



Theoretical basis and performance optimization analysis of a solid oxide fuel cell–gas turbine hybrid system with fuel reforming



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ABSTRACT

A novel model of the solid oxide fuel cell–gas turbine hybrid system with fuel reforming is established, where the residual fuel from the fuel cell is further burned in a combustor and the solid oxide fuel cell (SOFC) and combustor act as the high-temperature reservoirs of the gas turbine (GT). The irreversibilities existing in real systems including the overpotentials and heat leakage in the SOFC, the finite-rate heat transfer between the working substance of the gas turbine and the reservoirs, and the irreversible compression, expansion, and regeneration processes in the gas turbine are considered. By using the theories of electrochemistry and non-equilibrium thermodynamics, expressions for the power output and efficiency of the hybrid system are derived and the advantages of the hybrid system compared with the pure SOFC are represented. The optimally operating regions of some of the important parameters including the power output and efficiency of the hybrid system and the rate of the fuel flowing into the SOFC are determined. The rate of the air flowing into the cell at the optimal efficiency of the hybrid system is also derived. The results obtained here may provide some theoretical bases and optimization criterion for the design and operation of practical syngas SOFC-based hybrid systems.

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1. Introduction

The solid oxide fuel cell (SOFC) can use hydrocarbons as fuel with internal fuel reforming at the anode [1–3] due to its relatively high operating temperature. Compared with other fuel cells [4], one of the advantages of the SOFC is the ability to handle various hydrocarbons such as biogas, methane, methanol, ethanol, syngas, and propane [5–10]. The syngas as one of the fuels has attracted much attention because of its renewable status, widely available resource, relatively low feedstock cost, reduced environmental impact, etc. [9,11–14]. The syngas is produced from the biomass which comes from the living biological organisms and it is considered to be one of the renewable energy sources [12,15].

The effects of the materials of electrodes and electrolyte on the fuel reforming in the SOFC have been investigated [16–19], the mathematical models to analyze the performance of the SOFC have been developed [20–22], and the thermodynamic analyses to evaluate the key parameters have been carried out [23,24]. In order to efficiently utilize the residual fuel from the anode of the SOFC, a combustor may be introduced [25–28]. How to utilize the waste heat from the SOFC and the heat from the combustor and improve

the energy conversion efficiency of the SOFC is a significant problem. Here, a new model of indirect combined SOFC and gas turbine (GT) is established where not only the waste heat from the cell but also the combustion heat of the residual fuel is absorbed by the working substance in the GT. The optimal rates of fuel and air flowing into the SOFC are explored for the maximum efficiency of the hybrid system based on the conservation of energy. The general performance characteristics of the SOFC, and hybrid system are described, respectively. The advantages of the hybrid system are represented by numerical results.

The concrete contents are organized as follows. In Section 2, a model of the SOFC–GT hybrid system with fuel reforming is established, and the power output and efficiency of the hybrid system are derived. In Section 3, some general performance characteristics of the hybrid system are obtained and parametric optimal criteria are given. Finally, some important conclusions are drawn.

2. A model of the SOFC–GT hybrid system with fuel reforming

The hybrid system based on hydrocarbon is primarily composed of a SOFC, a GT and a combustor, as shown in Fig. 1, where the unreacted fuel from the SOFC is burnt in the combustor, the combustion products released from the combustor are used to preheat the

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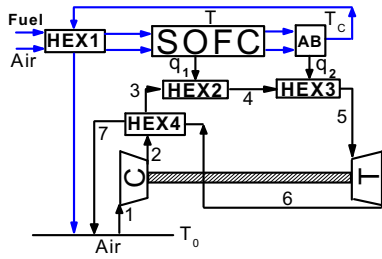
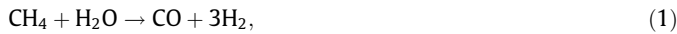


Fig. 1. A schematic diagram of the SOFC–GT hybrid system.

fuel and the air in heat exchanger 1, the high-temperature heats released from the fuel cell and combustor are, respectively, utilized as the heat input of the GT through heat exchangers 2 and 3, q_1 and q_2 are the rates of the heat flow from the SOFC at temperature T and from the combustor at temperature T_c to the working substance of the GT, respectively, and heat exchanger 4 is a regenerator in the gas turbine. The further analyses will be carried out on the basis of the following assumptions: (1) CH_4 and CO in the fuel are reacted fully at the anode of the SOFC; (2) the fuel is burned completely in the combustor; (3) the temperature and pressure are uniform and constant in the fuel cell; (4) the working substance of the GT is regard to be the ideal gas. In these assumptions, (1) and (2) can be approximated very well by engineering efforts and (3) and (4) are some idealized assumptions often used in the theoretical analysis, which can available capture the physical properties of the investigating problems. Below, the performance of the main components will be, respectively, analyzed and then the efficiency and power output of the hybrid system will be derived.

2.1. The SOFC with fuel reforming

In heat exchanger 1 in Fig. 1, the fuel and air are, respectively, preheated from the environment temperature T_0 to the operating temperature T of the SOFC by using the high-temperature gases from the combustor. According to the product of gasification of biomass [29–32], the fuel entering the anode of the SOFC may consist of H_2 , CH_4 , CO , CO_2 , H_2O , and N_2 . The chemical reactions in the cell can be summarized as



and



where Eqs. (1) and (2) are, respectively, the steam reforming and water gas shift reactions which occur at the anode of the SOFC [33,34], and Eq. (3) is the overall electrochemical reaction in the cell.

2.1.1. The power output and efficiency of the SOFC

According to Faraday's law, the molar rate of hydrogen consumed in Eq. (3) is $iA_c/(n_eF)$, where i is the current density of the cell, A_c is the surface area of mean active plates, n_e is the number of electrons transferred in reaction, and F is Faraday's constant.

