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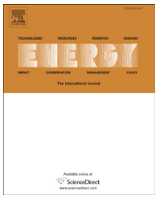

Performance optimum analysis of an irreversible molten carbonate fuel cell–Stirling heat engine hybrid system

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ABSTRACT

A new hybrid system mainly consists of a molten carbonate fuel cell (MCFC) and a Stirling heat engine is established, where the Stirling heat engine is driven by the high-quality waste heat generated in the MCFC. Based on the electrochemistry and non-equilibrium thermodynamics, analytical expressions for the efficiency and power output of the hybrid system are derived by taking various irreversible losses into account. It shows that the performance of the MCFC can be greatly enhanced by coupling a Stirling heat engine to further convert the waste heat for power generation. By employing numerical calculations, not only the influences of multiple irreversible losses on the performance of the hybrid system are analyzed, but also the impacts of some operating conditions such as the operating temperature, input gas compositions and operating pressure on the performance of the hybrid system are also discussed. The investigation method in the present paper is feasible for some other similar energy conversion systems as well.

1. Introduction

Due to the rising fuel prices, growing environmental concerns, and existing and upcoming environmental regulations, there is a growing pressure on power generation to operate in a more efficient, cost-effective and environment-friendly way. Because of their high efficiency and zero toxic emission levels, fuel cells are considered as a potential alternative to traditional power plant [1–3]. Among the existing fuel cell technologies [4–6], the molten carbonate fuel cell (MCFC) as a typical high-temperature fuel cell shows a great promise due to its fuel flexibility, high efficiency, and high temperature of the exhaust heat [7–9]. The high quality of the waste heat allows favorable co-generation and combination with other types of power generators such as heat engines and micro gas turbines [10–13].

Since it is difficult to experimentally quantify the interrelated parameters governing a hybrid system, theoretical modeling and numerical analysis become essential for the optimization of the system design and operating conditions. A number of numerical modeling investigations have been carried out about the MCFC-based hybrid system [12–17]. Some scholars theoretically simulated various MCFC–heat engine hybrid systems, and the performances of the hybrid systems are evaluated and optimized [5,6,12,13]. Some scholars modeled the MCFC-based hybrid systems for different usages from different viewpoint and different scale level [4,14–17], the obtained results may provide some theoretical basis for the development of practical MCFC-based hybrid systems. Recently, Masoud [18] performed the thermodynamic analysis of SOFC–Stirling hybrid plants using alternative fuels, it is found that the overall power production was increased by approximately 10% compared to that of a stand-alone SOFC plant. Among the numerous bottoming power generators, Stirling heat engine with its incomparable superiority becomes worthy of choice due to its simple construction and its manufacture being the same as the reciprocating internal combustion engine. The Stirling engine would obtain the economy of scale and could be built as a cheap power source [17,18,20]. The direct conversion of waste heat from the MCFC into mechanical power through Stirling heat engine may reduce not only the manufacture cost but also the manufacture complexity.

In the present paper, an irreversible thermodynamic–electrochemical model of a MCFC–Stirling heat engine hybrid system is established, in which not only the irreversible losses in the

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MCFC but also the heat-leak from the fuel cell to the environment as well as heat transfer between the fuel cell and the heat engine are considered. Based on the thermodynamic–electrochemical analysis, new expressions for some key parameters of the hybrid system such as the efficiency and power output are derived, from which the general performance characteristics are revealed and the optimal regions for some important performance parameters are given. The effects of some irreversible losses and operating conditions on the performance of the hybrid system are discussed, and consequently, the performance characteristics of the hybrid system are optimized. The results obtained will be useful in discovering feasible solutions that may lead to a preliminary conceptual design of a MCFC–Stirling heat engine hybrid system.

2. An irreversible model of the MCFC–Stirling heat engine hybrid system

A new hybrid system is considered to be composed of a MCFC, a Stirling heat engine and a regenerator, as shown in Fig. 1. The MCFC in the hybrid system plays a role of the high-temperature heat reservoir of a Stirling engine for a further use of the waste heat. The regenerator acts as a counter-flow heat exchanger, which economically absorbs the heat in the high-temperature exhaust gas to preheat the reactants to attain the reaction temperature.

In order to analyze the performance of the whole hybrid system, the following major assumptions are often adopted [7,8,12,20,21]:

(1) Both the MCFC and the Stirling engine are operated under steady-state condition;
(2) Operating temperature and pressure in the MCFC are uniform and kept as constants;
(3) All gases involved are assumed to be compressible ideal gases;
(4) Chemical reactions are complete and no reactants are remained after the reactions.

