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An efficient strategy exploiting the waste heat in a solid oxide fuel cell system

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A B S T R A C T

A novel model of the hybrid system consisting of a SOFC (solid oxide fuel cell) and a vacuum TIG (thermionic generator) is proposed so that the high temperature waste heat produced in the fuel cell can be efficiently exploited. Analytic expressions for the power outputs and efficiencies of the SOFC, TIG, and hybrid system are derived. The relation among the current density of the SOFC, the voltage output of the TIG, and the ratio of the areas of the SOFC and TIG is obtained by the energy balance equation. The influence of the current density of the SOFC on the power output density and efficiency is discussed for a given ratio of areas or voltage output. The maximum power output density and efficiency of the hybrid system are, respectively, equal to 0.560 W/cm^2 and 0.284 and the efficiency of the hybrid system at the maximum power output density is 0.240. The optimal regions of the power output and efficiency of the hybrid system are determined. The advantages of the hybrid system are expounded, compared with the single SOFC.

1. Introduction

Electrochemical energy conversion has particularly attractive as the demand of secure, clean, and sustainable energy sources. Fuel cells can directly convert chemical energy into electricity without ignition combustion and have aroused much speculation about application in different endeavors and are considered to be one of the most efficient energy conversion devices [1,2].

Among the existing types of fuel cells, high temperature SOFCs offer great promise for making the most use of various readily available carbon-containing fuels. For stand-alone applications, the efficiency of SOFCs can reach 45–65% [3], which can compete with internal combustion engines [4], but the efficiency will quickly decrease with the increase of the electric current. On the other hand, the conventional SOFCs operate at relative high temperatures (973–1473 K), resulting in high quality exhaust heat [5]. Therefore, the hybrid systems of SOFCs, which can overcome some shortcomings appearing in SOFCs and enhance the power output, have attracted considerable attention in the last years. Kaneko et al. developed a solid oxide fuel cell and micro GT (gas turbine) hybrid system [6]. Shirazi et al. analyzed an internal-reforming SOFC and GT hybrid system from the perspective of thermal, economic, and environment points [7]. Zhang and Chen established a hybrid system consisting of an SOFC and a heat engine and considered the influence of multi-irreversibilities on the performance of the system [8]. Facchinetti et al. optimized an SOFC-gas turbine (GT) hybrid cycle fueled with hydrothermally gasified waste biomass based on the first law of thermodynamics and exergy analysis [9]. Chen et al. put forward a fuel cell-thermoelectric generator hybrid system and determined the optimal operation condition [10].

TIGs (thermionic generators) are a kind of solid state generators. Renewed interests of TIGs are aroused due to the recent advances in device designs [11], electrode technology [12], and the desire to develop a high temperature topping cycle for thermal power systems [13,14]. Compared with traditional power plants, TIGs use electrons as the working substance without mechanically moving parts [15–17] and have advantages in aspect of small cubage and high power density. Moreover, a TIG has better performance at high temperatures (>1000 K) [18] and is more suitable for constituting a hybrid system together with an SOFC than a semiconductor thermoelectric generator [19,20].

In the present paper, we will establish a new model of the hybrid system composed of an SOFC as a topping cycle and a TIG as a bottom cycle, analyze the effects of main irreversibilities on the

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Nomenclature

a	ratio of areas
a_L	convective and/or conductive heat-leak coefficient, [W/(cm^2·K)]
A_0	Richardson–Dushmann constant, [A/(cm^2·K^2)]
A	area, [cm^2]
e	quantity of electric charge, [C]
E	reversible voltage of fuel cell, [V]
E_{el}	activation energy, [J/mol]
F	Faraday constant, [C/mol]
Δg°	standard molar enthalpy change, [J/mol]
Δh°	standard molar Gibbs free energy change, [J/mol]
$\Delta\dot{H}$	enthalpy change, [W]
i	current density, [A/cm^2]
i_0	exchange current density, [A/cm^2]
i_L	limiting current, [A/cm^2]
$i_{V,c}$	cutting current density for given voltage, [A/cm^2]
$i_{a,c}$	cutting current density for given ratio of areas, [A/cm^2]
I	electric current, [A]
k_B	Bolzmann constant, [J/K]
L_{el}	electrolyte thickness, [μm]
n_e	number of electrons
p	composition pressure, [atm]
p_0	standard atmospheric pressure, [atm]
P	power output, [W]
$P_{s,a}$	power output for given a, [W]
$P_{s,a,max}$	maximum power output for given a, [W]
$P_{s,max}$	maximum power output, [W]
$P_{s,V}$	power output for given V, [W]
$P_{s,V,max}$	maximum power output for given V, [W]
$P_{s,V,\eta}$	power output at maximum efficiency for given V, [W]
$P_{s,\eta}$	power output at maximum efficiency, [W]
q	heat flow, [W]
q_c	heat flow through TIG anode, [W]
q_L	heat leak, [W]
q_w	waste heat of SOFC, [W]
R	universal gas constant, [J/(mol·K)]
R_L	ratio of heat leak to waste heat
T	temperature of SOFC, [K]
T_0	environment temperature, [K]
T_2	temperature of TIG anode, [K]
V	voltage, [V]

