Energy 93 (2015) 2079–2086

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A hybrid system using a regenerative electrochemical cycle to harvest waste heat from the proton exchange membrane fuel cell

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ARTICLE INFO

Article history:
Received 10 April 2015
Received in revised form
24 August 2015
Accepted 30 September 2015
Available online 19 November 2015

Keywords:
Optimization
Hybrid power system
PEMFC (proton exchange membrane fuel cell)
TREC (thermally regenerative electrochemical cycle)

ABSTRACT

A new hybrid system consisting of a PEMFC (proton exchange membrane fuel cell) subsystem and a TREC (thermally regenerative electrochemical cycle) subsystem is proposed to convert the waste heat produced by the PEMFC system into electricity. The performance of the hybrid system and its corresponding subsystems is analyzed. Results reveal that there exists optimal current densities of the PEMFC and TREC systems leading to the maximum power output of the hybrid system. With the maximum power output as the objective function, an optimization of the hybrid system based on genetic algorithm method is conducted under different operating temperatures of the PEMFC subsystem. The power output of the hybrid system is 6.85%–20.59% larger than that of the PEMFC subsystem. And the total electrical efficiency is improved by 2.74%–8.27%. The corresponding electrical efficiency of the TREC is 4.56%–13.81%. The hybrid system proposed in this paper could contribute to utilizing the fuel energy more efficiently and sufficiently.

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1. Introduction

Due to growing concerns about the shortage of fossil fuel resources and global warming induced by their combustion, alternative clean technologies and energy recovery solutions have attracted much attention in the past few decades. Fuel cell is recognized as promising scheme based on the fact that its efficiency it not limited by the conventional Carnot efficiency. Its production are electricity, water, and heat. And no harmful byproduct is produced [1]. Among several types of fuel cell, the PEMFC (proton exchange membrane fuel cell) is the most popular one and has been extensively investigated. The efficiency of the PEMFC is usually limited by 50%–60% [2]. That is to say, the quantity of heat generated by the PEMFC is quite a lot. In order to maintain the temperature homogeneity, the heat produced must be removed by cooling systems.

Recently, some literatures have been dedicated to recovering waste heat from the PEMFC system. Most of the efforts are devoted to studying CHP (combined heat and power) applications to recover the waste heat of the PEMFC [3–6]. Chu et al. [7] investigated a PEMFC based CHP system, the waste heat was used to supply hot water. Barelli et al. [8] analyzed a fuel cell-based residential cogenerative (CHP) energy system by the method of Simulink. Later in their work, an energetic–exergetic comparison between two CHP units for residential applications based on PEMFC and SOFC (solid oxide fuel cell) was performed [9]. The found that the PEMFC-based CHP system, operating at atmospheric pressure and low temperature, is more efficient. Arsalis et al. [10] studied a micro-CHP residential system based on High Temperature PEMFC to provide electric power, hot water, and space heating for a typical Danish single-family household. Shabani [11] conducted an experimental investigation of a PEM (proton exchange membrane) fuel cell to supply both heat and power in a solar-hydrogen RAPS (remote area power supply) system. Furthermore, combined refrigeration system based on PEMFC has also been studied [12,13].

However, very few papers are focused on using the waste heat of the PEMFC to generate electricity. Zhao et al. [2] used an ORC (organic Rankine cycle) system to recovery the waste heat released by the PEMFC system. The electrical efficiency is improved by 5%. A hybrid system consisting of a PEMFC and a semiconductor thermoelectric generator was also investigated [14]. The waste heat was used to drive a semiconductor thermoelectric generator to generate electricity. Thermodynamic cycles converting low grade thermal energy into electricity have been extensively investigated in recent years [15–25]. Among them, TREC (thermally regenerative electrochemical cycle) attracts rising attentions, which exhibits an

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http://dx.doi.org/10.1016/j.energy.2015.09.132
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efficiency of 40–50% of the Carnot limit for high-temperature applications [26]. Much effort has recently been dedicated to applying TREC in harvesting low-grade thermal energy [27,28]. Lee et al. [29] conducted an experiment on an electrochemical system for efficiently harvesting low-grade heat energy, and found that the electrical efficiency reaches 5.7% when cycled between 10 °C and 60 °C.

In this paper, we proposed a hybrid power system consisting of a PEMFC system and a TREC system. The waste heat produced by the PEMFC is utilized by a TREC system to generate electricity. Hence the overall electrical efficiency is improved. A mathematical model is developed to analyze the hybrid system. And the impacts of key parameters on the performance of the hybrid system and its subsystems have been investigated. Furthermore, an optimal analysis based on genetic algorithm is conducted with the maximum power output as the objective function. The optimal parameters have been obtained under different operating temperature of the PEMFC subsystem. Finally some concluding remarks are given.