With the help of these assumptions, the expressions of the performance parameters for the hybrid system can be obtained. Below, we will analyze each component in the hybrid system respectively and then study the performance characteristics of the whole hybrid system.

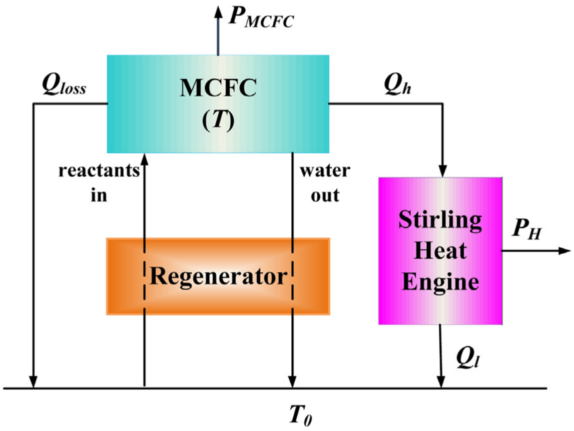

Fig. 1. The schematic diagram of an irreversible MCFC–Stirling heat engine hybrid system.

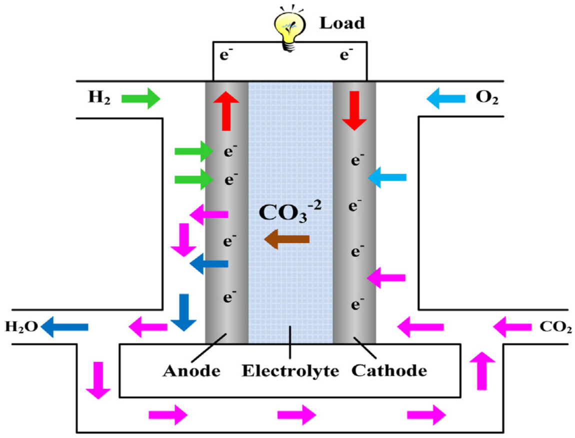

Fig. 2. The schematic diagram of an MCFC [5].

2.1. The MCFC model

The MCFC model presented in this study has been previously reported in Ref. [5]. As shown in Fig. 2, the produced carbon dioxide is transported from the anode to the cathode while the produced carbonate ions flow from cathode to anode. To sustain the total electrochemical reaction, the hydrogen and oxygen are provided continuously to the anode and the cathode, respectively. The overall electrochemical reaction is

$$H_2 + \frac{1}{2}O_2 + CO_{2,cat} \rightarrow H_2O + CO_{2,an} + \text{electricity} + \text{heat}, \quad (1)$$

where subscripts “an” and “cat” indicate, respectively, “anode” and “cathode”. In order to quantificationally describe the electrochemical reactions in the MCFC, it is quite important to understand the thermodynamic operation principles of the fuel cell. The basic thermodynamic relationship can be given as [5,12]

$$-\Delta\dot{H} = -\frac{\Delta h}{n_e F} jA, \quad (2)$$

where n_e is the number of electrons, F is Faraday’s constant, j is the current density, A is the polar plate area of the MCFC, Δh is the molar enthalpy change and can be calculated from the data in Table 1 [5]. According to the basic thermodynamic relationship: $-\Delta H = -\Delta G - T\Delta S$, the total energy $(-\Delta H)$ can be divided into two parts, i.e., $(-\Delta G)$ and $(-T\Delta S)$, which are representative of electrical energy and thermal energy, respectively. As long as the enthalpy change is more negative than the Gibbs free energy change of the reaction, a part of the total energy, which cannot be converted to electrical energy, will be released as heat.

Through agglomerate model developed by Yuh and Selman [21], the power output and efficiency of the MCFC system can be, respectively, expressed as [5]

Table 1
Thermodynamic parameters for the reactants/product at 1 atm, where (g) and (l) refer to gas and liquid phases, respectively.

Compound	$g(T_0)$ (J mol^{-1})	L_v (J mol^{-1})	Heat capacity
H_2 (g)	−38,960	–	$27.28 + 0.00326T + 50{,}000/T^2$
O_2 (g)	−61,120	–	$29.96 + 0.00418T - 167{,}000/T^2$
H_2O (g)	−298,130	–	$30.00 + 0.01071T + 33{,}000/T^2$
H_2O (l)	−306,690	40,700	75.44