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An efficient coupling system using a thermophotovoltaic cell to harvest the waste heat from a reforming solid oxide fuel cell

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ABSTRACT

The coupling system proposed here is composed of a reforming solid oxide fuel cell (R-SOFC) and a thermophotovoltaic cell (TPVC), where the synthesis gases (CH_4 and CO) replacing H_2 is used as fuel. The performance characteristics of the coupling system and R-SOFC are evaluated and compared. The optimal regions of the coupling system are determined and the parametric selection criteria are provided. The maximum power output densities of the R-SOFC-TPVC and SOFC-TPVC systems operated at 973–1273 K are calculated and compared with those of other SOFC-based coupling systems. It is found that the SOFC-TPVC or R-SOFC-TPVC system has some obvious advantages.

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Introduction

Solid oxide fuel cells (SOFCs) are a class of the best developing fuel cells. The simplest operation way of SOFCs is directly fueled by H_2. However, because of the difficulties of hydrogen production and preservation, SOFCs can directly use other inexpensive and resourceful gases as fuel by applying external [1] or internal [2,3] reforming technology. Thus, the performance investigation of reforming solid oxide fuel cells (R-SOFCs) has attracted great attention.

It is well-known that SOFCs or R-SOFCs can directly convert a part of the chemical energy into electric and simultaneously produce a large amount of heat. The recovery of the waste heat is an important subject in the development process of SOFCs [4–6]. In the last years, many researchers proposed various novel coupling systems composed of an SOFC and other devices such as the Carnot engine [4], thermoelectric generator (TG) [5], thermionic generator (TIG) [6], absorption refrigerator [7], gas turbine engine [8], Rankine engine [9], and Braysson engine [10]. The performances of these coupling systems are better than those of an SOFC or

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R-SOFC. Nevertheless, some of these coupling systems have still relatively low power output densities, and some of the coupling systems include the heat engine or refrigerator with a large size so that they may not be conveniently applied. Thus, it is a meaningful work to find some new coupling systems of SOFCs and study their performance. In contrast to the devices included in the coupling systems mentioned above, thermophotovoltaic cells (TPVCs) have many merits [11–13], such as the small size, stable operation, no noise, long life, large power output, and high efficiency. It can be expected that the coupling system including an R-SOFC and a TPVC will have some new advantages.

In this paper, the coupling system including an SOFC with fuel internal reforming and a TPVC is established. The work principle of the system is briefly introduced. The performances of the system are evaluated and the important parameters are optimized. Moreover, the performances of several SOFC-based coupling systems are compared, and consequently, it is expounded that the present coupling system is an excellent model and can efficiently harvest the waste heat from an R-SOFC or SOFC.

An R-SOFC-TPVC coupling system

The coupling system shown in Fig. 1 mainly consists of an R-SOFC and a TPVC, where the R-SOFC consists of a reformer, a fuel cell, and a regenerator, and the TPVC includes an emitter, a photovoltaic (PV) cell, and a vacuum gap between the PV cell and the emitter. In Fig. 1, P_c and P_f are the power outputs of the TPVC and SOFC, T_f, T_c, and T_e are the temperatures of the SOFC, PV cell, and emitter, T_0 is the environment temperature, q_1 and q_2 are the heat flows from the emitter to the PV cell and from the PV cell to the environment, respectively, and q_L is the heat leak flow from the fuel cell to the environment. The function of the regenerator is to preheat the impure fuels including CH_4 and CO and the air from T_0 to T_f through the high-temperature gases including H_2O, CO_2, and N_2 released from the fuel cell. The SOFC is operated at the steady temperature and pressure conditions. The TPVC in Fig. 1 [11,12] is different from that in Refs. [14,15]. When the TPVCs in Fig. 1 and Refs. [14,15] are operated at the same temperatures of high-temperature heat reservoirs, the maximum efficiency of the former [16] is larger than that of the latter [17]. Thus, such a coupling system in Fig. 1 can more efficiently harvest a part of the waste heat from the SOFC to obtain an additional power output.

