}
e	elementary charge, C
E	equilibrium potential, V
f_{rt}	emitter-to-cell view factor,
f_{tt}	cell-to-cell view factor,
F	Faraday's constant, C mol^{-1}
$\hbar$	reduced Planck constant, J s
j_{fc}	current density, A m^{-2}
j_0	exchange current density, A m^{-2}
J_{fc}	electrical current, A
k_B	Boltzmann constant, J K^{-1}
k_L	heat conductivity coefficient, W m^{-2} K^{-2}
n	number of transferred electron per electrochemical reaction,
p_x	gas partial pressure, Pa
P	power outputs, W
Q_e	heat flow from the external heat source to the DC-SOFC, W
Q_b	heat required by the Boudouard reaction, W
Q	heat flow released from the DC-SOFC, W
Q_{in}	heat flow released to the radiator, W
Q_L	heat flow dissipated to the ambient, W
Q_r	net heat flow from the radiator to the PV cell, W
Q_0	heat flow from the PV cell to the ambient, W
r	reflectivity,
R	universal gas constant, J mol^{-1} K^{-1}
$\Re$	refraction index
S	area, m^2
S_L	effective heat leakage area of the DC-SOFC, m^2
ΔS	entropy change of the electrochemical reactions, J mol^{-1} K^{-1}
T	temperature, K
u	velocity vector, m^3 s^{-1}
V_{tc}	voltage output of the TPVC, V
V_{act}	activation overpotential, V
V_{ohm}	ohmic overpotential, V
y_i	molar fraction of species i
z	direction

Greek letters

α	electron transfer coefficient,
β	area ratio of the DC-SOFC to the PV cell,
δ	Stefan-Boltzmann constant, W m^{-2} K^{-4}
ε	porosity of the electrode,
ζ	emissivity of the DC-SOFC,
μ	dynamic viscosity of fluid, Pa s
ξ_g	band gap energy, eV
ρ	density, Kg m^{-3}
σ^{ec}	effective conductivity, S m^{-1}
ϕ	electric potential, V

Subscripts

i	species (i = CO, O_2 or CO_2)
r	radiator
fc	fuel cell
tc	thermophotovoltaic cell

abbreviation

DC-SOFC	direct carbon solid oxide fuel cell
DCFC	direct carbon fuel cell
TPVC	thermophotovoltaic cell
BSR	back surface reflector

SOFC. It was found that the molar fraction of CO at the anode can be tuned by operating conditions, and the effect of the cell length on the current density of the DC-SOFC was weak. Similar to the other high-temperature fuel cells, excessive heat can be generated in the DC-SOFC when the DC-SOFC is operated at a high current density. The overall efficiency of the fuel cell system can be further enhanced if the excessive heat generated is further harvested by various approaches including thermoelectric generator (TEG) [14], thermionic converter (TIC) [15], thermophotovoltaic cell (TPVC) [16], gas turbine (GT) [17], Stirling cycle [18], Brayton cycle [19], etc [20]. The TPVC is a solid-state generator and enables to directly convert heat into electricity, which offers advantages such as silent, efficient, and clean [21]. Yang et al. [22] compared the above several technologies for waste heat recovery from the molten carbonate fuel cells (MCFCs) and found that the TPVC was more efficient than the other waste heat recovery technologies, as shown in Fig. 1. Obviously, the heat released from the DC-SOFC, if any, can be used to drive the TPVC for additional electricity production. Xu et al. [23,24] used Stirling engine and Otto engine to harvest the waste heat from the 2D DC-SOFC and found that the proposed approaches could efficiently harvest the waste heat from the DC-SOFC. However, no study has been conducted to recover the waste heat from the DC-SOFC using the TPVC and the performance comparisons of available DC-SOFC-based combined systems are rarely reported.

In this study, a solid-state TPVC is put forwarded to harvest the possible waste heat from a 2D tubular DC-SOFC. The adopted fuel cell model fully considers the ionic/electronic charge transport, mass transport, and momentum transport processes, which is more accurate than a black box fuel cell model before [14–22]. The output and thermal characteristics of the DC-SOFC are solved by finite element method. How to integrate these two subsystems and operate the combined system will be elaborated. The feasibility and effectiveness of this waste heat recovery technology will be evaluated. The impacts of operation conditions and designing parameters of the subsystems on the power density and efficiency of the combined system are discussed. The maximum power density is calculated and the optimal parameters are obtained. Finally, several DC-SOFC-based combined systems are compared. The obtained results may provide some theoretical bases for the optimal design and operation of practical DC-SOFC-based combined

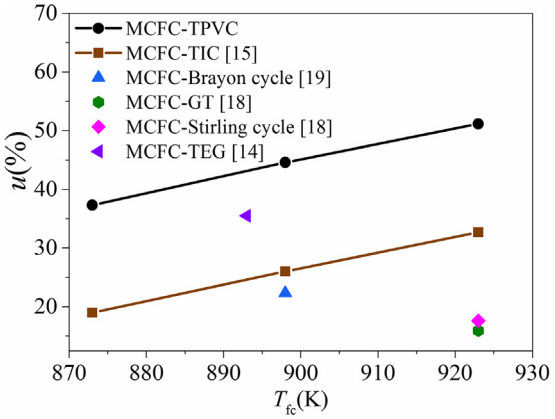

Fig. 1. Maximum power density improvement comparison of the different waste heat technologies for MCFCs [22], where $u = [(P^*_m - P^*_{m,f})/P^*_{m,f}] \times 100\%$, P^*_m is the maximum power density of the combined system and $P^*_{m,f}$ is the maximum power density of the MCFC.