



A feasible way to handle the heat management of direct carbon solid oxide fuel cells



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HIGHLIGHTS

- A novel system is proposed to handle the heat management of DC-SOFC.
- Three operation strategies are presented for different operation conditions.
- Power density and efficiency of the proposed system could reach 8100 W m^{-2} and 60%.
- Effects of some important parameters on system performance are revealed.

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ABSTRACT

A novel integrated system consisting of an external heat source, a direct carbon solid oxide fuel cell (DC-SOFC), a vacuum thermionic generator (VTIG) and a regenerator is proposed to handle the heat management of the DC-SOFC. The electrochemical/chemical reactions, ionic/electronic charge transport, mass/momentum transport and heat transfer are fully considered in the 2D tubular DC-SOFC model, which shows that the overall heat released in the cell is always different from the heat required by the internal Boudouard reaction. Three different operation strategies of the proposed system are presented, and accordingly, analytical expressions for the overall power output and efficiency for the proposed system are specified. The results show that the VTIG could effectively recover the waste heat for additional power production at a large operating current density, and the maximum power density and efficiency of the proposed system could reach more than 8100 W m^{-2} and 60% at $30,000 \text{ A m}^{-2}$ and 1173 K , respectively. The effects of the operating current density, the operating temperature and the distance between the carbon layer and anode of the DC-SOFC, and the size, anode temperature and work function of the VTIG on the performance of the proposed system are discussed through comprehensive parametric studies.

1. Introduction

Despite the tendency in decreasing the reliance on fossil fuels and the development of alternative renewable energy technologies due to energy crisis and relative environmental problems, solid carbon remains a main resource in the coming decades because of its abundant storage and low price [1]. However, the utilization of solid carbon in conventional thermal plants for electricity generation is low-efficient due to the limitation Carnot cycle and complex intermediate processes [2]. In addition, the pollution from thermal plants cause various environmental problems, e.g. acid rains and global warming. Therefore, an alternative high-efficient and clean energy conversion device for electricity generation from solid carbon is urgently needed, such as

solid oxide fuel cells (SOFCs) [3,4].

An SOFC is a whole solid-state device with a dense electrolyte sandwiched between two porous electrodes. As one of the most attractive energy conversion devices, SOFCs can directly convert gaseous fuels, such as H_2 and CO , into electricity through electrochemical reactions. The fuel flexibility characteristic of SOFCs also allows the utilization of other fuels, such as methane and solid carbon [5,6]. Solid carbon is an attractive fuel since it has a high volumetric energy density compared with gaseous fuels. Moreover, solid carbon is cheap and abundant, bringing huge economic advantages in exploring new markets [7–9]. However, the large particle size of solid carbon limits its direct contact with the triple phase boundaries (TPBs) in porous anode, resulting in a low output power density of direct carbon solid oxide fuel

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Nomenclature**Abbreviation**

DC-SOFC	direct-carbon solid oxide fuel cell
SOFC	solid oxide fuel cell
TPB	triple phase boundary
VTIG	vacuum thermionic generator
YSZ	yttrium stabilized zirconium