When studying the performance of a SOFC, one has to consider the electrochemical irreversibilities which mainly result from the activation overpotential (V_{act}), ohm overpotential (V_{ohm}), and concentration overpotential (V_{con}). Considering the influence of irreversible losses mentioned above on the performance of the SOFC, one can derive the power output and efficiency of the SOFC as [35–37].

$$\begin{aligned} P_e &= iA_c(E - V_{act} - V_{ohm} - V_{con}) \\ &= \frac{iA_c}{n_eF} \left[-\Delta g(T) + RT \ln \left(\frac{p_{\text{H}_2} p_{\text{O}_2}^{1/2}}{p_{\text{H}_2\text{O}}} \right) - 2RT \sinh^{-1} \left(\frac{i}{2i_{0,a}} \right) \right. \\ &\quad \left. - 2RT \sinh^{-1} \left(\frac{i}{2i_{0,c}} \right) - in_e F \sum_j \delta_j a_j \exp \left(\frac{b_j}{T} \right) + RT \ln \left(1 - \frac{i}{i_{L,\text{H}_2}} \right) \right. \\ &\quad \left. + \frac{RT}{2} \ln \left(1 - \frac{i}{i_{L,\text{O}_2}} \right) \right] \end{aligned} \quad (4)$$

and

$$\begin{aligned} \eta_e &= \frac{P_e}{-iA_c \Delta h(T)/(n_e F U_a)} \\ &= \frac{U_a RT}{-\Delta h(T)} \left[\frac{-\Delta g(T)}{RT} + \ln \left(\frac{p_{\text{H}_2} p_{\text{O}_2}^{1/2}}{p_{\text{H}_2\text{O}}} \right) - 2 \sinh^{-1} \left(\frac{i}{2i_{0,a}} \right) \right. \\ &\quad \left. - 2 \sinh^{-1} \left(\frac{i}{2i_{0,c}} \right) + \ln \left(1 - \frac{i}{i_{L,\text{H}_2}} \right) + \frac{1}{2} \ln \left(1 - \frac{i}{i_{L,\text{O}_2}} \right) \right. \\ &\quad \left. - \frac{in_e F}{RT} \sum_j \delta_j a_j \exp \left(\frac{b_j}{T} \right) \right] \end{aligned} \quad (5)$$

respectively, where E is the open-circuit voltage of the SOFC [38–40], $\Delta g(T)$ is the molar Gibbs free energy change of the electrochemical reaction at temperature T and standard pressure, R is the universal gas constant, and p_k ($k = \text{H}_2, \text{H}_2\text{O}, \text{O}_2$) are the partial pressures of different components at electrodes, $\Delta h(T)$ is the molar enthalpy change of the electrochemical reaction at temperature T and standard pressure, $i_{0,a}$ and $i_{0,c}$ are, respectively, the exchange current densities at the anode and cathode, i_{L,H_2} and i_{L,O_2} are, respectively, the limiting current densities at which the hydrogen and the oxygen are used up at a rate equal to their maximum supply speeds and assumed to be constant [41] because the expression of the concentration overpotential adopted here is obtained by simplifying the Fick's model, δ_j is the current flowing length in layer j ($j = \text{anode, cathode, electrolyte, and interconnectors}$), a_j and b_j are constants, and U_a is the hydrogen utilization factor of SOFC and defined as the ratio of the rate of hydrogen consumed in the electrochemical reaction to that supplied from the anode of the SOFC. $\Delta h(T)$ and $\Delta g(T)$ can be expressed as [42,43]

$$\begin{aligned} \Delta h(T) &= \Delta h_f^0(\text{H}_2\text{O}) + L_m + \int_{T_0}^T C_{\text{H}_2\text{O},m} d\tau \\ &\quad - \left[\Delta h_f^0(\text{H}_2) + \int_{T_0}^T C_{\text{H}_2,m} d\tau \right] \\ &\quad - \frac{1}{2} \left[\Delta h_f^0(\text{O}_2) + \int_{T_0}^T C_{\text{O}_2,m} d\tau \right] \end{aligned} \quad (6)$$

and

$$\begin{aligned} \Delta g(T) &= \Delta h(T) - T \left\{ \Delta s_f^0(\text{H}_2\text{O}) + \frac{L_m}{373} + \int_{T_0}^T \frac{C_{\text{H}_2\text{O},m}}{\tau} d\tau \right. \\ &\quad \left. - \left[\Delta s_f^0(\text{H}_2) + \int_{T_0}^T \frac{C_{\text{H}_2,m}}{\tau} d\tau \right] - \frac{1}{2} \left[\Delta s_f^0(\text{O}_2) + \int_{T_0}^T \frac{C_{\text{O}_2,m}}{\tau} d\tau \right] \right\}, \end{aligned} \quad (7)$$

respectively, where $\Delta h_f^0(k)$ and $\Delta s_f^0(k)$ are, respectively, the molar enthalpy and entropy changes of component k ($k = \text{H}_2, \text{H}_2\text{O}, \text{O}_2$) at standard pressure and temperature $T_0 = 298 \text{ K}$, $C_{k,m}$ is the corresponding molar heat capacity, and L_m is the molar latent heat of H_2O .

2.1.2. The waste heat of the SOFC

According to Eqs. (1)–(3), one can obtain

$$n_f U_a (x_{\text{H}_2} + x_{\text{CO}} + 4x_{\text{CH}_4}) = \frac{iA_c}{n_e F}, \quad (8)$$

where n_f is the molar flow rate of the fuel, x_k ($k = \text{H}_2, \text{CO}, \text{CH}_4, \dots$) are the molar fractions of different gases in the fuel stream. The fuel

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