Greek letters

γ	pre-factor for exchange current density, [A/cm^2]
ε_0	thermal emissivity
ε_L	thermal emissivity
η	efficiency
$\eta_{s,a}$	efficiency for given a
$\eta_{s,a,max}$	maximum efficiency for given a
$\eta_{s,a,P}$	efficiency at maximum power output for given a
$\eta_{s,max}$	maximum efficiency
$\eta_{s,P}$	efficiency at maximum power output
$\eta_{s,V}$	efficiency for given V
$\eta_{s,V,max}$	maximum efficiency for given V
σ	Stefan–Boltzmann constant, [W/(cm^2·K^4)]
σ_0	reference ionic conductivity, [S/cm]
Φ_c	work function of TIG anode, [eV]
Φ_h	work function of TIG cathode, [eV]

Subscripts

a	anode
act	activation
BV	Butler–Volmer equation
c	cathode
$conc$	concentration
el	electrolyte
f	SOFC
h	TIG cathode
ohm	ohmic
P	maximum power output
s	hybrid system
t	TIG
η	maximum efficiency

performance of the system, and determine the optimal ranges of key parameters. It is expected that the results obtained are of interest for readers in the research fields of fuel cells.

2. An SOFC-TIG hybrid system

Fig. 1 shows the schematic diagram of a hybrid system composed of an SOFC, a TIG, and a regenerator. In the hybrid system, the SOFC can produce power as well as act as the hot reservoir of the TIG. By using hydrogen as fuel and oxygen as an oxidant, the fuel cell can generate electricity via an electrochemical reaction. The regenerator is used to preheat the incoming gas and air. By using effectively a part of the waste heat produced in the fuel cell, the TIG can export an additional power. As a result, the hybrid system can obtain better performance than any one subsystem. In the hybrid system, it is assumed that the temperatures of the SOFC and the cathode of the TIG are uniform because it was experimentally demonstrated that the cell voltage variation caused by non-uniform temperature distribution of the SOFC can be controlled to be smaller than 1% [21]. It is further assumed that the temperature of the anode of the TIG is also kept to be constant through the control of the heat-transfer area and the electrodes of the TIG have the same inside area. It should be pointed out that it needs several hours for an SOFC to reach the working temperature from the room temperature [22,23]. Thus, the proposed model and

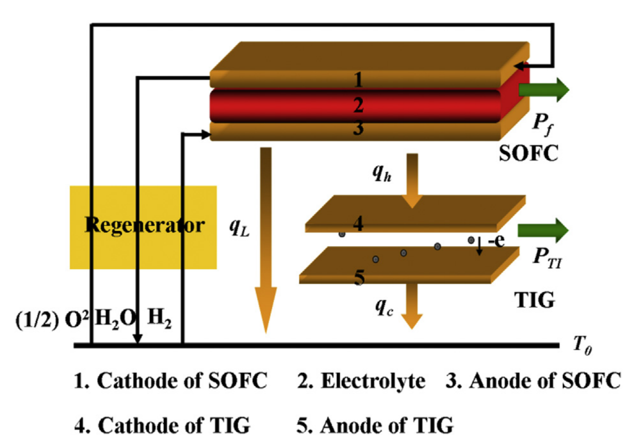

Fig. 1. The schematic diagram of an SOFC-TIG hybrid system.