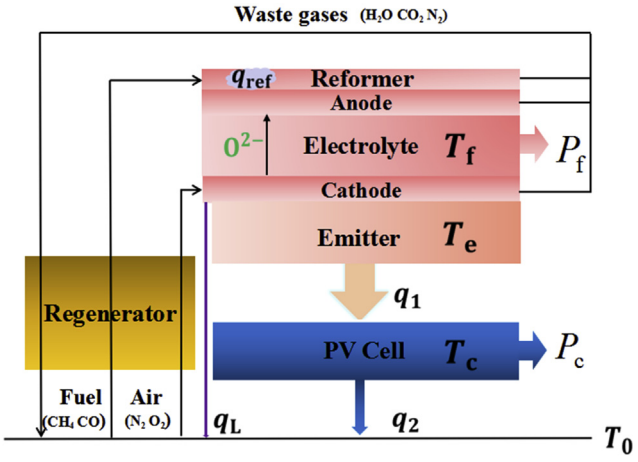

Fig. 1 – The schematic diagram of an R-SOFC-TPVC coupling system.

Power output and efficiency of an R-SOFC

The reformer shown in Fig. 1 is closely combined with the fuel cell, and consequently, they have the same temperature T_f. When the impure fuel including CH_4 and CO is preheated to T_f and inputted into the reformer, two steam reforming reactions occur simultaneously and can be written as [18–20] $CH_4+H_2O\rightarrow CO+3H_2$ (reforming) and $CO + H_2O\rightarrow CO_2+H_2$ (water-gas shift). There is a hypothesis that CH_4 and CO are consumed completely. The overall reforming reaction can be expressed as

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2. \tag{1}$$

When H_2 is inputted from the reformer to the anode of the SOFC and the preheated air including O_2 and N_2 is inputted into the cathode of the SOFC, two electrochemical reactions, $H_2\rightarrow 2H^+ + 2e$ and $(1/2)O_2+2e\rightarrow O^{2-}$, occur in the anode and cathode, and the overall reaction in the SOFC is $H_2+(1/2)O_2\rightarrow H_2O$. The substances in the anode include H_2 and H_2O. The molar rate $\dot{n}_H$ of Hydrogen consumed in the fuel cell reaction is dependent on the electric current I_f of the SOFC. According to the Faraday law [21],

$$\dot{n}_H = \frac{I_f}{n_e F}, \tag{2}$$

where n_e is the number of electrons and $F = 96485\ \mathrm{Cmol^{-1}}$ is the Faraday constant. According to Eq. (1), the molar rate $\dot{n}_f$ of fuel stream

$$\dot{n}_f = \frac{\dot{n}_H}{4\xi_{CH_4}}, \tag{3}$$

where ξ_{CH_4} is the molar fraction of CH_4 in the fuel flux. The reforming process needs an additional heat, i.e., [22].

$$q_{ref} = \dot{n}_f \xi_{CH_4} \left\{ 4\left[\Delta h_f^0(H_2) + \int_{T_0}^{T_f} C_{P,H_2} dT\right] + \left[\Delta h_f^0(CO_2) + \int_{T_0}^{T_f} C_{P,CO_2} dT\right] - \left[\Delta h_f^0(CH_4) + \int_{T_0}^{T_f} C_{P,CH_4} dT\right] - 2\left[\Delta h_f^0(H_2O) + L_m + \int_{T_0}^{T_f} C_{P,H_2O} dT\right]\right\}, \tag{4}$$

where $\Delta h_f^0(j)$ denotes the molar enthalpy change of the components $j = \{H_2, CO_2, CH_4, H_2O\}$ at room temperature, $C_{P,j}$ indicates the molar heat capacity at constant pressure of the given components j, and the molar latent heat of H_2O is denoted by L_m.

For the SOFC shown in Fig. 1, the terminal voltage output is [23].

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