2. The hybrid energy recovery system

Fig. 1 illustrates the schematic diagram of the hybrid power system using TREC to recover waste heat from the PEMFC. For the PEMFC with the cell reaction $H_2 + 0.5O_2 = H_2O$, at the anode, hydrogen dissociates into protons, which flow through the membrane to the cathode, electrons are collected as electrical current by an external circuit linking the two electrodes. In the cathode, oxygen combines with the electrons in the external circuit and the protons flowing through the membrane, thereby electricity is generated. Meanwhile water is produced and heat is released. The chemical reactions at the anode and cathode electrode of a PEMFC are as follows:

$$\text{Anode}: \; H_2 \rightarrow 2H^+ + 2e^-$$

$$\text{Cathode}: \; 2H^+ + 2e^- + 0.5O_2 \rightarrow H_2O + heat + electricity$$

The TREC system contains two cells: a hot cell in contact with the hot source (waste heat released by the PEMFC), and the other cold cell in contact with the cold source (cold water). Both the cells, where the electrochemical reactions take place, also function as heat exchangers. The electrolyte solution is cycled through the two cells. A separator is placed inside the cell to conduct ions and prevent the reactants from spontaneously mixing and reacting without exchanging electrons through the external circuitry [30]. As shown in Fig. 2, the TREC consists of four processes: heating, charging, cooling, and discharging. Due to difference of the charging voltage and the discharging voltage, and a net work equal to the difference between the charging and discharging energies is extracted.

2.1. Mathematical model of the PEMFC

The Nernst equation for the reaction at temperature T is [31]

$$E_{Nernst} = 1.229 - 0.85 \times 10^{-3}(T - 298.15) + 4.3085*10^{-5}T\left[\ln\left(P^*_{H_2}\right) + 0.5\ln\left(P^*_{O_2}\right)\right], \quad (1)$$

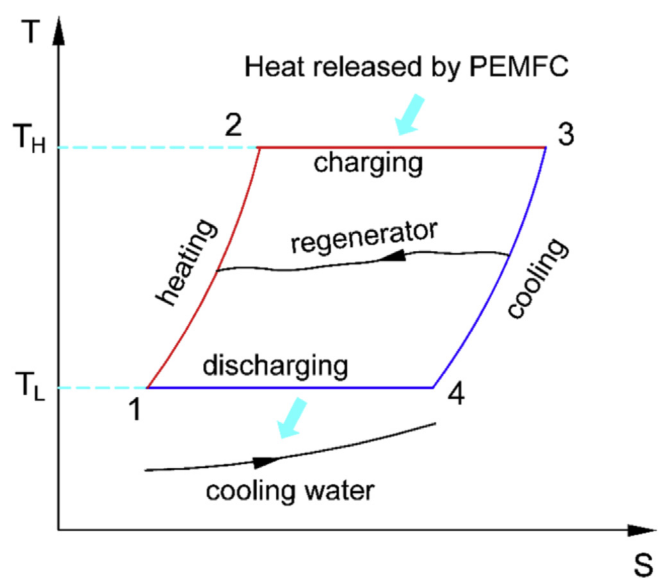

Fig. 2. T–S diagram for the TREC.

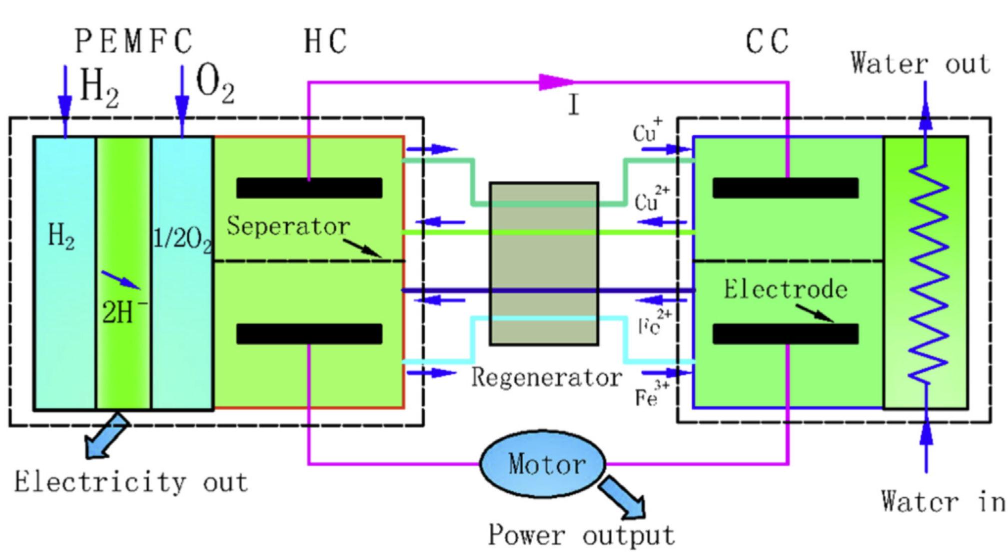

Fig. 1. Schematic diagram of the hybrid system consisting of a PEMFC and a TREC subsystems.

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