Roman

a	plate area ratio between VTIG and DC-SOFC
A	effective area of DC-SOFC, m^2
A_0	Richardson-Dushman constant, $A m^{-2} K^{-2}$
A_a	area of VTIG anode, m^2
A_c	area of VTIG cathode, m^2
B_0	permeability coefficient, m^2
c_{CO_2}	molar concentration of carbon dioxide, $mol \cdot m^{-3}$
C_p	constant-pressure heat capacity,
D_i^{eff}	effective diffusivity of species i , $m^2 \cdot s^{-1}$
e	charge of an electron, C
E_{acv}	activation energy, $J \cdot mol^{-1}$
E	equilibrium potential, V
E_{CO}^0	standard equilibrium potential for carbon monoxide oxidation, V
E_{eq}	equilibrium Nernst potential, V
E_{rb}	activation energy of Boudouard reaction, $J \cdot mol^{-1}$
F	Faraday constant, $96,485 C \cdot mol^{-1}$
i	current density, $A \cdot m^{-2}$
i_L	lowest working current density for VTIG, $A \cdot m^{-2}$
i_o	exchange current density, $A \cdot m^{-2}$
i_{tn}	thermal neutral current density, $A \cdot m^{-2}$
I	electrical current, A
I_a	reverse electric current from VTIG anode, A
I_c	reverse electric current from VTIG cathode, A
I_{TIG}	net thermionic electric current in VTIG, A
I_{tn}	thermal neutral current, A
J_{TIG}	net thermionic electric current density of VTIG, $A \cdot m^{-2}$
k_b	Boltzmann constant, $J K^{-1}$
k_{rb}	kinetic coefficient of Boudouard reaction, s^{-1}
n	number of electrons transferred per electrochemical reaction
N_i	flux of mass transport, $kg \cdot m^{-3} \cdot s^{-1}$
p	(partial) pressure, Pa
p_{CO}^L	local CO gas partial pressure, Pa
$p_{CO_2}^L$	local CO ₂ gas partial pressure, Pa
$p_{O_2}^L$	local O ₂ gas partial pressure, Pa
P	electricity power output, W
P_{SOFC}	electricity power output by DC-SOFC, W
P_{TIG}	electricity power output by VTIG, W
P^*	electricity power density, $W \cdot m^{-2}$
P_{max}^*	maximum electricity power density of DC-SOFC, $W \cdot m^{-2}$

P_{SOFC}^*	electricity power density of DC-SOFC, $W \cdot m^{-2}$
P_{TIG}^*	electricity power density of VTIG, $W \cdot m^{-2}$
Q	heat, W
Q_b	heat absorption by Boudouard reaction, W
Q_e	heat released by electrochemical reaction, W
Q_{SOFC}	heat rejection of DC-SOFC
R	gas constant, $8.314 J \cdot mol^{-1} \cdot K^{-1}$
R_{rb}	reaction rate of Boudouard reaction, $mol \cdot m^{-3} \cdot s^{-1}$
T	operating temperature, K
T_2	VTIG anode temperature, K
u	velocity field, $m^3 \cdot s^{-1}$
U	output voltage of VTIG, V
V	operating voltage, V
y_i	molar fraction of component i

Greek letters

α	charge transfer coefficient
β_{H_2}	electrochemical kinetics parameter for H ₂
ε	porosity
ε_0	effective thermal emissivity
η	electrical efficiency
η_{SOFC}	electrical efficiency of DC-SOFC
η_{TIG}	electrical efficiency of VTIG
η_{act}	activation polarization, V
η_{ohmic}	Ohmic polarization, V
κ	permeability, m^2
λ	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
λ_{eff}	effective thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
μ	dynamic viscosity of fluid, Pa·s
ρ	fluid density, $kg \cdot m^{-3}$
σ	Stefan-Boltzmann constant, $W \cdot m^{-2} \cdot K^{-4}$
σ^{eff}	effective conductivity, $S \cdot m^{-1}$
τ	tortuosity
\emptyset	potential, V
Φ_a	work function of the VTIG anode, eV
Φ_c	work function of the VTIG cathode, eV

Subscripts

an	anode
ca	cathode
co	carbon monoxide
H ₂	hydrogen
l	ionic phase
s	electronic phase

Superscripts

0	parameter at equilibrium conditions
eff	effective
L	local

cells (DC-SOFCs). To overcome this problem, *in situ* solid carbon gasification has been proposed. Through *in situ* gasification, solid carbon is converted to gaseous fuel (e.g. CO) before the electrochemical reaction, which keeps the high volumetric energy density of solid carbon and expands the electrochemical reaction area simultaneously. A number of studies have been conducted to further improve the performance of DC-SOFC by adopting catalysts for faster carbon gasification kinetics [10–13]. Moreover, it has been found that DC-SOFCs can co-generate fuel and electricity power, which further increases their economic advantage [14–18]. The thermal effect in DC-SOFC has been also studied

to examine its potential for combined heat, gaseous fuel and electricity power generation [19]. It was found that the DC-SOFC requires heat input at a small current density due to the endothermic carbon gasification reaction, while the cell releases waste heat at a large operating current density. Initial studies combining conventional Stirling cycle and Otto heat engine with the DC-SOFC for its performance improvement have been conducted [20,21]. However, a system combining DC-SOFC with more novel and advanced heat-to-electricity conversion device is still needed to examine the potential performance improvement.

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